THE APPLICATION OF POTENTIATION IN OPTIMISING WARM-UP PROCEDURES IN YOUNG MALE ATHLETES

By

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A submission presented in partial fulfilment of the requirements of the University of Glamorgan for the degree of Doctor of Philosophy

March 2010
STATEMENT OF ORIGINALITY

This work has not been submitted for any degree or doctoral candidate at any University. To the best of my knowledge and belief, the dissertation contains no material previously written by another person, except where due reference is made in the thesis itself.

Signature

Ian Jeffreys
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ABSTRACT

While warm-up is one of the more generally accepted elements of the strength and conditioning portfolio, direct evidence as to its optimal application in enhancing sports performance is sparse. Today, there is a trend to look at warm-up as performance preparation (Jeffreys, 2007a, Verstegen, 2004), with the aim of maximising performance from the outset of, and throughout, competition and training. Given that the majority of team sports can involve high intensity exercise from the start, then a warm-up needs to be able to ensure that athletes are capable of maximal performance at the outset of a game, and do not have to use the first minutes of a game to progress to a point where they are capable of maximal performance. Performance has been shown to be optimised by the inclusion of high intensity activities in warm-up procedures (Faigenbaum, et al., 2005; Burkett, et al., 2005). However, while warm-up procedures are common, there is great variability in their application, and the inclusion of high intensity activities is not uniform (Jeffreys, 2007b). For this reason, many team sport warm-ups may not currently be optimal in terms of optimising speed and power performance. Indeed, the trend is currently for team sport warm-ups to become very skill based, and the inclusion of maximal intensity exercises may be on the decline rather than being increased.

Jeffreys, (2007b) has previously asserted that all warm-ups should consist of a potentiation phase, over and above a general phase. This potentiation phase should consist of a progressive series of exercises, until maximum effort is achieved. Additionally, Tillin and Bishop, (2009) have suggested that post activation potentiation (PAP) may provide a mechanism by which a super-maximal performance can be achieved via the use of a carefully selected and applied pre-conditioning activity.

While previous studies have indicated the potential of PAP to enhance factors affecting power performance, such as the rate of force development, studies on the direct effects on performance are limited, and the conclusions mixed (Tillin and Bishop, 2009). This series of studies addressed this lack of research, and investigated the application of warm-up methods to the acute enhancement of performance. To maximise the benefits of these studies to coaching practice, specific measures of performance were selected as the dependent variable throughout, so that all conclusions drawn could be applied directly to
performance. Similarly, competing athletes were selected as subjects for all studies, and all studies were carried out in the athlete’s training environment to maximise ecological validity and to ensure transferability of the results directly into enhancing sports performance.

The results of study one clearly support the use of a potentiation phase in warm-up. Investigating the effects of three warm-up protocols (general, sprint potentiated and jump potentiated) on 10 metre sprint performance, significantly superior (p<0.05) 10 metre sprint scores were found with a potentiated warm-up (both jump and sprint) than were achieved via general warm-up alone. It also supported the specific nature of PAP with sprint potentiation able to elicit significantly (p<0.05) superior sprint performance than a jump potentiated warm-up.

Studies 2-6 looked at the potential of exploiting PAP based protocols, as an addition to a basic potentiation phase within a warm-up. A range of methods were used that worked on either a kinematic basis where biomechanically similar movement patterns were loaded (loaded CMJ’s, sprint resisted running and sprint assisted running) or a kinetic basis where high forces were elicited (squats, MVC’s). The results of these studies showed no significant (p>0.05) benefit of any of these activities on either sprint or jump performance. These studies evaluated the acute effects of sprint resisted running, sprint assisted running, loaded jumps, maximal voluntary contractions and heavy squats superimposed onto the warm-up protocol of study 1 on speed and/or jump performance. No significant performance enhancements were found in any of the studies, indicating that none had the potential to acutely enhance performance.

In conclusion, the results of these studies recommend that all warm-ups include a potentiation phase, where a series of specific exercises are increased in intensity until maximum intensity is achieved. The use of additional activities, aimed to induce an additional PAP based effect on subsequent enhanced performance cannot be recommended for warm-ups for youth athletes.
ACKNOWLEDGEMENTS

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to the best of their abilities.

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To my wife Catherine and son James, you sacrifice so much to enable me to pursue my passion. I am forever grateful.
PUBLICATIONS

Papers/Book Chapters generated from data generated via the studies associated within this thesis:


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<td>1 RM</td>
<td>1 repetition maximum</td>
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<tr>
<td>3RM</td>
<td>3 repetition max</td>
</tr>
<tr>
<td>5RM</td>
<td>5 repetition max</td>
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<tr>
<td>ANOVA</td>
<td>Analysis of Variance</td>
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<tr>
<td>ATP</td>
<td>Adenosine tri-phosphate</td>
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<tr>
<td>Ca&lt;sup&gt;2+&lt;/sup&gt;</td>
<td>Calcium</td>
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<tr>
<td>CNS</td>
<td>Central nervous system</td>
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<td>EPSP</td>
<td>Excitatory post synaptic potentials</td>
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<td>H reflex</td>
<td>Hoffmann reflex</td>
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<td>K+</td>
<td>Potassium</td>
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<td>MLC</td>
<td>Myosin Light chains</td>
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<td>MVC</td>
<td>Maximal Voluntary Contraction</td>
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<tr>
<td>Na&lt;sup&gt;+&lt;/sup&gt;</td>
<td>Sodium</td>
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<td>NFL</td>
<td>National Football League</td>
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<td>NSCA</td>
<td>National Strength and Conditioning Association</td>
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<td>O&lt;sub&gt;2&lt;/sub&gt;</td>
<td>Oxygen</td>
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<td>PAP</td>
<td>Post-activation potentiation</td>
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<td>PF</td>
<td>Peak force</td>
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<td>PNS</td>
<td>Peripheral nervous system</td>
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<td>PP</td>
<td>Peak power</td>
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<td>PV</td>
<td>Peak velocity</td>
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<td>RFD</td>
<td>Rate of force development</td>
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<td>RLC</td>
<td>Regulatory myosin light chains</td>
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<td>SR</td>
<td>Sarcoplasmic reticulum</td>
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<td>SSC</td>
<td>Stretch shorten cycle</td>
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INTRODUCTION
INTRODUCTION

Strength and conditioning has rapidly emerged as an integral part of the performance programmes of the vast majority of sports at elite level. Involving the application of training regimes aimed at enhancing the physical performance of athletes, strength and conditioning represents applied science, utilising evidence based training methods directly into the enhancement of performance. Additionally, strength and conditioning requires the integration of knowledge from a wide range of disciplines, including biomechanics, physiology, motor control, psychology and pedagogy. These are all integrated into the direct application of training methods with the aim of maximising athletic performance. This search for optimal application requires both a pure and applied science approach, ensuring that practices utilised have a sound theoretical underpinning, supported by direct evidence in terms of their ability to directly enhance performance. Research in the field reflects these elements with a continuum of research between identifying key mechanisms underpinning performance, through to evaluating the impact of training methodologies directly on performance.

While some elements of the strength and conditioning portfolio have yet to achieve acceptance in the preparation of athletes in all sports, one area of practice which is almost universally accepted is the principle of the warm-up (Bishop, 2003a; Jeffreys, 2007a). Warming up has been defined as a period of “preparatory exercise to enhance subsequent competition or training performance” (Hedrick, 1992). Today, few athletes at any level train or compete without some attempt at a “warm-up”, and a warm-up strategy of some kind is normally incorporated into the preparation for any athletic competition. Indeed it is generally seen as deficient to just start training or competition without a pre game warm-up routine (Vandervoort, 2009). While warm-up is considered by coaches and athletes as essential for optimal performance, there is little scientific evidence supporting its optimal effectiveness (Fradkin, et al., 2010; Bishop, 2003a). Additionally, most studies into warm-up have focussed on its effect on physiological mechanisms, and there is little evidence on the effects of warm-up on actual performance (Bishop, 2003b). As a result, many warm-up practices are based on the trial and error experiences of athletes and coaches rather than on scientific study (Fradkin, et al., 2010; Bishop, 2003b).
To emphasise this lack of scientific study into optimal warm-up practices, Bazett-Jones, et al., (2005) contend that the most beneficial application of warm-up procedures now need to be re-evaluated. An increasing body of evidence is building up which both questions some current practices, and provides possible opportunities to improve practice (Tillin and Bishop, 2009, Jeffreys 2007 a; Bishop 2003b). In this way, strength and conditioning professionals should carefully consider the warm-up activities utilised before various sporting activities (McBride, et al., 2005). Investigation into the application of warm-up is therefore a worthy research problem (Fradkin, et al., 2010) and this needs to focus on specific warm-up practices and their direct effects on performance (Tillin and Bishop, 2009).

To maximise external validity, this analysis needs to be based on measures of performance performed in a direct training or competition environment (Thomas and Nelson, 2001). This requires the careful selection of dependent variables that actually determine the effects on performance (e.g. running speed), rather than indirect measures that imply performance (e.g. peak power output). It is possible that some warm-up activities may be useful for some activities and not for others (Fradkin, et al., 2010), and this further emphasises the need to carefully choose direct performance variables, and to apply warm-up protocols in contextually specific warm-up environments. Whilst these measures may at first seem simple, they are essential to ensure maximal external validity (Jobson, et al., 2009).

To evaluate warm-up procedures, and their direct impact on performance, a number of key areas need to be the focus of sustained research, both in their scientific underpinning but especially in their optimal application (Fradkin, et al., 2010). To facilitate this, studies into the acute effects of warm up procedures on performance are imperative, and this series of studies was designed to contribute to the enhancement of knowledge in this area. The studies investigated the potential of optimising warm-up practices, via the application of specific high intensity pre-conditioning activities within a warm-up, in order to provide an improvement in subsequent performance via a potentiation effect. As such, the current studies take an applied approach, where the aim is to examine the effects of various methodologies on performance, rather than to elicit the physiological or mechanical adaptations that result in any performance changes.
In identifying the key focus of research, it was important to understand the current direction in which warm-up application is moving. In this way, the key questions facing coaches could be elicited, and research protocols instigated to directly address the key issues facing coaches in designing optimal warm-up procedures. However, at present there is little peer reviewed data to enable accurate assessment of current trends in warm-up for performance. For this reason, a number of non peer reviewed sources have been integrated into the thesis to ensure that current trends in performance are analysed. This is a typical scenario in strength and conditioning, where coaches explore and utilise new methods basing their methodologies around their own data and experiences, with these methods later becoming the subject of empirical research.

Analysis of current trends demonstrated that, while the traditional elements of a general warm-up aimed at preparing athletes physically and psychologically for performance continue to dominate practice (Jeffreys, 2008a), a movement is developing aimed at exploiting warm-ups to ensure optimal performance in training and competition. Here, warm-up is increasingly being viewed as “performance preparation” (Jeffreys, 2007b; Verstegen, 2004), with the specific aim of optimising subsequent performance, rather than simply being a preparation for performance. While this may initially appear as a semantic issue, a change of emphasis from general preparation, to the specific optimisation of performance opens up opportunities for enhanced practice, but also questions some traditional warm-up practices.

To facilitate the development of effective warm-ups as “performance preparation”, Jeffreys (2007) has suggested a RAMP methodology, with the aim of maximising athletic performance, and this has been adopted by the United Kingdom Strength and Conditioning Association, as their advised protocol structure. This identifies three key phases of a warm-up:

1. Raise
2. Activate and Mobilise
3. Potentiate.

Raise
This phase is congruent with the general phase of traditional warm-ups, and involves a period of low intensity activity. This has the stated aims of elevating body temperature, heart rate, respiration rate, blood flow and joint fluid viscosity via low intensity activities (Wilmore, et al., 2008; Jeffreys, 2008a; Bishop, 2003a; Bishop, 2003b; Hoffman, 2002).

**Activate and mobilize**

This phase normally consists of dynamic flexibility exercises, together with selected muscle activation techniques and has two key aims: Firstly, to activate key muscle groups, ensuring that they are actively contracting through a given range of motion, and secondly to mobilize key joints and ranges of motion used in the sport (Jeffreys, 2007a; Verstegen, 2004). This phase replaces the static stretching phase of the warm-up, which is generally not advised for performance for sports requiring high levels of speed, strength or power due to the deleterious effects on these variables (Vandervoort, 2009; Jeffreys, 2008b; Jeffreys, 2007a).

**Potentiate**

This phase of the warm-up is less universal and sees a gradual shift towards the actual sport performance or workout itself. It can involve execution of motions of optimal velocity and intensity that rehearse the desired motor patterns (Vandervoort, 2009). Where used, this normally involves sport specific activities of increasing intensity. This specific warm-up can provide ergogenic benefits compared to those provided by a general warm-up (Bishop, 2003b). Including these high intensity dynamic exercises can facilitate subsequent performance (Burkett, et al., 2005, Faigenbaum, et al., 2005), and is the essence of the potentiation phase of the warm-up.

The potentiation phase of the warm-up can have two aims.

1. The first, and most common, aim, is to increase the intensity of exercise to a point at which athletes are able to perform their training/match activities at the maximal levels (Jeffreys, 2007a; Faigenbaum, et al., 2005).

2. The second is to select activities that may contribute to a super-maximal effect, where the activities chosen contribute to an enhanced performance effect, via the utilisation of the post activation potentiation (PAP) effect (Tillin and Bishop, 2009;
Jeffreys, 2007a). PAP is an increase in muscular performance characteristics as a result of their contractile history (Tillin and Bishop; 2009; Hodgson, et al, 2005; Robbins, 2005) and can result in an enhancement in the explosive capability of the muscle (Comyns, et al., 2007). This has the potential to produce an acute increase in power output (Young, et al., 1998; Tillin and Bishop, 2009), and thus, the potential to positively impact on performance measures that depend upon high levels of power such as speed and agility (Stone, et al., 2007).

Whilst the first two stages of this warm-up classification are now generally accepted within the strength and conditioning field, the latter element is still in its formative stage. Application of PAP to aid athletic performance is an important area for research (Tillin and Bishop 2009; McBride, et al., 2005), and its use in warm-up protocols provides a potential for enhancing subsequent performance in a range of sports (Tillin and Bishop, 2009).

This series of investigations looked at the opportunities to utilise potentiation based activities in warm-up, and tried to evaluate the optimal application of the potentiation phase of a warm-up, for field based team sports. Its aim was to directly evaluate the effects of specific interventions on performance, and to make subsequent recommendations as to their application within coaching practice. To maximise the application of the research to sport, the emphasis of the research was on the acute enhancement of athletic performance, as this is the key determinant of whether potentiation can, or should, be applied in the athletic arena. Whilst the underlying physiological and mechanical aspects were considered, they were not the focus of these studies, instead, the important element examined was the effects of the warm-up interventions on direct measures of performance, such as running speed. This applied research design was utilised to maximise the transfer of the results into coaching practice. This would enable coaches to use any data generated to construct more effective warm-up protocols, and to ensure that warm-ups are based on a sound rationale, rather than merely replicating commonly used warm-up procedures (Bishop, 2003b).

Although PAP has been studied for many years, the research into its application to human performance is limited (Tillin and Bishop, 2009). Currently, research on PAP entails the utilisation of three broad categories of possible potentiation: a series of evoked twitches,
evoked tetanic contractions or sustained maximal contractions (Hodgson, et al. 2005; Sale, 2002), and methods within the latter category have varied from maximal isometric contractions to a series of heavy isotonic resistance exercise, such as a squat. Currently, the literature regarding both the efficacy and optimal application of PAP is limited. To date, the majority of the work published on the acute effects looks at the effectiveness of resistance training methods to increase subsequent power output, and little work has been carried out on a specific measure of sports performance such as running speed (Fradkin, et al., 2010; Tillin and Bishop, 2009; Jeffreys, 2007; McBride, et al., 2005).

If PAP is a viable phenomenon, then there could well be justification in utilising this phenomenon in the design of warm-ups, especially for speed and power based sports (Bishop, 2003a). In doing this, coaches require important information on both the effectiveness of PAP, and its optimal application. The present investigations evaluated whether PAP can enhance jumping and speed performance in 17 –19 year old team sport athletes, and investigated the effectiveness of incorporating PAP into warm-up routines for this age group. All studies were designed with a sports performance focus to help inform coaching practice, a key element of effective sport science (Stone, et al., 2004). This complies with the advice of Tillin and Bishop, (2009) who concluded that if the intention is to utilise PAP in a sport specific situation, only the results of studies reporting the effects of pre-conditioning activities on performance of an explosive sports activity should be considered. For this reason, direct measures of performance were analysed as the dependent variables rather than indicators of performance. This decision was further supported by Murphy and Wilson (1997) who found that the ability of tests of muscular function to reflect changes in performance is severely limited. They recommended that any studies designed to investigate the effects of interventions on performance should directly measure performance rather than report scores of changes in muscle function. The present investigations were designed in accordance with these guidelines. To maximise ecological validity, all studies were performed with training athletes in their normal training environment. Additionally, warm-up protocols were carried out prior to actual training sessions to further maximise ecological validity, and were thus subject to the unique constraints of the training arena. This ensured that any protocols developed could be applied directly into training or competition environments.
CHAPTER ONE – REVIEW OF LITERATURE
CHAPTER ONE – REVIEW OF LITERATURE

General Background

An important facet of sport science research is the possibility to generate information which can inform performance progression (Jobson et al., 2009). While a warm-up is now almost universally accepted as a key part of any training session or game, there is a general lack of research on the effects of warm-up procedures directly on measures of sports performance (Bishop, 2003a; Jeffreys, 2007). Given that the aim of a warm-up is to acutely maximise performance (Chiu et al., 2003), then the need to investigate the effects of differing warm-up procedures on performance is critical. An optimal warm-up is necessary to maximise the rate of force development and neuromuscular co-ordination, which are both key elements of speed and power performance (Gourgoulis et al., 2003). Performance in sports requiring speed and power can only be maximised via the application of appropriate warm-up protocols. This makes the investigation of methods of optimising warm-ups essential, and provides the context for this series of investigations. An investigation into optimal warm-up procedures first necessitates an examination of the fundamental aims of warming up.

The aim of warm-up

In its simplest terms, the goal of the warm-up is to prepare the athlete mentally and physically for exercise or competition (Hoffman, 2002). A well designed warm-up can increase muscle temperature, core temperature, blood flow (McArdle et al., 2007) and also disrupt transient connective tissue bonds, and affect neuromuscular function (Enoka, 2008). These effects have been reported to have the following positive effects on performance:

- Faster muscle contraction and relaxation of both agonist and antagonist muscles. (Hoffman, 2002).
- Improvements in rate of force development and reaction time (Enoka, 2008; Asmussen, 1976).
- Improvements in muscle strength and power (Enoka, 2008; Bergh and Ekblom, 1979).
• Lowered viscous resistance in muscles (Enoka, 2008).
• Improved oxygen delivery to the working muscles, where higher temperatures facilitate oxygen release from hemoglobin and myoglobin. (McArdle et al., 2007).
• Increased blood flow to active muscles (McArdle et al., 2007).
• Enhanced metabolic reactions (Enoka, 2008).

When warming up for strength and power based sports, the key elements of warm-up are both physiological and neuromuscular in nature, many of which could enhance power and speed performance. They include improvements in the rate of force development and reaction time (Asmussen, 1976) and improvements in muscle strength and power (Enoka, 2008; Bergh and Ekblom, 1979). Gourgoulis, et al., (2003) assert that an optimal warm-up is necessary to maximise the rate of force development, and neuromuscular coordination. The application of warm-up is crucial if speed and power performance is to be maximised. However, despite these opportunities, there is little research into the acute effects of warm-up on performance (Fradkin, et al., 2010; Faigenbaum, et al., 2005; Bishop, 2003b). While a general warm-up can increase body temperature and positively affect endurance performance, it may not be of sufficient intensity to maximise speed and power performance (Jeffreys, 2007a; Faigenbaum, et al., 2005; Bishop, 2003a). Where a warm-up includes maximal or near maximal muscular contractions, it may be able to improve subsequent strength and power performance (Bishop, 2003a). Active warm-up of a high intensity, especially if it includes a sprint component or maximal voluntary contractions (MVC's), may improve certain types of performance by “increasing muscle contraction performance” (Bishop, 2003b). This is the rationale behind the potentiation phase of a warm-up (Jeffreys, 2007a).

Clearly, any method that can maximise performance would have potential for athletes involved in strength, power and speed sports, especially as power is considered to be a fundamental aspect of success in sports that require speed, agility and explosive actions (Docherty et al., 2004). Despite this potential, there is little research into the exploitation of this phenomenon directly on performance.
Potentiation and warm-up – Current evidence

Skof and Strojnik, (2007) compared the effects of a general warm-up (running and stretching) to a potentiating type warm-up that included bounding and sprinting in addition to general warm-up. They found that the contractile properties of the muscle in both a single twitch test (where maximum twitch torque, electromechanical delay, contraction time, and relaxation half-time were calculated following five supramaximal electrical stimuli to the relaxed vastus lateralis muscle) and dynamic maximal voluntary extension (where the leg was fixed at 45 degrees and attached to a force transducer measuring peak torque during a 3 second isometric contraction) demonstrated a significant increase in the potentiation type warm-up when compared with the general alone. While this cannot necessarily be extrapolated to reflect actual performance, it does suggest that a warm-up should include some form of potentiation type activity. Burkett, et al., (2005) in a study of warm-ups on vertical jump performance, found that the use of a weighted jump warm-up resulted in vertical jump performance that was significantly (p<0.001) superior to that achieved with, either a sub-maximal jump, a running and stretching warm-up or no warm-up. Faigenbaum, et al., (2005) considered the effects of three warm-up procedures, (walking and stretching, dynamic exercises, dynamic exercise with 3 drop jumps from 15cm boxes) on vertical jump, long jump and shuttle run in children. They found that a general warm-up resulted in significantly reduced scores in all tests (P<0.05) compared to the dynamic exercise with drop jumps protocol. The general warm-up also resulted in significantly lower scores in the vertical jump and shuttle test (p<0.05) against the dynamic exercise warm-up. These studies support the application of a potentiation phase within a warm-up.

Post Activation Potentiation (PAP) and warm-up

As well as the advantage of utilising a potentiation phase, a further possibility exists for further developing the effects of this phase of warm-up, through the utilisation of the phenomenon of post activation potentiation (PAP). Post activation potentiation (PAP) refers to an “excited or sensitive neuromuscular condition following intense loading, a situation in which power performance can possibly be enhanced” (Robbins and Docherty, 2005). It is based upon an increase in muscle twitch and low frequency tetanic force after a
“conditioning” contractile activity (Sale, 2002). The concept of PAP and its effects on muscular performance is based on the known physiological processes of treppe and post-tetanic potentiation, where the force of twitch contraction commonly increases after a brief tetanic contraction (Belanger, et al., 1983). Postactivation potentiation simply refers to a situation where the increase in force is as a result of voluntary contraction, rather than an electrical contraction which is characteristic of posttetanic potentiation (Garland and Gossen, 2002). Clinical studies have traditionally focussed on posttetanic potentiation, being based upon an evoked muscle twitch via an electrical input into a muscle at rest, and a measure of a subsequent evoked twitch following an electrically evoked tetanic contraction. Typical results are shown in Figure 1.1, where the subsequent contraction demonstrates increased force and shortened time course. While the mechanisms of PAP have been studied for many years, their application to human performance is a more recent development and has received less study (Sale, 2002). The first authors to use the term PAP in relation to human athletic performance were Gullich and Schmidtbleicher, (1995) who investigated the effects of maximal voluntary contractions on power performance. While the practices of PAP, and its integration into complex training procedures has permeated the strength and conditioning profession, its effectiveness and its optimal application have received limited study.
If this phenomenon can be utilised to enhance performance, then it offers a possible mechanism by which performance can be acutely maximised, and therefore provides activities that could be productively incorporated into warm-up routines. By exploiting PAP, it may be possible to acutely enhance jumping ability, and/or running speed, through the efficacious use of a pre-conditioning activity (Jeffreys, 2007a; Bishop, 2003a).

Key elements of sport performance

In examining the potential effects of warm-up procedures on actual performance, it is critical to examine the key elements underpinning effective performance. In team sports it is impossible to get a quantitative score on the effect of warm-up on performance, as the performance requirements in any game vary, and measurements are impossible in game play. To enable accurate information to be elicited, key elements of successful performance in these sports need to be identified, and then utilised as performance indicators.
Stone, et al., (2007) claim that power production may determine the quality of performance. Power is the product of force and velocity \( p = f \times \frac{d}{t} \) (Robbins and Doherty, 2005), and has been proposed as a major influence on performance in a number of disciplines, especially those that require speed, agility and explosive actions (Docherty et al., 2004). However, the estimation that peak mechanical power directly corresponds to a meaningful neuromuscular performance in short high intensity movements has little scientific support (Knudson, 2009). Indeed, peak or average mechanical power are not strongly related to jumping and performance in many sports (Knudson, 2009). This is supported by a number of studies that report insignificant correlations between mechanical power output (from force plate and cinematographic measures) and jump height (Shetty, et al., 1986; Barlow, et al., 1971; Considine, 1971). This is especially the case when body mass associations are factored out (Barlow, et al., 1971). Therefore, maximising muscular power output is not meaningful or related to performance in most human movement based activities (Cronin and Sleivert, 2005), and cannot be associated with success in jumping, sprinting, throwing or other sport skills (Knudson, 2009). Therefore, it was important that in these studies neither peak power nor average power were assumed to be indicative of performance, and therefore neither was measured as a dependent variable.

In jumping, the only way to change the total mechanical energy is by pushing into the ground, and here the linear velocity of the centre of mass is the variable of primary importance (Bobbert and Van Soest, 2001). Based on Newton’s second law of motion, net vertical impulse exactly determines jump height (Knudson, 2009). Impulse can be defined as the product of force and the time which the force is applied. Any impulse acting over a given duration causes a change in momentum of the object over which the impulse is acting; this is the impulse-momentum relationship (McGinnis, 2005). In this way, the impulse-momentum relationship completely links kinetics to movement kinematics \( r = 1.00 \), as dictated by Newton’s second law of motion, where the change in momentum of an object is proportional to the force applied (Knudson, 2009). Impulse appears to have a much stronger association with jump and sprint performance than power (Harris, et al., 2008). Rapid increase in force is an important factor in maximising impulse (especially in the first 40ms).
and is associated with jumping height and sprint acceleration (De Ruiter, et al., 2006; Wilson, et al 1995; Young, et al. 1995).

Jumping is a relatively fast, fundamental movement pattern common in many sports (Knudson, 2009). To support this, jump height has been directly linked to superior performance in a number of sports such as American Football (McGee and Burkett, 2003), Volleyball, (Barnes, et al., 2007), and Ice Hockey (Burr, et al., 2007). However, maximal jump height will be dependent upon a number of factors such as maximising technique, speed, force or a combination of variables. So, while impulse and rate of force development may provide an indicator of performance, the best indicator will undoubtedly be jump performance itself (Knudson, 2009). Where the aim is to monitor performance, measures of performance should always be used rather than dynamometer based tests (Knudson, 2009; Murphy, et al., 1997). In other words, where training effects need to be measured, jump height is the best measure for monitoring these effects (Knudson, 2009). These tests also avoid the problems of factoring in stature and body mass, and transforming data into an inaccurate and likely meaningless estimate of maximal power (Knudson, 2009).

Additionally, speed continues to be one of the most important characteristics an athlete can possess (Dintiman and Ward, 2003; Counsilman, 1976). The ability to run fast is a major factor determining the level of performance in various sporting activities (Korhonen, et al., 2009) and remains one of the most sought after characteristics when selecting talent. However, in many sports athletes never attain maximum speed, and here, speed over the first few steps, together with the ability to rapidly increase velocity (acceleration) can be considered of greater importance to successful team sport performance (Cronin and Hansen, 2005). Specifically, acceleration, the rate of change of velocity is integral to successful performance in both rugby union and football (Spinks, et al., 2007; Deutsch, et al., 2002; Bangsbo, et al., 1991), and is potentially decisive in determining the outcome of a game (Spinks, et al., 2007; Cometti, et al., 2001; Rienzi, et al., 2000).

Running speed and the jump height are two important factors in determining the level of sports performance. These often form the basis of talent ID and selection processes such as the National Football League (NFL) combine (an annual testing event for prospective
professional players, where a range of physical performance measures are taken, and on
which eventual draft order is decided). Methods that can enhance their quality, either
acutely or chronically, need careful investigation, as they have the capacity to enhance
performance.

Research into warm-up effects should therefore focus on factors that contribute to
maximising propulsive impulse in a short amount of time, as most sports have temporal
limits to performance (Knudson, 2009). Specifically, it needs to focus on whether propulsive
impulse can be increased with the utilisation of specific pre-conditioning activities, namely
post-activation potentiation, and whether this directly enhances the quality of running
speed and/or jump height.

**Evidence of PAP**

The primary aim of the current investigations focussed on attempting to ascertain the
effectiveness of PAP protocols in the acute enhancement of speed and power performance.
This applied data allows the generation of coaching guidelines on the construction of
optimal warm-up protocols for team sports. Therefore an important starting point was the
examination of the current evidence relating to PAP and performance. Research to date into
PAP has taken two main approaches. The first has focussed on the twitch contractile
properties of a muscle, whilst the second has focussed on measures of performance.

**Clinical studies**

Clinical studies have focussed on post-tetanic potentiation, where the physiological
response to an evoked twitch is measured. A twitch is a brief contraction of a muscle in
response to short (<1ms) electrical stimulation of a nerve (O Leary et al., 1997). In these
studies, twitch characteristics are measured prior to, and after, muscle activity. These
activities have included evoked tetanic contractions (O Leary et al., 1997), sustained
maximal voluntary contractions (Gossen and Sale, 2000) or a series of sub-maximal evoked
twitches (Macintosh and Willis, 2000). These studies have consistently shown a potentiated response or twitch potentiation. These have been characterised by increases in the rate of force development, a decrease in relaxation time and an increase in peak twitch force (Docherty, et al., 2004). Additionally, studies on skinned mammalian skeletal muscle fibres have consistently shown increased twitch tension, increased rate of tension development and decreased post-stimulus relaxation time (Robbins, 2005). However, voluntary and evoked contractions respond differently to stimulation (Behm, et al., 2004), and so the relevance of post-tetanic potentiation to human performance cannot be assumed.

**Performance studies**

While of scientific interest, the result of clinical studies cannot be assumed to influence athletic performance. The key question for sports coaches is the potential effect of PAP on sports performance. Before PAP can be effectively used to enhance sports performance, research must confirm that PAP can be induced via a voluntary muscle contraction, and also show that its benefits can be realized during a subsequent sports activity (Tillin and Bishop, 2009). In terms of the studies into the effects of PAP on measures of athletic performance, the evidence is equivocal (Tillin and Bishop, 2009). To date, the majority of current human studies have utilised a high resistive load, whether in terms of isometric or concentric resistance as the preload stimulus to elicit PAP (Docherty et al., 2004). Subsequent performance was then analysed on measures of power or sports performance, normally a single bout of activity.

**Studies demonstrating PAP**

Initial studies suggesting the success of PAP protocols were training studies, rather than full research studies. Baker, (1994) found that performance on a set of jump squats preceded by a set of heavier squats resulted in a 17.2% increase over a set not preceded by a heavy squat set, however, no statistical evidence was given to support this data. Similarly, Radcliffe & Radcliffe, (1996) found improved standing long jump performance when preceded by heavy resistance work, in this case the power snatch. However, while
suggesting the existence of PAP, the robustness of these studies cannot be proved. Gullich & Schmidtbleicher, (1995) also found that speed strength performances of the lower extremities in sprinting and jumping events were considerably improved following maximal voluntary contractions. However the time course of this improvement was not noted and neither were the warm-up protocols used, limiting the ability of the studies to apply directly to human performance. These studies, initially suggested the opportunity of utilising PAP to acutely enhance performance, and later studies built upon these initial findings.

Young et al., (1998) using strength trained athletes, showed a significant (p < 0.05) increase of 2.8% for loaded counter movement jumps after the performance of a set of half squats, using a recovery time of 4 minutes. They suggested that a set of heavy resistance work results in a degree of heightened neural stimulation, and this results in an improved performance on a subsequent plyometric or maximal power movement. However, the warm-up used prior to initial testing was simply a jog and stretch, and this was unlikely to maximise initial performance, and so the increase in performance could simply have been down to enhanced warm-up methods used by the squat protocol, and not necessarily to PAP.

Gourgoulis, (2003) demonstrated a mean improvement of 2.39% (p< 0.05) on vertical jump height following 5 sets of half squats for 2 repetitions at 20%, 40%, 60% 80% and 90% 1RM. They also indicated that subjects with greater maximal strength levels in the squat experienced greater potentiation than those with lower maximal strength. It must be noted that while PAP was evident, the practical implications of this protocol are limited, as 5 sets of squats could be impractical for warm-ups. Similarly, the study could not isolate whether any PAP initiated was cumulative, or was a result of one or more of these applications. Therefore the practical application was further limited.

Hamada et al., (2000) showed significant PAP, as measured by twitch response, following maximal isometric contractions in recreationally active subjects. However, the use of recreational subjects tested in a resting state limits the application of these results to sports performance. Rixon, et al., (2007) found that PAP (as measured by counter-movement jump performance) could be induced with isometric squats (3 repetitions of 3 seconds of maximal voluntary isometric contraction in a squat against a fixed resistance with two
minutes between repetitions), but not with dynamic squats (1 set of 3 repetitions at 90% 1RM on a Cybex Smith machine). Unfortunately, this study did not report the warm-up protocols used, and thus the effectiveness of the control warm-ups cannot be evaluated. Additionally, the study used both males and females and athletes with some or no weightlifting experience, and so did not represent a homogenous group. Therefore, the results need to be treated with some caution, as they cannot be extrapolated to apply to an athletic population.

Kilduff, et al., (2007) found a statistical (p<0.05) difference between pre and post potentiating performance in both upper body power (bench throws) and lower body power (countermovement jump), but only after a rest period of 8 minutes. In this instance the potentiating activity was a 3RM bench press for upper body and 3RM squat for the lower body. Unfortunately, only power was measured and performance was not reported. While power is an important aspect of performance, it cannot predict performance, and so the results cannot necessarily be extrapolated to indicate an increase in actual performance. Weber, et al., (2008) using 5 repetitions of 85% 1 RM demonstrated significant improvement in mean and peak jump height and peak ground reaction force, after a recovery period of 3 minutes. Here, actual jump height was measured during five consecutive squat jumps, and increases in mean and peak height were reported, along with increases in ground reaction forces. The use of the squat jump removed the action of the SSC, and suggests that increases are found in the concentric part of muscle force.

As well as enhancing warm-up, PAP may provide an opportunity to enhance individual session structure. Stone et al., (2008) found that manipulating the order of sets into strength-power potentiating complexes by preceding lighter load sets with heavier sets resulted in improvements in peak force, peak power, rate of force development and peak velocity, but only the increase in peak velocity was significant (p<0.05). This reflects the complexity of sports performance, and the importance to evaluate against measures of performance rather than indicators of performance. Ruben, et al., (2010) found that an ascending squat protocol (5 repetitions at 30% 1RM, 3 at 70% 1RM, 3 at 90% 1RM) resulted in significantly (p< 0.05) higher power outputs (peak and mean) during 5 plyometric jumps
(maximum effort hurdle jumps) where measures were taken via an accelerometer. Unfortunately, no measures of jump height were reported, and so the results cannot be necessarily extrapolated to performance. It is important to note that in this study, no significant differences were found in peak velocity and average peak velocity, emphasising the need to focus on direct measures of performance.

Even within the studies demonstrating enhanced performance through PAP, there is a degree of variance between the results. The equivocal nature of the results is clearly demonstrated in the study by French et al., (2003) who found significant increases (p < 0.05) in drop jump height, maximal force production and acceleration impulse after a sequence of maximal isometric knee extensions of 3 repetitions of 3 seconds; yet found no statistical increase in counter-movement jump height. This is despite the fact the countermovement jump height is related to acceleration impulse. Additionally, no EMG differences were found in any measures. The use of a sub-maximal, non specific, warm-up (cycling) limits the conclusions drawn regarding the application potential of PAP based activities. Chiu et al., (2003) in establishing the effects of PAP on jump squats, utilised 5 sets of 1 repetition to stimulate PAP and demonstrated significant increases in peak power, but only in strength trained athletes, no significant differences were found in untrained athletes (or the subject group when taken as a whole). Gilbert, et al., (2001) demonstrated no increase in maximum voluntary contractions but a significant increase in Rate of Force Development (RFD) (p <0.05), after performance of 5 single repetitions of maximal squat exercises at 100% 1RM, although the effects on actual performance were not noted. This increase in RFD peaked at 20 minutes post squat. This supports the work of Sale, (2002) who suggests that PAP will have its greatest effects on RFD, with peak force remaining unchanged, and if so, could have an impact on performance in sports where the production of rapid forces are required such as sprinting, rather than on sports where maximal force is required such as power lifting. Unfortunately warm-up protocols utilised were not reported, and only seven athletes took part, thus limiting the robustness of this study.

Running speed is a key factor of performance in many sports, and is an important variable to evaluate in determining optimal warm-up procedures. McBride et al., (2005) investigating the effect of PAP on speed, found that athletes ran 0.87% faster in a 40 metre sprint, (p<0.05) when preceded by a set of heavy squats (1 set or 3 repetitions at 90% of 1 RM).
Interestingly no statistical difference was seen in the split times at 10 or 30 metres. This suggests that PAP has greatest effects at the highest running speeds. This is interesting given the relative change from the importance of maximal strength to elastic strength as a sprint progresses (Young and Pryor, 2001), and the results of Weber et al., (2010) who found changes in concentric muscle performance with PAP. However, prior to extensive evaluation it is important to note a number of major issues with this study. The use of cycling at low intensity as a warm-up prior to the runs is a major weakness, and it is highly unlikely that any initial performance measures were maximised after this protocol. Therefore these results should be treated with caution, as the results cannot be attributed to PAP. Chatzopoulis, et al., (2007) investigating the effects of PAP on speed found no change in performance over 10 metres and 30 metres following 10 sets of single squats at 90% 1RM, after 3 minutes recovery, but did find significant (p<0.05) improvements after 5 minutes. While the warm-up procedures in this study were appropriate, the application protocol of 10 sets would be extremely difficult to replicate in a real sports context. Therefore, again the applicability of this study needs to be questioned. Yetter and Moir, (2008) found significant improvements in the 10-20 metre section of a 40 metre sprint following back squats, (where the bar is placed on the trapezius muscle) but not front squats (where the bar is placed on the anterior deltoids). Again, supporting the variations found in the results of other studies, no differences were found at the other section of a 40 metre sprint. This suggests that there may be differences in the potentiation capacity of differing exercises, and that potentiation can affect different aspects of speed performance to varying degrees. PAP effects must therefore, be evaluated against the typical distances run in sports if they are to generate data that can be applied directly into sports performance. However, this study was severely limited by the use of a non specific sub maximal warm-up protocol (cycling), and it would be highly unlikely that the initial speed would be maximised. The results of this study therefore need to be treated with caution. Smith et al., (2001) also postulated that PAP may be able to increase running speed, following their findings of enhanced 10 second sprint cycling performance following 10 x 1 repetition 1RM back squats, although again, cycling performance cannot predict running performance. Here again the extreme protocol limits the applicability to warm-up practices. The studies to date suggesting the ability of PAP to increase running speed all have serious flaws, and this suggestion cannot be validated at present.
Studies showing no effects on performance.

While some studies have demonstrated the beneficial effects of PAP on different measures of performance, other studies show no enhancement of performance via PAP methodologies. Mangus, et al., (2006) in a study on weightlifters, reported no statistically significant enhancement in vertical jump performance after a set of squats of 1 repetition at 90% 1RM. Despite no statistical difference, they did report a trend (p=0.07) towards enhanced performance. In this protocol, it needs to be noted that a single repetition at 90% 1RM may not have been sufficient to maximise PAP, where most studies have used 3 repetitions at this load. Additionally, warm-up procedures in this study were reported as progressive, but not actually reported. However, this group did utilise a strength trained subject group, which has been suggested will benefit to a greater degree from PAP (Chiu, et al 2004).

Ebben, et al., (2000) found no acute enhancement on medicine ball power drop performance subsequent to a preceding set of high load bench press. Jensen and Ebben (2003) showed no improvement in jumping performance following a set of 5 RM squats, demonstrating a trend to decline at short rest intervals following the pre-conditioning activity, although they found increasing performance with increased rest, and suggested that had the recovery period been extended beyond 4 minutes, performance could have been enhanced. In both the studies warm-up procedures were not reported.

Gossen and Sale, (2000) found no improvement in isometric peak knee torque post PAP inducement via a 10 second MVC, indeed demonstrating a trend for decline in performance. However, in this study recovery time was 15 seconds, and the authors suggested that a longer recovery time, even at the cost of a diminished PAP, may have proved beneficial. However this is purely conjecture and not supported by data. Bazett-Jones, (2003) also found no PAP effect on peak force and rate of force development following 3 sets of leg presses at 90% 1RM for 3 repetitions. Again, a trend to a reduction in performance was reported three minutes after the completion of the conditioning exercise. Hrysomallis and Kidgell, (2001) also found that a heavy dynamic resistive upper body exercise (5 RM bench
press) was inadequate in augmenting short-term power (explosive push ups). Scott and Docherty, (2004) found no significant difference in either vertical jump or horizontal jump performance as a consequence of performing a set of 5 squats at 5RM load. Robbins and Docherty, (2005) also found no acute enhancement of countermovement jump performance after the execution of a maximal voluntary isometric contraction of seven seconds. Unfortunately, all of the above studies utilised general and sub-maximal warm-ups and so may not have maximised performance.

Hanson et al., (2007) found no enhancement of jump performance following the squat exercise in resistance trained men, at either high velocity/low load, or low velocity/high load. In this case, it needs to be noted that the resistance levels were set at 40% 1 RM (performed for 8 repetitions) on the first testing day and 80% 1 RM (performed for 4 repetitions) on the second day. Neither of these resistances may have been sufficient to induce PAP (Hilfiker, et al., 2007). Similarly. Bazett Jones et al., (2005) found no improvement in peak force or rate of force development subsequent to 3 sets of 3 repetitions in the leg press, with 90% of 1 RM. However, in this instance the authors contend that any potentiation effects could have been masked by the fatiguing nature of the protocol. Similarly the general nature of the warm-up would have confounded results. Smith and Fry, (2007) found no enhancement of force, velocity or power measures on the performance of a 1RM leg extension, 7 minutes subsequent to a 10 second MVC. Seven subjects in the study demonstrated elevated regulatory myosin light chain (RLC) phosphorylation,(measured via muscle biopsy and subsequent analysis via imaging of stained nitrocellulose paper) but showed no increase in performance. Therefore even where RLC phosphorylation is present, this does not guarantee enhanced performance. Interestingly, a further four subjects actually demonstrated a reduced RLC phosphorylation further emphasising the individuality of responses on a physiological, as well as performance, basis. It should be noted that this study used recreationally trained men, who may not be able to optimally utilise PAP. However, it does demonstrate that if the effects of PAP protocols on performance are to be elicited, then the dependent variable needs to focus on performance itself and not on a potential predictor of performance (Jobson et al., 2009)
Comyns et al., (2006) found no significant change in CMJ performance following 1 set of 5 back squats at a 5RM load, indeed, this study found a significant reduction in performance at 30 seconds and 6 minutes. Comyns et al., (2007) also found significant decreases in drop jump flight time subsequent to 3 repetitions of squats at 65%, 80% and 93%. No significant differences were reported for peak ground reaction force, and reactive strength index at all loads. However, they did see a significant increase in leg stiffness at 93% load. This study demonstrates the complexity of responses to any PAP inducing activity, and the difficulties in relating a specific physiological change to a change in performance.

Brandenburg and Henderson, (2003) found no significant change in performance in concentric-only bench press throws, following the prior application of either 5 repetitions of bench press at either 5RM load, or 50% of 5RM load. However, the study used recreationally trained female athletes who may not have been able to maximise PAP protocols. Brandenburg, (2005) in a study of recreationally trained men, also found no change in performance in concentric-only bench press performance following 5 repetitions at either 100, 70% or 50% of %RM loads. Again, the use of recreationally trained athletes may have been a limiting factor in the study, and similarly, the loads may not have been of sufficient intensity to induce PAP. Till and Cooke, (2009) found no significant changes in sprint (10 & 20 metres) or counter movement jump performance following either deadlift (1 x 5RM), 5 tuck jumps or Maximal Voluntary Contractions (3 x 3 seconds) on a leg extension. This study used male professional academy soccer players, and so utilised trained athletes. However, the initial warm-up protocol was submaximal (jogging), making the initial scores difficult to accurately evaluate. Jo, et al., (2010) found no significant change in peak power, relative power or fatigue index on a 30 second Wingate following a back squat protocol of 1 set of 5 repetitions at 85% 1RM. The lack of a performance score again makes the extrapolation of this data to performance difficult.
General Findings

The results for the effectiveness of PAP in enhancing performance are highly equivocal. While studies have reported PAP, the review clearly shows that many of these are limited by design. In many cases indicators of performance are used, and so extrapolation of the information to sports performance cannot be presumed. In others, the inadequacies of pretesting warm-up are a major design fault, in that pre application performance would not be maximised. Similarly, design issues also exist with many of the studies reporting no change in performance and here again poor warm-up protocols and the lack of performance scores make conclusions difficult to extrapolate to performance. Given the diversity of results, both between studies, and within individuals within each study, it is likely that the variety of factors highlighted within this review will influence the effectiveness of PAP in enhancing acute power performance (Ruben, 2010; Jeffreys 2008b). However based on the current research, PAP cannot be assumed to acutely improve performance. Given the flaws in the research designs all that can be effectively reported at present are trends. Trends that emerge are:

1. Where PAP is suggested, it is most pronounced in stronger and/or highly trained athletes.
2. PAP seems require rest periods of at least four minutes, although further research is needed to determine the optimal time course for each type of activity.
3. PAP is more evident on lower body exercises than upper body exercises.
4. Effects of performance (positive and negative) seems to be greatest at high loads

The possibility of enhancing speed performance via PAP.

Where PAP has been previously demonstrated, measures have traditionally been on force output, power output or jump performance. With the previously highlighted enhancement of jump performance in a number of studies, then the propensity for PAP to enhance speed is logical. Counter movement jump performance correlates highly with sprint velocity (McBride et al., 2005). Activities that enhance jump performance should have the potential
to enhance sprint performance (McBride et al., 2005). However, while these arguments are logical, little direct research on the influence of PAP on speed has been carried out. As speed is a major factor in team sport performance (Dintiman and Ward, 2003; Baker and Nance, 1999; Counsilman, 1976), and is potentially decisive in determining the outcome of a game (Spinks, et al., 2007; Cometti, et al., 2001; Rienzi, et al., 2000) then the possibility of acutely enhancing running speed via PAP needs to be closely investigated.

In establishing whether the PAP phenomenon, from either heavy resistance work or from other conditioning exercise, can be applied to speed performance it is important to look at the factors likely to affect sprint performance. As most sports depend upon performance over short distances then the ability to accelerate is paramount (Cronin and Hansen, 2005). McFarlane, (1993) divides acceleration into two phases; pure acceleration (zero to twelve metres), and transition acceleration (twelve to thirty metres). Kraemer, (2000) supports this dividing acceleration into an initial phase (zero to ten metres) and a transition phase (eleven to thirty six metres).

Running speed is the product of stride length and stride cadence (Plisk 2008; Weyand, et al., 2000), and higher running speed is promoted by anatomic and physiological features that increase both of these factors (Weyand, et al., 2000). Within each running stride, two phases can be identified, a stance phase and a swing phase (Cronin and Hansen 2006). The stance phase refers to the time that the foot is in contact with the ground, while the swing phase is from ipsilateral foot strike to ipsilateral toe off (Cronin and Hansen, 2006). The possibility of enhancing speed performance is based on the defined relationship between ground reaction force and subsequent running velocity (McBride, et al., 2009; Weyand, et al., 2006; Wright, and Weyand, 2001; Weyand, et al., 2000). Increased ground forces have the effect of increasing the athlete’s vertical velocity at take off, subsequently increasing the aerial time and forward distance travelled between steps, and this is the primary way in which runners achieve higher running speeds, (Weyand, et al., 2000). Hunter, et al., (2005) also found a significant correlation \( r=0.780 \) between ground reaction force (horizontal impulse) and sprinting velocity. Sprint training should therefore focus on mechanisms that allow for enhanced ground forces, rather than on attempting to achieve higher stride
frequencies, which are largely the result of elastic recoil and energy transfers between body segments (Kram and Taylor, 1990). Weyand, et al., (2000) found that swing time for the legs was identical between slow and fast runners at approximately 0.360 seconds. An examination into the kinetic parameters of force production for different phases of sprinting provides an insight into the how ground forces can be maximised.

During the acceleration phase, the stance phase is predominantly propulsive, with minimal braking forces (Cronin and Hansen, 2006), and therefore propulsive based forces dominate. For pure acceleration Ozolin, (1986) suggests that training needs to develop the absolute strength of the thigh extensor and trunk extensor muscles and shorten the latent reaction time. Kraaijenhof, (1990) supports this, stressing that, as athletes have a relatively longer ground contact time in this phase, the power output of the muscles is paramount and resistance training is the primary training method for improvement in this area. Baker & Nance, (1999) also stress that start ability over short distances is strongly related to concentric muscle force parameters with Veloso, et al., (2000) suggesting that during the acceleration phase of sprinting, the ability to produce force at the hip, knee and ankle extensor muscles is crucial, with maximal isometric force highly correlated with performance. Thus, maximal force and the rate of force development are the key to acceleration. As both peak force and rate of force development can be potentially enhanced via PAP (Sale, 2002), then this could provide a method of enhancing speed performance.

For transition acceleration, Ozolin, (1986) has stated that the athlete needs to develop the speed strength (power) characteristics of the leg extensor muscles, with resistance, plyometric and sprint resistance methods stressed, with improvements in stride length of greatest concern, with little emphasis on the development of stride cadence. However, whilst Kraemer et al., (2000) contradict this, stating that this phase is characterised by greater stride frequency, they both emphasise that this phase is very dependent on an athlete’s ability to generate force during propulsion, and thus agree about the need for speed strength characteristics.
At maximum speed, there are significant kinetic and kinematic differences in running technique. As ground contact time is reduced, athletes need to produce force in a shorter time period, and the need for greater stride cadence is essential (Lemaire & Robertson, 1990). Additionally, braking accounts for up to 43% of the stance phase, resulting in different kinetic patterns than the acceleration phase (Mero and Komi, 1987). While rate of force development is again key, the role of the stretch-shorten cycle is greatest at maximum speed, reflecting the differing kinematic profile of maximal speed running (Mero and Komi, 1987; Mann and Herman, 1985). It can be concluded that acceleration and maximum velocity are relatively separate and specific qualities (Young, et al., 2001; Delecluse, et al., 1995). While PAP may provide a mechanism where maximum speed performance could be acutely enhanced, this will need to address different parameters of force production.

Speed performance can therefore be seen as force oriented (Newton, 2000) with the power output of the leg musculature important in determining performance. Therefore, if PAP can increase subsequent power output via enhancing the rate of force development, which Sale, (2002) maintains is the key role of PAP in enhancing power, then this could have the potential of increasing speed. Given the need to produce ground forces and the importance of force at the hip, knee and ankle, any PAP inducing exercise needs to attempt to replicate these force patterns. Multiple joint, structural exercises are more likely to replicate these patterns, and should be the chosen modality of PAP inducing exercise (McBride, et al., 2009).

If PAP is able to enhance speed performance then it presents an opportunity for enhanced warming up procedures in preparation for team sports. Reddin, (1999) suggests that this procedure of utilising a maximum voluntary contraction in warm-up was used by Ben Johnson prior to his infamous 9.79sec 100 metres in the Seoul Olympics. However, this has never been substantiated and a knowledge of the warm-up facilities in holding areas prior to Olympic sprints would question this assertion. Zentz and Fees, (1999) further support the use of strength training in warm-ups, claiming that it increases nerve conduction velocity and promotes more efficient cellular metabolism.
The variations in results between the studies outlined previously and the flaws in the previous studies mean that at present speed improvement through PAP is yet to be proved. Additionally, the variations in previous results between different distances suggest that if the application of PAP protocols to speed enhancement are to be investigated in terms of their potential to affect warm-up procedures, then a single indicator needs to be selected, that best indicates speed performance in a given sport. Only in this way can decisions be made on the results of the study.

**Key issues in PAP application**

Despite the potential of PAP for enhancing power performance, the logistics of optimising these in coaching situations provides a major challenge. In determining the optimal application of any PAP inducing activity in the training of athletes a coach needs key information on a number of factors: these include:

1. The nature of the activity to be enhanced.
2. The nature of the PAP inducing modality.
3. The determination of optimal loads to elicit PAP.
4. The determination of the optimal time-course of PAP.
5. The characteristics of the athlete.

   (Jeffreys 2008b)

**The nature of the activity to be enhanced**

The nature of the activity to be enhanced must be the starting point in the effective utilisation of PAP. It must be analysed in terms of the kinetic and kinematics of the movement itself. An analysis of a given task needs to focus on the magnitude of the force required, the velocity of the force required, the specific muscles involved in the movement, and the co-ordinated nature of the movement. This will aid in establishing whether PAP could enhance performance, and in selecting an appropriate pre-conditioning activity. It is
also important that the conditioning exercise results in a high degree of stimulation of the Type II muscle fibres, involved in the activity.

The nature of PAP inducing modalities

PAP has been demonstrated to be produced via both MVC’s and dynamic resisted exercises such as squats, although it should be noted that other studies have demonstrated no significant effects on performance with either modality (Tillin and Bishop 2009). Whatever protocols are used, it is important that a high degree of stimulation occurs from the conditioning activity, and evidence currently suggests that any pre-conditioning activity needs to be intense, consisting of maximal or near maximal efforts (Hodgson, et al., 2005). To ensure that any potentiation occurs in the appropriate motor units, the conditioning activity should focus on the major muscles involved in the subsequent sports performance, and should try to replicate the direction and range of movement found in that sport. Based on this premise, it would seem logical to perform single leg squats as a pre-conditioning activity rather than double leg, given the single leg nature of running. However, a study by Smith et al., (2001) shows that single leg protocols do not elicit the same potentiation as previously reported with two legged exercises. They therefore recommend that two legged protocols be used within the PAP protocol.

PAP seems to be a phenomenon that is independent of contraction type, isometric, concentric or eccentric (Stone et al., 2008) and at present, no contraction type appears to have an advantage. However, Hilfiker et al., (2007) suggest that eccentric muscle action appears to influence subsequent muscle performance more than isometric action, suggesting that dynamic exercise (which naturally includes an eccentric element) would have a greater effect on PAP than isometric activity. Future studies need to focus on the potential for the use of eccentric loads in eliciting PAP, as Doan et al., (2002) showed a significant ($p < 0.008$) acute increase in 1RM bench press after an additional eccentric loading.
Where an optimally potentiated warm-up is the aim, then consistent access and availability of the methodology may be of great concern. The use of MVC's may provide a viable option in these circumstances, where the logistics of modulating loads etc, may prove a challenge to the application of the dynamic exercise. However, the use of potentiation in warm-up has yet to be validated, and the individuality of PAP response adds a further layer of complexity to this application.

PAP is modulated by the volume of the pre-conditioning stimulus (Hodgson et al., 2005), and so, in addition to the nature of the PAP inducing exercise, another important element to consider will be the duration of the activity. As each activity will have both potentiating and fatiguing effects, then the duration of exercise becomes a critical question. Hilfiker et al., (2007) suggest that total contraction time should be less than 10 seconds to avoid undue fatigue. Again, further research is needed to validate an optimal duration of PAP inducing activity, and here again, the individual response characteristics will further complicate the quest (Jeffreys, 2008b; Hodgson, et al., 2005). The vast majority of studies have used traditional “sets” of consecutive MVC’s or resistance exercises to induce PAP, where the overall duration of the exercise is largely determined by the number of repetitions. Batista et al., (2007) found that PAP could be elicited via intermittent exercise, and this may be another option whereby PAP can be elicited whilst controlling fatigue.

In selecting other exercises to investigate PAP on sports performance, Yessis, (1995) suggested that when setting up training programmes aimed at developing power, the following guidelines should be adhered to:

1. The exercise should correspond as closely as possible to the sport by form, muscle work and range of movement, duplicating the sport wherever possible.
2. The exercises should correspond to the direction of movement experienced within the sport.
3. The exercises should have accentuated action where the effort is at maximum in the range of movement.
4. Maximum effort should be displayed during the exercise.

Therefore, the PAP exercise should focus on the major muscles involved in the sports performance, and try to replicate the direction and range of movement found within that sport. As PAP can enhance acceleration with loads from zero through to peak isometric force (Sale, 2002), then other methodologies may be able to elicit PAP. Similarly, a series of contractions may have an accumulative effect on PAP (Sale, 2002). This may be especially so for running if the contractions elicited a form of overload. In all cases, it would be important that the conditioning activity was of a sufficient intensity to elicit PAP. In this way, other training methodologies need to be investigated in terms of their ability to generate PAP, and the current investigations involved the application of novel methods such as sprint resisted training, sprint assisted training and weighted plyometrics.

PAP can be generated via both dynamic and isometric methodologies, and it is not limited by the modality of muscle activation (Baudry and Duchateau, 2007). Methods need to be investigated on their efficacy, but also on the feasibility of their application into sport specific warm-up settings. Methodologies that focus on power and speed development such as plyometrics, resisted sprints, assisted sprints etc. may be able to induce PAP (Gilbert and Lees, 2005), and may be more functional in sport specific settings. Additionally, intermittent exercises may offer an additional method of initiating potentiation (Batista et al., 2007), although a saturation process limits the possible contribution of PAP when using successive stimuli (Baudry and Duchateau, 2004).

Given the great variety in the above factors it is likely that a degree of trial and error will be required in eliciting the most efficacious methodology for enhancing performance via PAP for each individual, and that different protocols may be necessary for each activity, and even for each individual (Till and Cooke, 2009: Jeffreys, 2008b).
Determining the optimal load

If dynamic exercises such as squats are to be used as the pre-conditioning activity, then a key variable will be the load utilised. As PAP is most associated with Type II muscle fibres (Hamada et al., 2000), then the pre-conditioning activity needs to ensure that a maximal number of Type II fibres are stimulated, whether through high resistance or high velocity. Verkoshansky, (1986) suggests a load of 90% 1 RM is utilised to optimise the development of PAP. The majority of current human studies have therefore utilised a high resistive load, whether in terms of isometric or concentric resistance as the preload stimulus to elicit PAP (Docherty et al., 2004). Unfortunately, again the results on the optimal load for eliciting PAP are equivocal.

While 5RM loads have been used in the majority of studies (Comyns et al., 2007) the results from this resistance have been mixed. In a number of studies significant increases in subsequent performances were found (Evans et al., 2000; Young et al., 1998; Radcliffe and Radcliffe, 1996), while in others, no significant differences were noted (Scott and Docherty, 2004; Jones and Lees, 2003; Jensen and Ebben, 2003; Hrysomallis and Kidgell, 2001).

Research into other loads is sparse (Docherty et al., 2004). Baker, (2003) found an increase in an explosive bench throw with a load of 65% of 1RM, and Yetter and Moir, (2008), found an increase in running speed with loads of 30%, 50% and 70% of 1RM, suggesting that PAP can be induced with a relatively light load, questioning the assertion that PAP only affects Type II fibres. Weber et al., (2008) also found an increase in jump performance using 85% 1 RM loads, again suggesting that lighter loads may produce potentiation. However, Hanson et al., (2007) investigating the effects of squats at 40% 1RM and 80% 1 RM on repeated CMJ performance found no change in either ground contact time, or peak ground reaction forces, suggesting that these loads were too light to produce potentiation. However, this suggestion is no more than conjecture.
Chiu et al., (2003) found an increase in PAP with a load of 90% of 1RM but only found significant differences in strength trained athletes. Additionally McBride et al., (2005) and Chatzopoulis et al., (2007) found that a load of 90% was able to produce an improved 40 metres sprint time (McBride et al., 2005) and 30 metre sprint time (Chatzopoulis, et al., 2007) although McBride et al., (2005) found no change at 10 and 30 metres. Mangus et al., (2006) on the other hand, found no potentiation effects on CMJ performance following squats at 90% 1 RM (although only 1 repetition was used which may have produced an insufficient stimulus). Bazett Jones et al., (2005) investigating the effects of 3 sets of 3 repetitions of leg press at 90% 1 RM on isometric squat performance showed no change in peak force and a significant decrease in rate of force development. Gilbert et al., (2001) found potentiation to be elicited at 100% of 1RM loads.

Clearly, the evidence on optimal loads is equivocal, and at present, no definitive guidelines can be advised with which to optimise PAP. However, based on the suggested physiological adaptations and the studies to date, it would appear that any potentiation is greatest where heavy loads are utilised.

The optimal time frame of PAP.

In order to optimally utilise the effects of PAP on subsequent measures of athletic performance, it is important to optimise the time delay between the potentiating activity and subsequent performance, a time often termed the intra-complex rest interval. The traditional view has been that this time period should be minimal (Ebben and Watts, 1998) to maximise the heightened neural stimulation provided by the strength exercise. Initial recommendations for rest periods between exercises within a complex pair ranged from 30 seconds to five minutes (Chu, 1996). However, given the complex interactions between potentiation and fatigue, this thinking could be flawed, and while potentiation may peak immediately post exercise, accumulated fatigue may mask this effect on subsequent performance (Jeffreys, 2008b). This balancing of PAP with fatigue has led to a wider variety of time intervals to be proposed (Jeffreys, 2008b).
Empirical research has investigated a much greater range of rest intervals varying between 10 seconds (Jensen and Ebben, 2003) and 20 minutes (Jones and Lees, 2003). PAP has been demonstrated at timeframes from 1 minute (Hilfiker et al., 2007) to 20 minutes (Gilbert et al., 2001). General evidence from these studies to date suggest that shorter rest periods (less than 4 minutes) are less effective than longer rest periods, although again, the results are equivocal (Jeffreys, 2008b). Jensen and Ebben, (2003) investigating a range of time frames, found non-significant improvements in performance following 5RM squats at 1, 2, 3 and four minutes, while performance at 10 seconds was unchanged. They concluded that short rest periods are less effective at enhancing performance than longer rest periods. However, Jo, et al., (2010) suggest that stronger subjects might potentiate with less rest than weaker subjects, although this has yet to be validated.

These varied timescales of optimal PAP supports the concept that potentiation and fatigue can co-exist, and that subsequent performance will depend upon the interaction between these factors, which is likely to depend upon both the characteristics of the preconditioning activity, and the athlete (Jeffreys, 2008b). The fact that no timeframe is optimal is supported by Jones and Lees (2003), who found no significant performance changes at 3, 10 and 20 minutes post 5RM squats, suggesting that neither long nor short time frames are optimal for PAP. Kilduff, et al., (2007) investigating the effects of PAP in both the lower body (squats) and upper body (bench press) found potentiation at 8, 12 and 16 minutes for the lower body, and 4, 8 and 12 minutes for the upper body, recommending a rest period of 8 minutes as the optimal timeframe for PAP. It would appear that the extent of any PAP produced will vary over time, as the balance between PAP and fatigue shifts (Tillin and Bishop, 2009; Jeffreys, 2008b).

The practical application of PAP will rely greatly on the timescale, and the current findings are ambiguous and do not provide the coach with the required degree of accuracy with which to develop optimal protocols. It seems likely that optimal PAP will only be elicited at a given window of opportunity and at other time frames performance could be impaired, have no impact on performance, or show a limited degree of PAP (Jeffreys, 2008b).
further complicate the matter, Paasuke et al., (2007) suggest that the timeframe of PAP will be related to both the training status of the athlete and the type of training undertaken. In measuring the decline in PAP following 10 second MVC’s, differences were found between the endurance and power trained athletes in the rate of decay of PAP (Paasuke et al., 2007), supporting the assertion that training status will affect PAP.

The impact of timeframe is clearly demonstrated by Chatzopoulis et al., (2007) who found no performance increases in sprint times 3 minutes subsequent to squats, but significant improvements 5 minutes post. This great variation in findings makes defining an optimal time frame for PAP impossible at present. Additionally, the suggestion that the optimal timeframe is highly individual (Comyns, 2006) adds to the challenge in optimally utilising PAP, especially in group situations. If this is the case, then group applications of PAP may be limited by design, and PAP should be seen as an individually targeted training phenomenon (Jeffreys 2008b).

An interesting feature is that Gilbert and Lees, (2005) also found that PAP could be induced by a maximal power protocol, but in this case PAP occurs immediately, but does not last as long as when induced by a maximal strength based activity. This may present opportunities to utilise other methods of inducing PAP by utilising power or speed based exercises rather than strength based exercises.

**Athlete differences**

The characteristics of the individual will also play an important role in establishing the optimal method of inducing PAP. Twitch contractile studies in mammals have consistently demonstrated that PAP is at its greatest in Type II fibres, although in humans this correlation has not been consistently proved (Hamada et al., 2000). The findings of their study suggest that “human muscles with shorter twitch contraction times and a higher percentage of Type II fibres exhibit greater PAP”. Type II fibres undergo greater phosphorylation of myosin
regulatory light chains in a response to a conditioning activity, and may therefore have a
greater capacity for PAP (Sale, 2002). Thus, PAP is more likely to be evident in athletes with
a higher percentage of Type II fibres, and within muscles with a higher percentage of Type II
fibres (Jeffreys, 2008b).

Given the role of Type II fibres, and the net balance between potentiation and fatigue, the
characteristics of the individual will play an important role in establishing the optimal
method of inducing PAP. Studies have demonstrated that PAP is greater amongst stronger
subjects (Ruben, et al., 2010; Stone, et al., 2008; Chiu, et al., 2004; Gourgoulis, et al., 2003;
Chiu, et al., 2003; and Duthie, et al., 2002), and suggest that strength levels may be an
important predictor of PAP. Ruben, et al., (2010) suggest that only athletes able to squat 2 x
bodyweight are able to optimally utilise PAP. If this is the case then only select populations
will be able to utilise PAP, and team based protocols may be impossible to implement.
Hamada et al., (2000) in a study of triathletes, runners and active controls, demonstrated
that PAP was greatest in trained muscles and where muscles were untrained, PAP was not
evident. Thus, the degree of training, relative to the activity to be enhanced is likely to
influence the extent of PAP experienced, and thus may not be a product of strength alone.
This could be due to the ability of advanced athletes to activate the high threshold fast
motor units, whose muscle fibres exhibit the greatest PAP (Sale, 2002), along with selective
hypertrophy of Type II fibres in strength trained athletes, again increasing the potential for
PAP. Sale, (2002) also suggests that training may alter light chain myosin composition, again
increasing the potential for PAP. This ties in with the higher levels of Type II fibres found in
stronger individuals, and the neural advantages these have for PAP. These findings are not
universal, and McBride, et al., (2005) in a study on NCAA footballers found that PAP effects
were independent of strength level. This conclusion was also supported by Mangus et al.,
(2006) who found that strength ratio did not predict individuals likely to gain from PAP
activities.

Similarly, the resistance to fatigue is likely to affect the effectiveness of the PAP, and will
significantly affect the optimum time delay between conditioning activity and performance.
Resistance to fatigue is again dependent on training status, and PAP is likely to be most effective at enhancing the performance of highly developed athletes when compared to untrained or recreationally trained athletes (Jeffreys, 2008b). This also produces a challenge to the individualisation of PAP methodologies, as it may be that fatigue tolerance will vary over time (Jeffreys, 2008c). If this is the case, then conceivably, the optimal timeframe of PAP may be an ever changing variable depending upon the condition and stress tolerance of an athlete at any specific time (Jeffreys, 2008b).

**Potential Physiological Mechanisms of PAP**

Currently, there is general consensus regarding the existence of PAP, although its ability to enhance performance is yet to be proved, the mechanisms underlying it are yet to be determined (Tillin and Bishop, 2009; Robbins, 2005). Skeletal muscle performance is affected by its contractile history (Hodgson, et al., 2005), and “twitch potentiation and fatigue in skeletal muscle are two conditions in which force production is affected by the stimulation history” (Rassier and Macintosh, 2000). Two mechanisms have been proposed to explain PAP (Comyns, et al., 2007). The first is an increase in neural excitability (Gullich and Schmitbleicher, 1995), and the second is based upon the phosphorylation of myosin light chains (Docherty, 2004).

Additionally, Tillin and Bishop (2009) have suggested that muscle pennation may be a third factor contributing to PAP, although this has only been proposed as a possibility. However, the angle of pennation increases during a contraction, which may decrease the force, and newly recruited motor units may therefore contribute less force because of the disadvantageous position (Sandercock, 2005). Given this acute effect of contraction on pennation angle, and the failure of Tillin and Bishop (2009) to produce any evidence to support their suggestion that muscle pennation angle could contribute to PAP, this phenomenon will be excluded from this review.

PAP is generally believed to be a neuromuscular phenomenon (Tillin and Bishop, 2009), and therefore, in order to critically examine its function, it is important to ascertain the key components of both the muscular and neural system, that are affected by a muscle’s
contractile history. This allows the potential elements within these systems that may be affected by PAP to be identified and investigated.

**Underpinning Physiology**

In order to examine the potential mechanisms that could contribute to PAP, a general overview of the underlying muscular and neural mechanisms of muscle control and contraction is required. It should be noted that this review is not intended to be a totally comprehensive analysis of the physiology of muscle control and contraction. Instead, its aim is simply to provide a general overview of muscle control and contraction. This will enable the possible mechanisms of PAP to be more effectively analysed and allow for a detailed review of PAP mechanisms to be subsequently made against acknowledged physiological processes. It will then enable current opinions as to the exact mechanisms of PAP to be evaluated, and to form a theoretical background against which the development of appropriate warm-up interventions can be made.

**Determinants of muscle force**

Increases in maximal contraction force and power, as well as the maximal rate of force development are dependent upon muscle morphology and architecture, and the inputs from the neural system triggering muscle contraction (Aagard, 2003). Therefore, analysis of the physiological factors that could affect PAP needs to focus upon the entire mechanism of muscle contraction, from its neural stimulation, through to the contraction process in the muscle.

**The neural control of muscular action**

The muscle, no matter how sophisticated in design and composition, acts in response to neural commands to produce the required range of motor outputs (Bawa, 2002). Any movement is the consequence of a highly detailed and precise pattern of activity of many motoneurons involved with the production of force (Rekling, et al., 2000). In studying any aspect of muscle force production, it is therefore important to ascertain the neural
mechanisms responsible for force production, and possible mechanisms by which force production can be modulated. This requires a general overview of the structure and mechanisms of the neural system of initiating muscle contractions. A summary of these processes is presented in Figure 1.2.

The neural system of movement control

In voluntary contractions, muscles are activated by complex pathways starting in the cortex, and leading to excitation of lower motoneurons in the spinal cord (Allen, et al., 2008). Motoneurons transform the internal actions of the brain into behaviour, translating patterns of interneuronal activity into commands for skeletal muscle contraction and relaxation (Rekling, et al., 2000). Commands for skeletal muscle contraction take the form of action potentials, which are carried to the neuromuscular junction of the muscle via the axon of the lower motoneuron. The processes inside the spinal cord and above are defined as central, while the processes in the peripheral nerve, neuromuscular junction and muscle are defined as peripheral (Allen, et al., 2008). At the peripheral level, the basic functional unit of the nervous system and muscle that produces force, is the motor unit, which comprises a motoneuron in the ventral horn of the spinal cord, its axon and the muscle fibres that it innervates (Liddel and Sherrington, 1925).

Stimulation of the central nervous system initiates an electrical impulse, that is propagated along the length of a nerve cell or neuron and which results in muscle contraction. All movement is initiated via nerve impulses, and the associated depolarisation, leading to the propagation of action potentials (Payne and Delbono, 2004). An action potential is a brief reversal of membrane potential, and only cells with excitable membranes (muscle cells and neurons) can produce action potentials (Marieb and Hoehn, 2009). Action potentials are important in human movement, and allow for information transmission over considerable distances within the neuromuscular system. An action potential does not stay in one place, but rather propagates, travelling along nerve or muscle fibres (Payne and Delbono, 2004).
The Central and Peripheral Nervous Systems (adapted from numerous sources)

Central Nervous system
- Spinal Cord
- Motoneuron

Peripheral Nervous system
- The Neuromuscular Junction
- Motor unit

Motor end plate
- Skeletal muscle fiber
- Neurotransmitter receptors

Neurotransmitter vesicles
- Synaptic cleft
- Axon of motor neuron
- Mitochondria

Dendrites
- Axon Terminals
- Node of Ranvier
- Myelin Sheath
- Nucleus

Cell Body
An action potential depends upon polarisation, or a difference in charges. The cell membranes of nerves and muscle fibres are polarised, with a high concentration of sodium ions (Na⁺) on the outside, and a high concentration of potassium ions (K⁺) on the inside (see fig 1.3).

![Figure 1.3: Resting Membrane charges inside and outside the cell](Adapted from Latash 2008)

At rest, the internal cell membrane charge is 70 millivolts less than on the outside than on the inside (Hicks and McComas, 1989), representing the cells resting membrane potential. This potential is maintained in two ways, one via the sodium-potassium pump see fig 1.4, and the second via the differences in cell membrane permeability to potassium and sodium ions. The sodium potassium pump helps to regulate the balance of potassium and sodium ions.
ions on each side of the cell by actively transporting potassium ions in and sodium ions out of the neuron (Nordstrom, et al., 2006). The pump moves three sodium ions out for each two potassium ions it brings in, resulting in more positively charged ions being located outside the cell than inside, creating a polarization of the cell (Guyton and Hall, 2006). Additionally, the cell membrane is far more permeable to potassium than to sodium, allowing potassium to move much more freely. The action potential is much greater in fast twitch muscle fibres than in slow twitch fibres and this may represent faster $\text{Ca}^{2+}$ transport through the sarcoplasmic reticulum in these fibres, and ultimately to the contractile proteins (Nordstrom, et al., 2006).

![Diagram of the sodium-potassium pump](image)

**Fig 1.4 The sodium-potassium pump (adapted from Latash, 2008)**

The diffusion potential across a membrane is termed the Nernst potential, and is determined by the concentrations of a specific ion on both sides of the membrane (Guyton and Hall, 2006). The potential for diffusion can then be calculated by the abbreviated Nernst equation, where:

$$\text{EMF (millivolts)} = \pm 61 \log \left( \frac{\text{Concentration inside}}{\text{Concentration outside}} \right)$$
Although minor changes in electrical charge happen regularly, (graded potentials) an action potential is only initiated if the cell reaches its electrical threshold (McArdle et al., 2007). This is normally as a result of a transmitted impulse from another neuron, or in response to sensory stimuli (Rekling, et al., 2000). This response to sensory stimuli represents an important method by which force output can potentially be enhanced or inhibited via prior contractile activity, whereby the potential can be brought nearer to the threshold (excitatory) see fig 1.5, or taken further away from threshold (inhibitory) see fig 1.6. These mechanisms will be explored in more depth later in the review.

*Fig 1.5 Excitatory postsynaptic potential*
An action potential is a rapid and substantial depolarisation of the neuron’s membrane and usually lasts about 1ms, and is generated if the electrical threshold (depolarisation threshold) is reached (normally -50 to -55 millivolts (Payne and Delbono, 2004)). While initiated at a single point on a membrane, a key factor in the ability of an action potential to produce a muscle contraction is that the excitation at one point of a membrane will excite adjacent portions of the membrane (Nordstrom, et al., 2006). Here, positive electrical charges are carried by inward, diffusing sodium ions through the depolarised membrane, and then on for several millimetres in both directions along the axon core (Guyton and Hall, 2006). This process then continues, and will eventually be conducted along the axon to the target muscle or organ. During an action potential, the membrane potential will change from -70 millivolts, to +30 millivolts (Hicks and McComas, 2004), this is due to sodium ions rushing into the cell. Following this, the motor nerve restores itself to its resting potential (repolarisation), which involves potassium ions moving to the outside of the cell, to regain the resting membrane potential (McArdle et al., 2007). Following this regaining of resting potential, the sodium-potassium pump restores the ion concentration to the correct side of
the cell membrane (Hicks and McComas, 2004). Here sodium ions that have diffused to the interior of the cell during action potentials, together with potassium ions that have diffused to the exterior, are returned to their original state (Guyton and Hall, 2006). This pump is an active metabolic process and utilises the ATP generating capacity of the cell (Hicks and McComas, 2004).

Alpha motoneurons communicate with muscle fibres, and this occurs at the neuromuscular junction where, electrical impulses are transmitted from the nerve to the muscle, a process called synaptic transmission (Payne and Delbono, 2004), a process which occurs at the motor end plate (Guyton and Hall, 2006). Motor end plates, are trough-like segments on the plasmalemma and are invaginated, to form cavities called the synaptic gutter (Guyton and Hall, 2006). At the junction is a gap between the nerve fibre and the muscle, called the neuromuscular junction, which consists of three components: a presynaptic membrane, the synaptic cleft and the postsynaptic membrane (Guyton and Hall, 2006) see fig 1.2. The presynaptic membrane belongs to the cell transmitting information, with the postsynaptic membrane belonging to the cell receiving information (Latash, 2008).

In terms of muscle contraction, action potentials are received at the axon terminals of the motoneuron (the presynaptic membrane), and these induce chemical changes in the membrane properties (Payne and Delbono, 2004). This results in the movement of vesicles containing neurotransmitters to the membrane. Here, they fuse with the membrane resulting in the release of neurotransmitters (e.g. acetylcholine) into the synaptic cleft, a process called exocytosis (Latash, 2008). In essence, the neurotransmitters change an electrical impulse into a chemical stimulus (Fon and Edwards, 2001). These neurotransmitters diffuse across the synaptic cleft to the post synaptic membrane of the neuromuscular junction. These changes in electrical properties elicit an endplate potential that spreads from the motor endplate to the extrajunctional sarcolemma (Rossi and Dirksen, 2006). Here the neurotransmitter binds with the receptor on the post synaptic side, causing an increase in the permeability of Na⁺ and K⁺, and resulting in the propagation of the action potential. (Fon and Edwards, 2001). This action potential produces a wave of depolarisation, which travels the length of the fibre, enters the t tubule system and spreads to the inner structures of the muscle fibre to prime the contractile machinery (Rossi and Dirksen, 2006). This propagation causes a release of calcium from the sarcoplasmic
reticulum and initiates muscle contraction. This type of synapse (i.e. between neural cells and muscle cells) is an obligatory one as the action potential will always be transmitted (Rossi and Dirksen, 2006).

Acetylcholine is the most important excitatory mediator in transmitting signals from neuron to muscle fibres (Fon and Edwards, 2001). Acetylcholine is synthesised in the cytoplasm of the terminal, but is absorbed rapidly into many small synaptic vesicles, about 300,000 of which are normally in the terminals of a single end plate (Guyton and Hall, 2006). When a nerve impulse reaches the neuromuscular junction, about 125 vesicles of acetylcholine are released from the terminals into the synaptic space, see fig 1.2 (Guyton and Hall, 2006). The principal effect of acetylcholine action is to allow a large number of sodium ions to enter the fibre, carrying with them large numbers of positive charges (Fon and Edwards, 2001). This creates a positive potential change on the muscle fibre membrane, termed an end plate potential (Guyton and Hall, 2006). Ordinarily, each impulse that arrives at the neuromuscular junction, is three times that needed to stimulate the muscle fibre (Rossi and Dirksen, 2006). This impulse, in turn, initiates an action potential that spreads along the muscle membrane in both directions towards the muscle fibre ends, and initiates the muscle contraction process in the whole muscle fibre (Payne and Delbono, 2004). Following release, acetylcholine is rapidly destroyed by the enzyme acetylcholinesterase (Fon and Edwards, 2001), which is concentrated at the junctional folds of the synaptic cleft. This can degrade acetylcholine within 5ms of its release from the synaptic vesicles, allowing the postsynaptic membrane to repolarise rapidly (McArdle, et al., 2007).

**Muscular Elements of force production**

Once the action potential reaches the muscle fibre, subsequent force output will be affected by the intrinsic properties of the muscle fibre itself. Locomotion is generally driven by mechanical work generated by skeletal muscle, with the speed of locomotion depending upon the mechanical power provided by the muscles (Allen, et al., 2008). The primary
intrinsic properties governing muscle power and work in high velocity movements are the dynamics of muscle activation and deactivation (Neptune and Kautz, 2001).

Once an action potential has been generated, muscle fibre force is produced by a number of processes, which together are known as excitation-contraction coupling – the complex signalling processes from nerve depolarisation to muscular contraction (Payne and Delbono, 2004). These are outlined in Fig 1.7 and involve:

1. Propagation of the action potential along the muscle fibre.
2. Propagation of the action potential down the transverse tubule.
3. Coupling of the action potential to the change in \( \text{Ca}^{2+} \) conductance of the sarcoplasmic reticulum.
4. Release of \( \text{Ca}^{2+} \) from the sarcoplasmic reticulum.
5. Re-uptake of \( \text{Ca}^{2+} \) into the sarcoplasmic reticulum.
6. \( \text{Ca}^{2+} \) binding to troponin.
7. The interaction of the contractile proteins.
8. Relaxation of the muscle fibre via the active removal of \( \text{Ca}^{2+} \).

(Payne and Delbono, 2004)

Each of these mechanisms provides a focus for potential enhancement of performance through potentiation, or inhibition of performance via fatigue. Evaluation of their contribution requires a more detailed overview of the physiology underpinning these processes.
Propagation of the action potential along the muscle fibre and into the transverse tubules.

Coupling of the action potential to the change in Ca\(^{2+}\) conductance in the sarcoplasmic reticulum.

Release of Ca\(^{2+}\) from the sarcoplasmic reticulum.

Ca\(^{2+}\) binds to troponin, tropomyosin on the actin filament, allowing binding sites to become active.

Cross bridges formed, and power stroke initiated.

Reuptake of Ca\(^{2+}\) ions via the calcium pump into the sarcoplasmic reticulum.
The myofibril

One of the mechanisms previously proposed for PAP is the phosphorylation of myosin light chains (Miyamota, et al., 2009). To evaluate this, and prior to examining the physiological processes involved in muscle contraction, it is necessary to provide a brief overview of the anatomical structure of the contractile elements of a muscle fibre (see fig 1.8). The muscle fibre itself is made up of several hundred to several thousands of myofibrils, which lie parallel to one another (Guyton and Hall, 2006). These are the contractile elements of the muscle and consist primarily of two large polymerised protein molecules, actin and myosin, which together are termed myofilaments, and together account for 85% of the complex but with other proteins present including tropinin, tropomyosin, alpha-actinin, beta-actinin, M protein, C protein and titin (McArdle, et al., 2007). Each myofibril is composed of approximately 1500 adjacent myosin filaments and 3,000 actin filaments.

Under low magnification of the myofibril, alternating light and dark bands are visible. The darker zone is termed the A band, and the lighter zone the I band. The Z line bisects the I band and adheres to the sarcolemma giving stability to the structure (Nigg, et al., 2000). The sarcomere then consists of the basic repeating patterns between the Z lines with sarcomeres lying in series, with the length of the sarcomere determining the muscle's functional properties (McArdle, et al 2007).

Actin filaments are joined to the Z line, and on either side of the Z line is the lighter I band region, which contains only the actin protein. The darker A band contains both actin and myosin, although a region does exist within this band where only myosin is present and this band is termed the H zone (Guyton and Hall, 2006). Within the centre of the H zone is the M line (the centre of the sarcomere), which is produced by proteins that link adjacent myosin filaments (Guyton and Hall, 2006).
Fig 1.8 Structure of skeletal muscle, adapted from numerous sources
Actin-Myosin Alignment

Myosin filaments are thicker than actin, and consist of bundles of six polypeptide chains, two heavy chains (molecular weight 200,000) and four light chains (molecular weight 20,000) (Guyton and Hall, 2006). The two heavy chains wrap spirally forming a double helix called the tail of the myosin molecule. One end of these chains is folded bi-laterally into a globular polypeptide structure termed the myosin head (Guyton and Hall, 2006). The four light chains also form part of the myosin head and help control the function of the head during contraction (Guyton and Hall, 2006).

The myosin filaments are made up of 200 or more individual myosin molecules packed tail to tail in a sheath, with globular heads pointing in one direction along half the filament and in the opposite direction in the other half (Guyton and Hall, 2006) (See Fig 1.8). This allows myosin, once activated by ATP, to bind on actin's active sites (Astrand, et al., 2003). The protruding arms and heads together are called cross bridges (Guyton and Hall, 2006). Cross bridges are extremely flexible at their “hinges”, allowing the myosin heads to both extend far outward from the myosin filament body or to be brought close to the filament body (Guyton and Hall, 2006). The myosin head also acts as an ATPase enzyme, allowing the head to cleave ATP and use the energy to drive the contraction process (Guyton and Hall, 2006).

Actin consists of two twisted chains of monomers bound by tropomyosin polypeptide chains (McArdle et al., 2007). An Actin filament is about 1 micrometer long, composed of three protein components, actin, tropomyosin and troponin (Guyton and Hall, 2006). The backbone of the actin filament is a double stranded F-actin protein molecule wound into a helix (Guyton and Hall, 2006). Each strand is itself composed of polymerised G actin molecules, onto which is attached one molecule of ADP (Guyton and Hall, 2006). The ADP molecules provide the active site on which the cross bridges of the myosin filaments interact causing muscle contraction (Guyton and Hall, 2006). The spatial orientation of the filaments can be seen in figure 1.8, where the actin molecules are strongly attached to the Z discs, and
where the ends protrude to occupy the spaces between the myosin molecules (Guyton and Hall, 2006).

Attached to the actin are two other important protein constituents, tropomyosin and troponin, which assist in muscle contraction (Gordon, et al., 2000). Tropomyosin, a long rope-like spiral, is distributed along the length of the actin filament, located in the groove formed by the double helix of the actin (Guyton and Hall, 2006). In its resting state, it prevents the permanent bonding of actin and myosin, inhibiting the interaction between the two protein filaments by blocking the binding sites for actin-myosin coupling (McArdle et al., 2007).

Troponin, a globular molecule is attached intermittently along the sides of the tropomyosin molecules (Gordon, et al., 2000). It consists of three protein subunits, each of which plays a specific role in muscle contraction (Guyton and Hall, 2006). Troponin C exhibits a high affinity for calcium ions (Ca\(^{2+}\)), troponin I has a strong affinity for actin and troponin T a strong affinity for tropomyosin and it is the strong affinity for calcium that is believed to initiate the contraction process (Gordon, et al., 2000).

**Excitation Contraction Coupling and The Sliding Filament Theory**

The sliding filament - cross bridge theory of muscle contraction was first proposed by Huxley (1957), and further developed by Huxley and Simmons (1971). The sliding filament theory together with the cross bridge model has been accepted to the point that it may be considered a true scientific paradigm (Rassier and Herzog, 2004). This states that the change in muscle length is caused by the actin and myosin filaments sliding past each other (Rassier and Herzog, 2004). No change in length of the myofilaments occurs, simply a change in sarcomere length, either shortening (concentric action) or lengthening (eccentric action), resulting in force production (Guyton and Hall, 2006). This is caused by the myosin cross bridges binding to the active actin sites and rotating. This causes the actin filaments to slide over the myosin filaments, the contraction being facilitated by the myosin cross bridges (McArdle et al., 2007). As shortening occurs, the Z lines are pulled together with an associated decrease in the I band and H zone (Rassier and Herzog, 2004).
The sliding filament theory is the contractile element involved within the excitation-contraction coupling, and depends upon the processes outlined in Figure 1. In a resting state, the active sites on the actin filament are inhibited by the troponin-tropomyosin complex, preventing attachment of the sites to the myosin heads (Payne and Delbono, 2004).

Muscle action is initiated by a postsynaptic action potential travelling along the sarcolemma and entering the t tubules and sarcoplasmic reticulum (Alien, et al 2008). The t tubular membrane expresses high levels of L-type Ca\(^{2+}\) channels, which change their conformation in response to an action potential with a subsequent charge movement (Schneider and Chandler, 1973). This change in electrical activity causes the release of Ca\(^{2+}\) into the sarcoplasm (Alien, et al 2008), increasing the concentration by a factor of 100 (Latash, 2008). In a resting state, tropomyosin strands cover the binding sites on actin filaments. As Ca\(^{2+}\) is released into the sarcoplasm, it binds with troponin C and instigates movement of tropomyosin (Ashley, et al., 1991). This allows the myosin cross bridges to attach to the binding sites of the actin, initiating muscle action (Allen, et al., 2008). This alignment causes the myosin head to tilt towards the arm and to drag the actin filament along (Guyton and Hall, 2006). This tilt of the myosin head is called the power stroke, after which the head breaks from the active site and returns to its extended position, allowing it to join with another site further down the actin filament - the walk along mechanism (Payne and Delbono, 2004). As the cross bridges are believed to act independently, the greater the number of cross bridges in contact with the actin at any given time, the greater the force of contraction (Guyton and Hall, 2006). The magnitude of the Ca\(^{2+}\) transients depends upon the SR release and all the Ca\(^{2+}\) buffers in the cell, including the SR Ca\(^{2+}\) pump, troponin C, calmodulin, parvalbumin and ATP (Rossi and Dirksen, 2006; Baylor and Hollingsworth, 1998).

Muscle contraction requires the provision of energy, the process is facilitated by ATP, and large amounts of ATP are cleaved to form ADP during the contraction process, and in fast twitch muscle, consumption of ATP can be much faster than regeneration (Allen, et al., 2008). The greater the amount of work performed, the greater the requirements of ATP, a relationship known as the Fenn effect (Fenn, 1923). Prior to contraction, the heads of the...
cross bridges bind with ATP. The myosin head functions as an ATPase enzyme and cleaves the ATP, but leaves the cleavage products (ADP and phosphate ion) bound to the head. This ATP splitting is relatively slow when actin and myosin are apart, but increases substantially once they join (Gordon, et al., 2000). With the influx of calcium, the active sites are uncovered and myosin heads attach to the crossbridges and provide the power stroke and the energy to fuel this movement is the energy already stored by the previous cleavage (Guyton and Hall, 2006). Immediately after the power stroke, the myosin cross bridges detach and rotate back to their original position (Cooke, 2007). At this site of ADP release, a new ATP molecule is formed, and this causes the detachment of the myosin head from the actin (Gordon, et al., 2000). This new molecule of ATP is then cleaved, producing ADP and a phosphate ion (Cooke, 2007). The myosin can then attach to a new binding site further along the actin filament and initiate another power stroke (Cooke, 2007). This continuous oscillatory movement allows force to be produced over a period of time. In all muscle actions, each pair of cross bridges acts independently, and this sequence of power strokes allows for a smooth muscle action (Latash, 2008).

The muscle action continues until stimulation ceases, i.e. whilst Ca^{2+} concentrations remain sufficiently high to inhibit the troponin- tropomyosin system (Cooke, 2007). Once stimulation ceases, this prevents further release of Ca^{2+} from the sarcoplasmic reticulum (Latash, 2008). Finally, the muscle relaxes as the elevated Ca^{2+} is pumped back into the SR by the ATP-driven SR Ca^{2+} pumps (Allen, et al., 2008). With this removal of Ca^{2+}, troponin is deactivated, tropomyosin returns to its original position, and the actin receptor sites for myosin cross bridges are covered (Payne and Delbono, 2004). ATP hydrolysis ceases and the muscle returns to its resting state (McArdle et al., 2007). Given the importance of rate coding to muscle force production, especially during rapid contractions, the relaxation rate of a muscle can be a limiting factor (Bawa, 2002). However, this element has to date not been investigated in terms of the effects of prior activation on the mechanisms leading to muscle relaxation.
Challenging the sliding filament theory in rapid contractions

While the sliding filament theory has been universally accepted as the mechanism of muscle contraction, it does have limitations in exclusively explaining muscular contractions. An important factor to note is that the sliding filament theory excluded the neuromuscular and molecular history dependent nature of force production, despite the fact that this history dependent nature of force production has been known and accepted since the 1950's (Abbott and Aubert, 1952). This is an especially important factor in explaining the physiological processes of treppe, posttetanic potentiation and postactivation potentiation. In terms of treppe, when a muscle begins to contract, its contractions will not be maximal, and may even be less than half the force of later contractions (Marieb and Hoehn, 2009). This probably reflects the increasing availability of calcium in the sarcoplasm, and the associated increase in active sites on the actin filaments. Additionally, the increase in heat can increase enzyme efficiency, thus enhancing force production. The net result is a slightly stronger contraction with each successive stimulus. This, theoretically, could contribute to PAP, but may be maximised by high intensity warm-up activity of the associated task e.g. sprinting, without the need for a supermaximal stimulus. However, it does flag up issues with previous research where only sub maximal activities have been used in control warm-up protocols.

The force exerted by a sarcomere is not a static property, instead it is dependent upon factors such as activation, contractile history and temperature (Petrovsky and Phillips, 1980), with these factors merely being the most important variables. Prior contractile history has the capacity to both potentiate subsequent performance or to reduce performance via fatigue (Van Soest and Schenau, 1998). This fluid nature of a muscle’s force capability opens up the opportunity to exploit this phenomenon via targeted training approaches. Warm-up procedures have the capacity to influence activation patterns, contractile history and temperature, and so may offer the potential to optimise performance via carefully designed and targeted protocols, with PAP offering the potential to be a key element within these systems.
The sliding filament theory has also proved insufficient to explain several spring-like features of muscle function, including enhancement of force with stretch, depression of force with shortening, and the low cost of force production during active stretch, and these are the very same characteristics expected of springs (Monroy, et al., 2007). This is an important limitation, as these spring like qualities play an important role in movement (Lindstedt, et al., 2002), and can contribute to power output, especially in events where the stretch shortening cycle is an important component, for example, in events such as sprinting, jumping etc. Therefore, these elements need to be examined in terms of their effects on force production.

During muscle contraction where a resistance is present, and where the resistance is subsequently reduced, a muscle will elastically recoil, (Monroy, et al., 2007) acting like a non-linear load dependent spring (Lappin, et al., 2006). During this recoil, muscle stiffness will decrease with increasing force (Monroy, et al., 2007), and where load changes are unexpected, stiffness can be adjusted rapidly without neural input. Thus, subsequent force production is dependent upon its immediate contractile history. This cannot be explained by the sliding filament theory, which predicts that each contraction occurs independently of preceding conditions (Monroy, et al., 2007). Force production measures during changes in length have been shown to exceed maximal isometric force (Rassier and Herzog, 2004), and this value can almost double (Monroy, et al., 2007). This, again, cannot be explained by the sliding filament theory, and suggests that another mechanism must contribute to force production, one in which the muscle acts like a spring, able to store energy for more than one cross bridge cycle (Cooke, 1997).

Force and power output will be influenced by elastic elements within muscle sarcomeres (Monroy, et al., 2007), and titin has been suggested to have a spring like function in active muscle. Titin is a filamentous protein that extends from the Z line to the M line and acts like a molecular spring, which can increase tension when sarcomeres are stretched (Nigg et al., 2000). Titin acts as a framework that holds the actin and myosin in place, and by providing a connection between the Z band and the thick filaments, Titin can contribute significantly to the passive tension of muscle (Enoka, 2008). It has been suggested that titin attaches to
actin in a calcium-dependent manner so that its length becomes shorter, and stiffness increases, upon muscle activation, when calcium is released from the sarcoplasmic reticulum into the sarcoplasm (Lee, et al., 2007; Labeit, et al., 2003). Support for the proposal that titin develops passive force in response to sarcomere stretch has been obtained by experiments with low doses of ionizing radiation to degrade titin, which demonstrated a reduced ability of relaxed muscle to generate passive force (Horrowits, et al., 1986). The contribution of titin to muscle tension is not fixed, and can be adjusted in response to changing conditions, especially its response to calcium (Granzier and Lebeit, 2006; McBride, 2004). Titin has also been shown to increase stiffness in non cross bridge structure (Campbell and Moss, 2002), while Kearney and Hunter, (1990) have demonstrated that activation of muscle can increase its stiffness, possibly through this mechanism. This increased stiffness can, in turn, increase power production, and be a contributor to PAP.

**Fundamental Principles of Force modulation**

Exploitation of PAP in warm-ups will be based upon the augmentation of effective force output, subsequent to a pre-conditioning activity. This requires a general overview of the mechanisms by which force is modulated. Muscle force production is modulated primarily by the number of motor units activated, together with the rates at which action potentials are discharged by motoneurons - rate coding (Bawa, 2002). Petit, et al., (2003) suggest that contraction speed is largely controlled by changes in rate coding whilst force production is controlled by motor unit recruitment. Motor unit recruitment, and subsequent force output is primarily guided by two basic principles: the all-or-none principle and the size principle (Bawa, 2002)

**The all-or-none principle**

Not all local depolarisation events produce action potentials, and depolarisation must reach threshold values if an axon is to fire. The critical factor in determining whether or not an action potential is produced is the total amount of current that flows through the membrane during a stimulus, and is the product of electrical charge and time (Marieb and
Hoehn, 2009). Where signals are sufficiently strong, and an action potential produced, a subsequent muscle contraction will be propagated (Bawa, 2002). Once generated, all action potentials are independent of stimulus strength and are alike (Marieb and Hoehn, 2009).

A muscle contraction is limited to the fibres of the motor unit innervated (Hoffman, 2002). When a motor unit is activated, all of its fibres contract, the all-or-none principle (Zatsiorsky and Kraemer, 2006). However, not all muscle fibres are activated, a mechanism which allows force output to be modulated (Stone et al., 2007). "Individual neurons can generate only single action potentials of a relatively constant duration and amplitude. The only way a neuron can encode significant amounts of information is by generating sequences of action potentials" (Latash, 2008). However, neurons never fire at a constant rate and the type of information transmission is termed frequency coding (rate coding), with the firing rate of a neuron depending upon both the frequency and the magnitude of the input (Bawa, 2002). Force outputs can therefore be controlled by the number of motor units activated, and the ability to activate greater numbers of motor units will increase force potential. This capacity is not constant, and can be enhanced chronically through training. It is yet to be fully established as to whether this can be modulated acutely, but if so, it could be a contributory factor to PAP.

**The Henneman (Size) principle**

This principle, first outlined by Henneman, et al., (1965), states that the recruitment of motor units within a muscle proceeds from small motor units to large ones (Bawa, 2002). At low force outputs, only the slowest motor units will be recruited, and as force requirements rise, the larger motor units will be recruited (Henneman and Mendell, 1981) In this way, the largest units will only be recruited at high force outputs. Similarly, decruitment occurs in the reverse order with the larger units decruited first (Zatsiorsky and Kraemer, 2006; Gandevia, 2001). Although this is generally accepted to take place (Bawa, 2002), this principle can be overridden in situations where explosive force is required (Fleck and Kraemer, 2004). As PAP is normally evident in explosive force output, then preferred recruitment of fast twitch fibres, through a pre-conditioning activity could be a contributory factor. In this case, these
fibres, previously recruited through the preconditioning exercise, could subsequently contribute to enhanced performance on the power based activity.

**Control of muscle actions**

If PAP is able to acutely modify force output, then it is important to evaluate how muscle actions are controlled during activity. Complex movement normally originates in the structures of the lower brain and mid brain (Allen, et al., 2008). Here, the pattern of action potentials that leave the brain is refined resulting in co-ordinated movement. Motoneurons receive inputs from the cortex, brain stem, spinal cords and directly from the sensory afferents (Henneman and Mendell, 1981), and it is the interaction between synaptic inputs and the biophysical properties of the motor units that provides an enormous force and movement repertoire (Bawa, 2002). Force production can be moderated by a number of mechanisms within the body, where the firing pattern produced can be dramatically different depending upon the level of neuro-modulatory input (Nordstrom, et al., 2006). These reflexes change dramatically depending upon the movement performed, and the phase of any given movement, there existing a task-dependent reflex modulation (Stein and Thompson, 2006) which could contribute to PAP.

However, it is important note a number of caveats prior to an examination of these factors. Reflexes have traditionally been measured at rest, and so their contribution to locomotor tasks, especially those that involve maximal intensity exercise remain unclear (Stein and Thompson, 2006; Aagard, 2003). Additionally, there may exist animal species-specific or cell-specific modulations which may make generalisations from specific studies difficult (Nordstrom, et al., 2006). Similarly, many studies have used a bottom up approach, where muscles are studies *in vitro*, and where the effects of motor inputs are not accounted for, and where generalisations made may not have a place in the greater scheme of the organisms (Nordstrom, et al., 2006; Loeb 1987).

However, Stein and Thompson, (2006) suggest that the evidence that excitatory reflexes contribute a substantial fraction of the force generated during human walking is convincing, and this is likely to be similar for more intense tasks such as running. Similarly, Woods, et al., (1987) contend that motoneuron firing rates are affected by reflexes originating in the
muscle. Therefore the examination of reflexive actions and their effect on force output is warranted.

Control of force is governed by recruitment of motor units and the rate coding of firing rates, so that when force needs to be increased larger motor units are recruited and the already recruited units increase their firing rates (Bawa, 2002). If PAP is to be able to enhance force output then enhanced force would require changes in the synaptic inputs to motoneurons (both descending and reflex) or changes in the contractile performance of the muscle fibre (Bawa, 2002). In establishing the mechanisms by which the synaptic inputs can be changed; the following three aspects are worthy of consideration:

1. Receptors
2. The spinal cord
3. Monosynaptic reflexes

Receptors

Receptors are specialised cells that change their properties in response to stimuli of a special type or modality (Latash, 2008). Their ability to modulate force is based upon short latency connections between the afferent signal and the motor response (efferent signal) (Prochazka, et al., 2000). Different receptor systems allow the body to differentiate the type of energy being absorbed. The obvious function of these, is to enable information about particular types of stimuli to be made available to other neurons within the Central Nervous System (CNS) (Nielsen, 2004). There are three types of receptors:

1. Interoceptors which transduce information from within the body
2. Exteroceptors which transmit information from the environment.
3. Proprioceptors which transduce information about the relative configuration of the body segments.

(Latash, 2008)
In terms of mechanical movement, the most important class are the proprioceptors (Enoka, 2008). These relay information to the CNS about muscular changes in the body and limbs. Of the proprioceptors the most important are:

- The muscle spindles
- The golgi tendon organs
- The gamma system (Enoka, 2008)

**Muscle spindles** lie parallel to muscle fibres and provide sensory feedback regarding length changes and rate of length changes in muscle fibres (Stone et al., 2007). Muscle spindles have inhibitory pathways, so that if changes in length are too rapid they can induce the stretch reflex of the CNS, which inhibits the stretch in the muscle and causes contraction. In this, the muscle spindles protect the muscle from stretches that are too extreme in terms of range, rate of stretch or both (Stein and Thompson, 2006). This is the same mechanism exploited during plyometric training (Turner and Jeffreys, 2010)

**Golgi tendon organs** lie within the tendons, close to the junction between tendons and muscle fibres. In essence, they are force sensors, and can recognise changes in the tension of a muscle (Jami, 1992). Their role is to safeguard the muscles from excessive force. They can suppress force production via a reflexively sent message to the CNS (Jami, 1992). However, the golgi tendon organs can only recognise and react to the force generated by the associated muscle fibres of their area. It is possible that if the preconditioning exercise in a PAP complex could suppress the sensitivity of the golgi-tendon organ, then this could contribute to subsequent force expression. For this to be possible the initial exercise needs to be as similar as possible to the subsequent action, thus affecting the associated muscle fibres. The chronic suppression of golgi tendon organ sensitivity is a premise of sequential plyometric training (Turner and Jeffreys, 2010)

**The gamma system** are a special group of neurons called γ motoneurons (Enoka, 2008). These can be further divided into static and dynamic types. Dynamic γ motoneurons
innervate dynamic bag muscle fibres, and affect the sensitivity of primary spindle endings in these fibres, a process which is determined by the CNS (Taylor, 2002). Static y motoneurons send their axons to static bag and chain fibres, and can change the sensitivity of both primary and secondary endings. With this system being able to acutely affect the sensitivity of muscle spindles, then potentially they have the ability to moderate force output positively and negatively.

The information from proprioceptors bypasses consciousness and some of the effects are termed reflexes. They also inform as to where the limbs are in relation to the body, and create an internal system of co-ordinates that the brain can use to plan and execute movement. It is possible that these reflexes are affected by pre-conditioning activities (Enoka, 2008), and if so, could contribute to PAP.

Signals from proprioceptors travel along afferent axons into the spinal cord (Taylor, 2002). Whilst primary afferents make direct contact with spinal motoneurons, the majority make synapses on interneurons (Nordstrom, et al., 2006). These are typically smaller cells and make projections onto other neurons. However, some afferent fibres travel to the brain with no other connections, and there facilitate processes such as limb position, movement planning body perception etc. In this way, the information processed and which results in muscle contraction, could be modulated in relation to a pre-conditioning activity, and could contribute to PAP by modulating subsequent muscle activity.

The Spinal Cord (Excitation and inhibition)

Within the CNS, virtually every neuron is connected to every other neuron through a certain number of synapses (Latash, 2008). Therefore, excitation in one area theoretically has the chance to spread to each and every neural cell and to consequently induce contractions of each and every muscle of the body. Gullich and Schmidtbleicher (1996), using research carried out on animals, have demonstrated that induced tetanic contractions elevates the transmittance of excitation potentials across synaptic junctions at the spinal cord, a state
which can last for several minutes. This could result in an increase in postsynaptic potential for the same presynaptic potential during subsequent activity (Tillin and Bishop, 2009), and which could acutely enhance force production.

Thus, the CNS is always subject to excitatory stimuli, and therefore must have available, appropriate inhibitory stimuli to provide a balance, and prevent the uncontrolled spread of excitation (Pierrot-Dessilligny and Burke, 2005), and mechanisms exist to make excitatory stimuli ineffective. Within the CNS, two basic systems exist, postsynaptic inhibition (which makes a neuron less sensitive) and presynaptic inhibition (which makes certain inputs less effective without affecting other inputs) (Latash, 2008). If these excitatory and inhibitory mechanisms are affected by pre contractile history, then they could provide a mechanism for PAP.

**Postsynaptic inhibitions**

Synapses between neurons can be excitatory or inhibitory. Inhibitory synapses work by raising the value of the membrane resting potential via special mediators. In this way membranes are less likely to generate an action potential (Enoka, 2008). Two important postsynaptic inhibition systems for voluntary muscle contraction are:

- Renshaw cells
- Ia- Interneurons

**Renshaw cells**

The axons of α motoneurons are organised in pools, or groups, with similar functions. In addition, the axons of y motoneurons innervate intrafusal muscle fibres, changing the length and velocity sensitivity of the endings of muscle spindles (Windhorst, 2007). The α motoneurons axons branch very close to the cell body. These make excitatory synapses on
Renshaw cells (Renshaw, 1941) which are special interneurons, which provide classical autogenic inhibition to homonymous and synergist motoneurons (Gandevia, 2001). The Renshaw cell axons go back to the bodies of both α motoneurons and γ motoneurons forming inhibitory synapses. This inhibition then spreads over the entire motoneuron pool, acting in a negative feedback fashion (Windhorst, 2007). The brain can also produce input into the Renshaw cells, and can control their effectiveness (Gandevia, 2001). Thus, if the body wishes to achieve a high level of muscle contraction force in the shortest possible time, then it may turn off the Renshaw cells, whereas the opposite would be the case for activities where high levels of control are needed (Latash, 2008). While this could theoretically contribute to PAP, a factor to note is that recurrent inhibition is highest on the excitability of smaller motoneurons, but smallest during strong contractions (Windhorst, 2007; Gandevia, 2001), which would limit its potential to modulate the type of recruitment patterns required for high levels of power or speed. Recurrent inhibition may also decrease during fatiguing contractions (Gandevia, 2001), again limiting the possible contribution to PAP.

**la Interneurons**

la interneurons receive signals from la muscle spindle afferents, signals that are always excitatory (Astrand et al., 2003). These then send their signals to α motoneurons that control an antagonist muscle, a heterogenic system. Here, they make inhibitory synapses on the membrane of the antagonist pools α motoneurons (Latash, 2008). It is not currently known whether these are able to be modulated by prior contraction.

**Presynaptic inhibition**

This involves modulation of an inclining afferent signal before it reaches the motoneuron, (Enoka, 2008). In relation to the postsynaptic methodologies, this is more selective, decreasing the effectiveness of just one or a few types of inputs, without affecting others
(Brooke and Zehr, 2006). It does this by generating an inhibitory synaptic potential in the axon, modifying the afferent action potential before it contacts the motoneuron. The response is to decrease the amount of mediator released into the synaptic cleft (Enoka, 2008). In this way, depolarisation decreases and the subsequent action is reduced or negated. Presynaptic inhibition contributes greatly to the modulation of reflexes during movement and varies in response to the type and complexity of movement (Zehr, 2006; Perez, et al., 2005), and could conceivably be affected by prior contractions.

**Monosynaptic reflexes**

A muscle reflex is a muscle contraction induced by an external stimulus. (Latash, 2008), although this definition is limited, with reflexes normally involving actions that cannot be changed by a volitional act not accompanied by another muscle contraction. Studies of reflexes normally utilise the central notion of a reflex arc, consisting of an afferent neuron, a central processing unit and an efferent neuron (Latash, 2008).

The central processor itself can vary in complexity, from single synapse (monosynaptic) to multiple (polysynaptic), and can involve single or multiple sources of information (Nordstrom, et al., 2006). The time lag between stimulus and reaction is called reflex latency and consists of the time of afferent and efferent conduction, (which is normally dependent on speed of action propagation and fibre length) and central delay (which is dependent on the number of synapses involved) (Enoka, 2008).

Within a muscle nerve, the biggest fibres are the la afferent, which travel from muscle spindle to spinal cord with the $\alpha$ motoneurons being a little smaller (Latash, 2008). Activity in the la afferents normally results in a monosynaptic reflex. In terms of possible contributory factors to PAP, the following monosynaptic reflexes could play a contributory role:
**Hoffmann (H) reflexes**

Electrical stimuli produce two responses in the muscle; a direct motor, or M, wave from stimulating motor axons and a H reflex, which arises mainly from monosynaptic excitation of motoneurons by sensory nerve fibres from muscle spindles. (Stein and Thompson, 2006) The response is in relation to the stimulus, with the greater response generated by greatest stimulus (Enoka, 2008). Hoffman reflexes largely comprise monosynaptic inputs to the spinal motoneurons, whereas the long latency reflex includes multiple synapses that can involve the evoked potential travelling to suprasinal centres before the output is initiated by the motoneuron (Hunter, et al., 2004).

The stimulus will elicit a response at the muscle called the M response. As stimulation strength increases, so does the M response, whilst the amplitude of the H response will rise for a while and then start to decrease (Enoka, 2008). Supramaximal intensity stimulus results in a maximal direct M response by orthodromically activating all the motor axons in the peripheral nerve (Aagard, 2003). At high intensities of stimulation, the H reflex response is abolished, due to collisions between action potentials that travel antidromically in the motor axon towards the spinal cord, and action potentials that propagate orthodromically from the spinal cord towards toward the muscle fibres due to the volley of H reflex impulses (Aagard, 2003). These reflexes have the potential to increase muscle force, and prior stimulation, caused by a preconditioning activity, could contribute to PAP. However, the functional significance of these reflexes remains unclear (Hodgson, et al., 2005).

**Tendon (T) reflex**

This is induced by a rapid muscle stretch; a physiological stimulus. This stretch initiates rapid firing of the muscle spindles, and sends action potentials along la afferents which produce a reflex response in α motoneurons, and the result is a twitch contraction of the muscle - a T (tendon) reflex (Stein and Thompson, 2006). The T reflex is modulated in relation to the amplitude and/or velocity of the stretch, until it reaches its maximum value (Latash, 2008). Whilst this could be a possible contributory factor, the fact that preconditioning activities
associated with PAP have not used rapid stretch activities suggests that its role may be limited, and would only contribute via the use of pre-conditioning activities that utilise the stretch reflex such as plyometric activities.

**F wave**

The F wave results from antidromic (toward the motoneuron) conduction along the axons of a motoneurons (Latash, 2008). This is similar in nature to the H reflex, but does not become smaller with an increase in the amplitude of stimulation, nor does it decrease with an increase in the frequency of stimulation (Latash, 2008). As pre conditioning activities utilised in PAP do result in an increased amplitude of stimulation, together with an increased frequency of stimulation, then this mechanism could possibly contribute to PAP.

**Modulating these reflexes**

An important factor to consider is that reflexes are not fixed responses, and the input output relationship can vary (Enoka, 2008). It would appear that this ability can be developed, and that voluntary activation of the agonist muscle can increase the H reflex, whilst activation of the antagonist muscle can decrease the H reflex (Enoka, 2008). In addition, activation of distant large muscle groups can lead to a modulation of the H reflex in the calf muscle. Tillin and Bishop, (2009) suggest that PAP can increase H wave amplitude, possibly as a result of increased higher order motoneuron recruitment at the spinal cord. However, at high intensities of stimulation, the H reflex response is abolished, due to collisions between action potentials that travel antidromically in the motor axon towards the spinal cord, and action potentials that propagate orthodromically form the spinal cord towards toward the muscle fibres due to the volley of H reflex impulses (Aagard, 2003). Supramaximal intensity stimulus results in a maximal direct M response by orthodromically activating all the motor axons in the peripheral nerve (Aagard, 2003). It still remains to be seen whether these can enhance performance on a subsequent voluntary contraction, this
is especially due to the fact that reflexes change dramatically depending upon the specific movement being performed (Stein and Thompson, 2006). Measuring these reflexes at rest, which has been the focus of the vast majority of work to date, has no relation to dynamic performance, and dynamic performance demonstrates a task-dependent reflex modulation (Stein and Thompson, 2006). Additionally, work has also focussed on single muscle responses (Aagard, 2003) which again bear little relationship to the type of movements seen in sports. Application to performance is also complicated by the findings of Trimble and Harp, (1998) who found great inter-subject variability in the amplitude and time-course of postactivation potentiation and post-activation depression following electrical stimulation.

**Muscle stiffness**

Stiffness is defined as the force required per unit length to deform a sample (Nigg et al., 2000). A key element is that muscle behaves as a non linear spring (Monroy, et al., 2007) and that these spring like properties can contribute to force production in stretch shorten cycle (SSC) type activities. The stiffness will depend upon the muscle’s elastic qualities, which determines the resistance it has to movement (Enoka, 2008). When stiffness is high, there is a large increase in tension when the muscle is stretched (Edman, 2003). A muscle’s stiffness has two apparent components, one is purely peripheral and is independent of any reflex effects, whilst the second has a reflex nature (Latash, 2008). In this way the muscle itself has the capacity to adjust its stiffness rapidly without requiring neural inputs (Monroy, et al, 2007)

The greater the stiffness of the muscle, the greater the potential for force production. Activation of the muscle increases its apparent stiffness (Kearney and Hunter, 1990). These activities may evoke segmental reflexes, which, in turn, could potentiate muscle activation and contribute to an increase in muscle stiffness (Moritani, 2003). Therefore, increased muscle stiffness, as a result of prior muscle activity could be a contributing factor to PAP (Harrison, 2007).
Muscles have also been shown to demonstrate pre-activation, that is activity prior to ground contact in activities such as depth jumps, hopping etc (Moritani, 2003). This pre-activation is thought to be important for the enhancement of the stretch reflex and for advancing the onset of muscular action during rapid movements such as running and jumping (Moritani, 2003), and could be a major contribution of PAP (Harrison, 2007). Comyns et al., (2007) found that fast stretch shortening cycle activity can be performed with greater stiffness in the leg spring action subsequent to heavy lifting (back squats at 93% 1RM). This mechanism has the potential to be a major contributor to PAP, especially in activities such as sprinting, where SSC activity plays an important role (Harrison, 2007).

**Mechanisms of fatigue and potentiation – Implications for PAP**

Contractile activity produces both fatigue and PAP (Robbins, 2005), with the resultant performance depending upon the timelines of both. This forms the basis of the fitness fatigue model of muscle activation, which is summarised in Figure 1.9. In evaluating the performance effect of prior contractile history, together with the postulated mechanisms of PAP, it is therefore important to have a fundamental grasp of the mechanisms which contribute to both fatigue and potentiation, and to evaluate how these elements are affected by a muscle’s contractile history.
**Mechanisms of fatigue**

Fatigue can be defined as "an exercise induced reduction in the maximal force capacity of muscle" (Hunter et al., 2004) and is often quantified as a reduction in maximal voluntary contraction force after, or during, maximal and submaximal exercise (Enoka and Duchateau, 2008). The mechanisms of fatigue are specific to the details of the specific task (Hunter, 2009), and in different physical activities both the mechanisms involved, and their quantitative importance can vary (Allen, et al., 2008). It is therefore important to take a task oriented approach to analysing the likely contributions of various mechanisms of fatigue.

In terms of the fatigue associated with intermittent high intensity activities, fatigue is associated with a reduction in maximum force output on the subsequent effort, caused by the pre-conditioning exercise. An investigation into the likely causes of fatigue will need to consider the pre-conditioning exercise in terms of the type, and intensity, of contractions,
the muscle groups involved and the limb support provided (Hunter, 2009). Given the type of activities utilised to generate PAP, focus will need to be on any mechanism that reduces muscle force when undertaking relatively brief but high intensity exercise. If a muscle is stimulated continuously at a frequency close to that which gives maximal force, force production shows a rapid decline, called high frequency fatigue, a feature of which is also a rapid recovery of force capacity (Bigland-Ritchie, et al., 1979).

A decline in force after a fatiguing task may be due to impairments at a number of sites (Hunter, 2009). Studies of fatigue normally focus on determining whether the mechanism responsible for fatigue is located in the working muscles or within the nervous system activating the muscles (Di Giulio, et al., 2006). This normally differentiates between a decrease in the activation signal magnitude, or an impairment of muscle contractile function (Enoka, 2008).

Establishing the causes of fatigue is exacerbated by the fact that fatigue is not normally caused by a single mechanism, but rather by several mechanisms both motor and sensory (Enoka, 2008). The contribution of each will vary with the specific exercise being undertaken, and is hence task-dependent – the task-dependency of muscle fatigue (Enoka & Duchateau 2008). When establishing mechanisms of fatigue, it is important to undertake a task-failure approach, emphasising the mechanisms of fatigue occurring within a given task (Enoka & Duchateau, 2008).

Kent-Braun, (2008) states that fatigue can be seen to involve one or more of the following, and these are summarised in Figure 1.10:

- Changes in the motor command.
- Changes in the activity of peripheral receptors, leading to changes in reflex effects.
- A decrease in the efficiency of neuromuscular synapses.
- Changes in the recruitment patterns of α motoneurons.
• A decrease in the ability of muscle fibres to generate force.
• Metabolic factors (a decrease in substrate availability or a build up of metabolic by products)
• Psychological factors.

Fig 1.10 Potential sites of failure during muscle contraction (adapted from Kent-Braun, 2008)
In looking at these mechanisms, it is possible to differentiate between muscular mechanisms of fatigue and neural mechanisms of fatigue, always keeping in mind that total fatigue levels will involve a balance between a number of fatigue causes.

**Muscular mechanisms of fatigue**

A number of mechanisms can contribute to muscular fatigue, and the relative contribution will be task-dependent. These include:

*Slowing of conduction velocity*, leading to an increase in the duration, and a reduction in the amplitude of an action potential, and eventually propagation may cease. This has been associated with an efflux of K⁺ ions, increased extracellular K⁺ and decreased intracellular K⁺ (Alien, et al., 2008).

*Slowing of the relaxation phase*, resulting in a marked increase in the time from peak contraction to 50% of the value. Factors thought to contribute to this include a decrease in the rate of Ca²⁺ removal, following a decrease in ATP concentration, and alterations in the time course of cross bridge detachment after the removal of Ca²⁺ ions (Allen, et al., 2008; Latash, 2008).

*Changes in excitation threshold*, whereby muscle fibres will change in their response to external stimulation, with a consequent slowing of action potential conduction (Allen, et al., 2008).

*Reduction in twitch peak*, whereby, although a short tetanic stimulation can result in a potentiation effect, longer tetanic contractions can result in smaller and longer twitch peaks and a resultant drop in performance (Allen, et al., 2008).
It is important to note that each of the above will be specific to the task involved and will depend upon the functional characteristics of the individual and so the functional role of the inputs during fatiguing contractions remains uncertain (Hunter, et al., 2004). Additionally, the above mechanisms may work in tandem or independently depending upon the task performed, and therefore have distinct effects on specific activities (Allen, et al., 2008). This emphasises the need for PAP based research to focus upon the effects of distinct activities, upon specific aspects of sports performance.

As well as the above mechanisms, it is also possible to differentiate between fatigue caused by either the failure of activation or myofibrillar fatigue (Edman, 1995).

Activation failure is caused by a decrease in myofibrillar sensitivity to Ca$^{2+}$ and a reduction in Ca$^{2+}$ release from the sarcoplasmic reticulum (Allen, et al., 2008). This can occur independently of acidosis, via ATP dependent components, which are in addition to the effects of low ATP on Ca$^{2+}$ release channels (Allen, et al 2008). These include sarcolemma Na$^+$, K$^+$ ATPase pumps, sarcolemma K$^+$ channels that open when ATP concentration is low, sarcoplasmic reticulum Ca$^{2+}$ ATPase, (which returns Ca$^{2+}$ to the sarcoplasmic reticulum) and processes that connect T tubule activity to the terminal cisterna of the sarcoplasmic reticulum (Astrand et al., 2003).

Myofibrillar fatigue is caused by an impairment of cross bridge function (Enoka, 2008), and the inability of the muscle fibre to react properly to elevated cystolic Ca$^{2+}$ concentrations (Allen, et al., 2008). This is evidenced by a reduction in the force and velocity of shortening. The force reduction is not due to acidification and may be due to accumulation of P$^-$ ions (Cooke, 2007). The decline in velocity appears to involve other factors beside H$^+$, although the causes still need to be determined (Allen, et al., 2008). It is important to note that during high force contractions, myofibrillar fatigue normally precedes activation failure (Enoka, 2008).

**Metabolic Substrates**

Studies of metabolic causes of fatigue traditionally focus on the availability of energy substrates, and metabolic by products that affect performance (Hunter, et al., 2004). Fatigue is task-dependent, and the predominant causes of fatigue will relate closely to the
type of activity undertaken (Hunter, 2009). PAP inducing exercises are normally of a high intensity, intermittent, and short duration, e.g. 1RM, 3RM, 5RM Squats. Therefore, they predominantly utilise stored ATP and ATP/PCr energy systems (Baechle, et al., 2008). Thus, availability of substrates is unlikely to be a contributing factor in the potential fatigue produced from the pre-conditioning exercise. Similarly, the short duration of contraction is unlikely to lead to a significant build up of H⁺, and thus, bi-products are unlikely to be a large contributing factor in any fatigue development produced by a single activity of short duration (Hunter, et al., 2004). These issues are therefore not discussed within this review.

**Neural Mechanisms of fatigue**

As neural mechanisms contribute significantly to muscle contraction, then these need to be evaluated in terms of fatigue mechanisms. Neural mechanisms of fatigue can be subdivided into spinal mechanisms and supraspinal mechanisms (Latash, 2008).

**Spinal mechanisms.**

During a series of contractions, there is normally a drop in peak force (Allen, et al., 2008). This is usually associated with a decrease in the frequency of firing of individual motor units, and of α motoneurons excitability (Hunter, et al., 2004). This is especially the case in larger fast twitch fibres, whose recruitment and de-recruitment is normally thought to follow the Henneman (size) principle, where they are recruited last and de-recruited first (Latash, 2008).

Fatigue has been shown to occur at the neuromuscular junction and this is thought to be the result of autogenic reflex inhibition of the α motoneuron pool. (Latash, 2008). In addition, a decrease in the short latency responses, especially the H reflex, is characteristic of fatigue, and this is thought to involve an impairment of central neural mechanisms, as opposed to a change in muscle spindle responsiveness (Hunter, et al., 2004). This reduction is thought to be caused either by enhanced inhibition of the motor pool, or by impaired
synaptic transmission within the spinal cord (Hunter, et al., 2004). However, long latency
reflexes, which involve multiple synapses, show little change, or even an increase in activity.
This suggests an increase in the excitatory descending drive during the fatiguing contraction,
perhaps as a compensatory effect, which may contribute to PAP. Changes in the balance of
the excitatory and inhibitory inputs into the motoneuron pool, including the reduction in
excitatory input by presynaptic inhibition, contribute to task failure (Hunter, et al., 2004).

Supraspinal mechanisms

Muscle force is modulated via variations in the number, and rate of, motor unit recruitment
(Bawa, 2002). In general, all of the supraspinal structures involved in control of voluntary
muscle activation can contribute to muscle force decrease due to fatigue (Latash, 2008).
Fatiguing contractions result in a gradual increase in cortical neuron activity, followed by a
decrease (Benwell, et al., 2005). Additionally, excitability of neurons in the primary motor
area changes during prolonged muscular activity (Taylor and Gandevia, 2001). Increases in
the duration of a task are accompanied by corresponding reductions in the rate of increase
in motor unit activity. This supports the notion that fatigue and potentiation can co-exist,
and emphasises the task-dependent nature of both. These changes can vary from task to
task, and from subject to subject and so, at present, it is difficult to identify supraspinal
structures that can play a particularly important role in the fatigue induced drop in
voluntary muscle contraction force (Latash, 2008).

Muscle Potentiation

The use of PAP in sports performance is centred around the possible performance
enhancing possibilities of pre-conditioning exercises (Tillin and Bishop, 2009). It has been
postulated that under voluntary control, the neuromuscular system might have a reserve
capacity for generating unusual levels of force for brief periods of time (Moritani, 2003), and
PAP may be a way of harnessing this potential. A brief period of activity can increase both
the electrical and mechanical output above resting values, a potentiation effect (Enoka,
2008). This potentiation effect is the main principle of PAP, and it is important to identify possible causes of acute performance potentiation.

Potentiation capabilities can be seen in:

- Monosynaptic responses.
- Miniature endplate potentials.
- M waves.
- Twitch force.
- Muscle spindle receptor discharge.

(Enoka, 2008)

**Monosynaptic reflexes**

It can be assumed that most processes in the motor system can be augmented by brief periods of activity (Allen, et al., 2008). This has been proved at the level of input-output relations for the spinal cord including the H reflex and T-reflexes, and was originally reported by Lloyd (1949). The mechanism here appears to be presynaptic, occurring before the synaptic contact with the motoneurons (Enoka, 2008), and probably involves group Ia afferents (Koerber and Mendell, 1991). Effects could include an increase in volume and/or efficiency of released neurotransmitters or a reduction in axomai branch point failure along the Ia afferents. (Enoka, 2008; Luscher, et al., 1983).

**Miniature end plate potentials**

At the postsynaptic membrane, miniature end plate potentials can be elicited via the release of neurotransmitters (including acetylcholine) at the neuromuscular junction (Enoka, 2008). These are known as excitatory post synaptic potentials (EPSP’s) and tend to be greater in amplitude in fast twitch fibres, and are increased in frequency and amplitude following high frequency stimulation (Pawson & Grinnell, 1990). The frequency effect is brief (a few
minutes), whereas the amplitude effect can last for several hours (Pawson & Grinnell, 1990), and is greater at the neuromuscular junctions where more neurotransmitter is released per unit length of the junction. Activation of an α motoneuron works in an all-or-none fashion, where presynaptic transmitter release must coincide with postsynaptic receptor sensitivity (Tillin and Bishop, 2009). The process appears to involve increased sensitivity to the influx of Ca\(^{2+}\) at the postsynaptic membrane. This increases the response of the neurotransmitter, increasing the amplitude of the synaptic potential, whilst the greater influx of Ca\(^{2+}\) enhances the frequency of neurotransmitter release (Elrick and Charlton, 1999). The net effect of these processes is to make a muscle fibre more responsive to incoming action potentials (Enoka, 2008).

**M wave amplitude**

During muscle contraction, there is often an increase in M wave amplitude, which has been reported as up to 24% (Hicks, et.al., 1989) and supramaximal intensity stimulus results in a maximal direct M response by orthodromically activating all the motor axons in the peripheral nerve (Aagard, 2003). Any increase in M wave amplitude must be the result of postsynaptic factors, and these include a reduction in the temporal dispersion of muscle fibre potentials, and an increase in the amplitude of individual muscle fibre potentials (Dimitrova and Dimitrov, 2002).

An increase in M wave amplitude appears to be due to an activity-dependent increase in the amplitude of muscle fibre action potentials (Hicks and McComas, 1989). This has the effect of increasing the Na\(^+/K^+\) pump, which lowers the resting membrane potential resulting in a greater change in voltage across the membrane during an action potential (Enoka, 2008). This can cause a modest reduction in the decline of force during a fatiguing contraction (Gong, et al., 2003), but does not appear to increase force production (Enoka, 2008).

While these physiological mechanisms have been observed, it still remains to be seen whether these can enhance performance on a subsequent voluntary contraction. This is
especially due to the fact that reflexes change dramatically depending upon the specific movement being performed (Stein and Thompson, 2006).

**Post Tetanic potentiation**

Post tetanic potentiation refers to the enhancement of twitch force following a brief tetanus (Hodgson et al., 2005) and its effect is variable depending upon the activation history of the muscle (Enoka, 2008). This effect can be elicited via electrical or voluntary contractions and can be substantial (O Leary, et al., 1997). The potentiation can occur after both maximal and submaximal voluntary contractions (Vandervoort et al., 1983), and is similar for isometric, concentric and eccentric actions (Baudry and Duchateau, 2004). Where sub maximal twitches are elicited in close succession, a staircase effect of potentiation can be achieved (Enoka, 2008). Two processes are involved in post-tetanic twitch potentiation. (Garner et al., 1989; Vandervoort et al., 1983)

1. Early potentiation. This occurs after brief contractions, and decays rapidly.

2. Late potentiation. After 60 seconds a late potentiating process emerges and this reaches a peak at 200 seconds, retuning to control levels after 8-12 minutes of recovery.

In terms of PAP affecting sports performance, the latter of these is more likely to be a major contributor. It is thought that the mechanism by which this occurs involves changes in calcium kinetics, changes in the force velocity characteristics of cross bridges and the phosphorylation of myosin light chains (O Leary, et al., 1997; Duchateau and Hainaut, 1986). Potentiation is seen to occur in all muscle fibre types, but is greatest in fast twitch fibres (Duchateau and Hainaut, 1984). This would correlate with findings that PAP tends to occur in stronger athletes, who are likely to have a greater degree of fast twitch fibres (Ruben, et al., 2010; Chiu, et al., 2003).
Studies in this area clearly demonstrate the coexistence of fatigue and potentiation which occur concurrently, beginning at the onset of activation (Hamada, et al., 2003). This can be summarised in Fig 1.9, the fitness fatigue model. The time course of the change in performance is due to the temporal interaction of the processes that mediate potentiation and fatigue. Enhancement of tetanic force has been demonstrated to last for up to 15 minutes (Sale 2002), with the specific time course depending upon the interaction of the processes that mediate potentiation and fatigue (Tillin and Bishop 2009). It has been associated with a reduction in phosphate availability, (but not in intracellular calcium concentrations), a change in temperature or a decrease in intracellular pH, and could contribute to the enhancing effects of warm-up or PAP (Baudry and Duchateau 2007).

Post contraction sensory discharge

Brief activity has the capacity to affect sensory processes, in addition to motor processes. At the onset of rapid muscle contractions in vivo, discharge doublets may be observed in the firing pattern of motoneurons (Aagard 2003). It is possible that these serve to enhance the initial generation of muscle contraction force by taking advantage of these catch-like properties, hence increasing rate of force development (Aagard, 2003). Ballistic-type training, has been shown to markedly increase the incidence of discharge doublets in the firing pattern of individual motor units, while also increasing the rate of force development (Van Cutsem, et al., 1998)

Post contraction sensory discharge increases the excitatory input to the motoneuron pool, and can affect subsequent activity for up to 15 minutes (but peaking at 5 - 20 seconds) (Enoka, 2008). It is caused by the development of stable cross bridges in the intrafusal fibres, which develop during contraction and persist during subsequent relaxation of the extrafusal fibres (Gregory, et al., 1986). The consequence is that a muscle spindle is in a state of increased tension with a subsequent increase in resting discharge (Gregory et al., 1986). The strength of postcontraction sensory discharge can be sufficient to increase the resting discharge of motoneurons (Suzuki and Hutton, 1976). It must be noted that if a muscle is stretched following the contraction, the cross bridges are broken and the whole
effect is negated. The fact that Vandervoort et al., (1983) found that potentiation was
greatest when muscles were tested in a shortened position, suggest that this mechanism
could contribute to PAP. However, in the case of PAP possibly enhancing sports
performance, the fact that natural stretching will occur during the majority of sports
activities, including running, would mean that this mechanism’s potential for enhancing
performance through warm-up would be limited to a few activities where stretching
between the pre conditioning exercise and subsequent performance does not occur.

Mechanisms of PAP – Current Opinion

Clearly, a large number of mechanisms exist by which PAP could be induced, and these
include both neural and muscular mechanisms. At this time, the exact mechanisms of PAP
are yet to be fully investigated, and while some mechanisms to explain the phenomena
have been postulated, these have yet to be consistently validated (Tillin and Bishop, 2009).
Currently, the two main views on PAP reflect both a muscular basis and a neural basis. One
of the proposed mechanisms involves the phosphorylation of myosin regulatory chains,
while the second involves the recruitment of higher order motor units (Tillin and Bishop,
2009).

Rassier and Macintosh, (2000) and Paasuke, et al., (1996) suggest that the mechanism
responsible for PAP is the “phosphorylation of the regulatory light chains of myosin”, with
Miyamoto, et al., (2009) identifying this as the most likely mechanism responsible for PAP.
The amino termini of each myosin heavy chain contains two regulatory light chains, each
with a specific binding site for incorporation of a phosphate molecule (Tillin and Bishop,
2009). Neurological muscle stimulus causes an increase in sarcoplasmic Ca²⁺, that activates
myosin light chain kinase (MLCK) (Szczesna, et al., 2002), which can increase actin-myosin
crossbridging, through increasing ATP availability (Docherty et al., 2004). Additionally, the
phosphorylation of the Myosin Light Chain (MLC) renders the actin-myosin interaction more
sensitive to Ca²⁺ released from the sarcoplasmic reticulum (Sale, 2002). MLC
phosphorylation is believed to move the cross bridges toward the thin filament, closer to
actin attachment sites, thereby increasing the probability of myosin actin attachments
(Rassier and Herzog, 2004). However, this effect is at its peak at low myoplasmic levels, which occurs at low frequency contractions, and which would not enhance power performance. At high frequency, tetanic contractions, increased sensitivity to Ca\(^{2+}\) has little or no effect in saturating Ca\(^{2+}\) (Sale, 2002). This would suggest that PAP’s effect would be smallest where motor unit firing rates are likely to be at their highest i.e. during high power outputs (Sale, 2002). Additionally, while this phenomenon has been consistently demonstrated in animals, its effects in humans is not as consistent (Tillin and Bishop, 2009). Tubman, et al., (1996) examined MLC phosphorylation and post-tetanic potentiation, and concluded that it was not the only mechanism contributing to PAP, and PAP is likely to be the result of the interaction between neural and muscular mechanisms (Docherty, et al., 2004). Stuart, et al., (1988) stress that the significance of MLC phosphorylation in human skeletal muscle remains unclear, and that other factors may provide the major contribution to PAP. Additionally the relationship between MLC phosphorylation and enhanced performance is questioned by the work of Smith and Fry, (2007) who measured change of force, velocity or power measures on the performance of a 1RM leg extension, 7 minutes subsequent to a 10 second MVC. Seven subjects in the study demonstrated elevated regulatory myosin light chain (RLC) phosphorylation,(measured via muscle biopsy and subsequent analysis via imaging of stained nitrocellulose paper) but showed no increase in performance.

In terms of the enhanced neural excitability, PAP may increase motoneuron pool excitability, as evidenced by a potentiated reflex response (Trimble and Harp, 1998). Animal research has consistently shown that induced tetanic contractions can elevate potentials across synaptic junctions at the spinal cord (Tillin and Bishop, 2009; Gullich and Schmidtbleicher 1996). As a result there is an increase on postsynaptic potentials for the same presynaptic potential during subsequent activity (Tillin and Bishop, 2009; Luscher, et al., 1983). As activation works in an all-or-none fashion, transmitter failure at various synaptic junctions can inhibit force production (Tillin and Bishop, 2009). However, transmitter failure is a common occurrence during normal reflex or voluntary responses. (Luscher, et al. 1983). This is due to an autonomously protected activation reserve (Tillin and Bishop, 2009; Luscher, et. al. 1983). An induced tetanic contraction could decrease
transmitter failure, and the following mechanisms have been proposed for this effect, which may work in isolation or combination:

1. An increase in neurotransmitter release
2. An increase in neurotransmitter efficiency
3. A reduction in branch point failure along afferent neural fibres
   (Enoka, 2008, Tillin and Bishop, 2009)

If a muscular action could induce an increase in higher order motoneuron recruitment in humans, then this effect would have the capacity to increase fast twitch fibre contribution to muscular contraction (Tillin and Bishop, 2009) This, in turn, would have the potential to enhance subsequent performance of explosive exercises (Tillin and Bishop, 2009; Gullich and Schmidtbleicher, 1996).

Animal studies have demonstrated an increase in H wave activity following muscle stimulation (Gullich and Schmidtbleicher, 1996), and this could indicate a decrease in transmitter failure at the synaptic junctions. Folland, et al., (2008), and Maffiuletti, et al., (2001) have demonstrated similar effects in humans, suggesting that PAP increases H wave amplitude in humans, which may be the result of increased higher order motoneuron recruitment at the spinal cord (Tillin and Bishop, 2009). Additionally, Trimble and Harp (1998) found that this enhancement in H wave activity can be evoked via maximal voluntary isometric contractions (MVC's) using 8 sets of 10 second actions.

In addition to H wave studies, studies on excitatory post synaptic potentials (EPSP’s) have also shown potentiated activity following electrical stimulation (Luscher, et al., 1983; Hirst, et al., 1981). Hirst, et al., (1981) found a 54% increase in EPSP’s for the same presynaptic input following a 20 second tetanic isometric contraction. Enhanced EPSP’s represent greater motoneuron membrane depolarization, enhancing the likelihood of action potential initiation, and enhancing the subsequent muscle contraction. Luscher, et al., (1983) found a positive correlation between EPSP amplitude and motoneuron input resistance. This indicated larger motoneurons experience greater transmitter failure, and suggested that a tetanic contraction decreased transmitter failure predominantly at larger motoneurons (Luscher, et al., 1983). This would have clear implications for the activation of fast twitch muscle fibres, and provide the possibility of generating PAP in these fibres (Tillin and Bishop,
If the same effect could be proved in humans, and additionally be provided via dynamic activities, then it might theoretically increase fast twitch fibre contribution to muscular contraction which, in turn, would provide the potential for performance enhancement during explosive exercises (Tillin and Bishop, 2009).

While the above represent possible mechanisms for PAP in humans at present the exact mechanisms of PAP remain unclear (Tillin and Bishop, 2009; Aagard, 2003). Additionally, it is important to look at the net effect of these physiological mechanisms which could result in: the recruitment of more motor units, better motor unit synchronisation, a decrease on presynaptic inhibition of greater central input to the motoneuron or a combination of these mechanisms (Aagard, et al., 2002). All of these factors have been associated with muscle force and power production, and clearly would have an impact on sports performance (Stone, et al., 2007) However, whether subsequent voluntary muscular activity can enhance motoneuron recruitment, and more significantly actual performance, is yet to be determined (Tillin and Bishop, 2009).

The interaction between neural and muscular mechanisms produces another potential complication in the application of PAP to sports performance. If a number of mechanisms exist, then the likelihood is that there could be large inter-individual differences in PAP capabilities, and also potential intra-individual differences, depending upon the athlete’s capability within each contributory factor at any one time. If this is the case, then the task of constructing optimal protocol in group situations becomes increasingly difficult.

PAP has consistently been shown to be greatest in Type II fibres in mammals (Hamada, et al., 2000). In humans this correlation has not been found consistently, although Hamada et al., (2000) suggest that “human muscles with shorter twitch contraction times and a higher percentage of Type II fibres exhibit greater PAP”. Type II fibres have been shown to undergo greater phosphorylation of myosin regulatory light chains in a response to a conditioning activity (Sale, 2002). Thus, PAP is more likely to be evident in athletes with a higher percentage of Type II fibres, and within muscles with a higher percentage of Type II fibres. However, the muscular mechanisms of PAP highlighted to date seem to offer limited effectiveness in enhancing strength, power and speed performance as they cannot
“increase high frequency force” (Sale, 2002). It could be that the neural factors are the main components of performance enhancement through PAP.

Rather than simply focussing on force, a key effect of PAP in Type II fibres is the enhancement of the rate of force development (RFD) (Tillin and Bishop, 2009). Although peak isometric force, and maximum unresisted shortening velocity cannot be enhanced by PAP (Gossen and Sale, 2000), the rate of force development can be enhanced, even at very high stimulation frequencies (Sale, 2002). This is important for speed and power performance, as they are characterised by brief maximal efforts, with a higher number of motor units recruited and firing at maximal rates (Sale, 2002). This can positively affect acceleration, which is important to performance in a whole range of sports. A rightward and upward shift of the velocity load curve (Fig 1.11), should result in enhanced accelerative performance at all loads between maximal velocity and peak isometric force. Thus, both running speed, and jumping ability could theoretically be enhanced via this method. Abbate, et al., (2000) found that peak power velocity post PAP tended to shift to a higher velocity in rats, and further mammal studies suggest that PAP can enhance force and power of iso-velocity concentric contractions particularly at high velocities, although they also suggest that there may be an upper limit of stimulation frequency at which PAP can be elicited (Sale, 2002).
Rate of force development is controlled by the actual activation of fast twitch muscle fibres, and as Gandevia (1999) states, “muscles are the servants of the brain”. In studying the force output of a muscle, it is important to note that motor units are capable of firing at different frequencies, and that the activation depends upon the level of excitation of the motoneurons by the CNS (Sale, 1992). Corcos, et al., (1996) states that movements performed at different speeds are controlled by “increasing the intensity of activation to the motoneuron pool, and activating the antagonistic muscles earlier for faster movements”. Thus, there are subtle changes that take place in the neural control of speed-based movements, and it is important to determine whether these can be influenced by training.

Training motor units requires changes in the synaptic inputs to motoneurons (both descending and reflex), changes in the motoneurons themselves, and changes in the innervated muscle fibres (Bawa, 2002). Training can affect the firing rates of muscles, and high velocity training develops a pre movement silence in agonist muscles, which may increase the rate of force production and peak force of ballistic actions (Bawa 2002; Sale, 1992). This is achieved by bringing all motoneurons into a non-refractory state, allowing them all to be more readily recruited and brought to the maximum possible firing rates.
(Sale, 1992). It appears that the balance between inhibition and excitation changes with practice, and can occur quickly (Bawa, 2002)

In addition, it may induce a brief stretch shortening cycle, again increasing peak force and the rate of force development of the ensuing ballistic action. Corcos et al., (1996) observed that when practice leads to changes in the rate at which force is produced, this increase is achieved by increasing the intensity of neural activation to antagonistic muscle groups and decreasing the time delay between them. Thus, heightened excitability of the neuromuscular system, a possible benefit of PAP, could have a beneficial effect on subsequent power performance by enhancing RFD. In this way, PAP may be related to the degree of training of an individual, and not necessarily to solely their strength level.

**Potential neuro-endocrine influences on PAP**

One area not adequately addressed in previous discussions on PAP is the potential influence of the hormonal system, and its net effect on muscular performance. The neuro-endocrine system contributes to exercise induced homeostatic adjustments (Stone, et al., 2007). It does this by releasing neurotransmitters and hormones that interact with specific receptors, alerting metabolisms and eliciting specific responses (Stone, et al., 2007). The effects of the neuro-endocrine system on performance are best viewed as an interaction between a variety of neural and hormonal factors rather than from the isolated effects of single neurotransmitters or hormones (Stone, et al., 2007).

In relation to PAP, the critical factor to examine is whether the neuro-endocrine system is able to acutely modulate force production. Therefore, the discussion needs to focus on the response of hormones principally involved in force production, rather than muscle hypertrophy. Previously the following hormones have been linked to enhanced force production levels (French et. al. 2007):

1. Testosterone
2. Catecholamines
Testosterone is an androgen produced predominantly in the testes. Circulatory testosterone levels have been highlighted as an important factor in the performance of elite weightlifters, where elevated levels have been shown to influence muscular performance (Kraemer, et al., 1992). Exercise response patterns of testosterone vary with a number of factors including intensity, volume and rest periods (Hoffman, 2002). This response appears biphasic, and dependent upon exercise duration, where exercise of short duration has little effect, with increases occurring at 20-30 minutes duration (Hoffman, 2002). Given the short duration of the pre-conditioning activities associated with PAP, increases in testosterone would not appear to be a major influence on PAP.

Catecholamines are neurotransmitters, with the primary catecholamines being epinephrine and norepinephrine (Stone, et al., 2007). Norepinephrine is the primary catecholamine released by the neuron, with epinephrine the primary catecholamine released by the adrenal medulla (Stone, et al., 2007). The direct and indirect actions of catecholamines on muscle function, include an increase in force production, an increase in contraction rate and an augmented secretion of other hormones, and may be the most important hormones for the acute expression of strength (Kraemer, 1992).

In terms of acute responses, the catecholamines appear to have regulatory properties that modulate homeostasis to meet the elevated psycho-physiological demands of muscle force production (French, et al., 2007). During repeated muscular actions, membrane excitability is reduced, caused by a disruption in the ionic balance across the sarcolemma (Balog, et al., 1994). The exposure of muscle fibres to catecholamines can reduce this effect, and contribute to net muscular force (Mikkelson, et al., 2006). Catecholamines assist in force generation and membrane excitability, via their effects on the sodium/potassium pump function and on the restoration of ionic balance across the sarcolemma, thus promoting actin-myosin interaction in depolarised skeletal muscle cells (Mikkelson, et al., 2006).

Psychological drive, both before and during exercise, induces catecholamine secretion. Catecholamine levels will increase pre-exercise in anticipation of the demands of the oncoming exercise or in response to the intensity of the exercise (French, et al., 2007). Pre-exercise catecholamine level is an important factor in force production (Shelton and
Mahoney, 1978). It can be hypothesised that the anticipatory rise in catecholamines before resistance exercise is critical for achieving optimal force production at the onset of exercise (French, et al., 2007). In this way any warm-up procedure must ensure that sufficient stimulation is given to ensure optimal levels of catecholamine secretion. This factor has important implications for study design in the investigations into PAP. The anticipation of heavy resistance exercise may result in an elevation of the catecholamines, over and above that found in groups where only a general warm-up and subsequent performance measured. In this case, control warm-up protocols should at least aim to express maximal intensity (whether it be running/jumping etc) prior to any performance measures being taken. Short duration sprints of maximal intensity have been shown to elevate epinephrine and norepinephrine concentrations (Kraemer, et al., 1990). The failure to control this, and the use of low intensity general warm-ups in the vast majority of PAP studies, could explain the contradictory findings of studies to date. These could also be explained by the fact that the relationship between circulating catecholamines and muscular force may be individual in nature, and therefore, the development of optimal group warm-ups is made more difficult (French, et al., 2007).

In any discussion on the mechanisms of PAP the role of the catecholamines needs to be taken into account, and is a major omission in the current literature. The failure to control for this in previous PAP studies questions the findings to date, as it is impossible to determine whether the changes in performance was due to PAP, or a failure of the protocols in the control groups to maximise baseline performance.

**Balancing PAP with Fatigue**

Any conditioning activity, whilst potentially enhancing PAP, will also have a fatiguing effect on skeletal muscle, and can be said to have both potentiating and fatiguing responses (Chiu et. al. 2003). Contractile activity produces both fatigue and PAP, and the subsequent effect on performance is determined by the balance between these phenomena (Macintosh and Rassier, 2002). The time lines of fatigue and PAP will influence the post-stimulus state (Robbins, 2005), and the optimal recovery window is dependent upon the decay of PAP and
fatigue, and this will depend upon the nature of the activity, and the temporal characteristics of the individual (Jeffreys, 2008b). Macintosh and Rassier, (2000) maintain that despite the contradictory effects of PAP and fatigue, these two presumed mechanisms can coexist.

Any PAP inducing activity is going to have a trade off effect on fatigue, and this must be accounted for when planning for PAP, and also when evaluating the effectiveness of PAP in enhancing performance. Peak PAP will occur immediately after the conditioning activity whilst this will also be the time of peak fatigue; the relative magnitude of these is dependent upon the nature of the exercise and the characteristics of the athlete (Jeffreys, 2008b). Intense activities, whilst evoking greater PAP, will also likely evoke greater fatigue and vice versa (Jeffreys, 2008b). Similarly, the greater the time difference between the conditioning activity and subsequent performance, the greater the recovery from fatigue, but also the greater the decrement in PAP (Jeffreys, 2008b). This effect is summarised in figure 1.12.

![Figure 1.12: The simultaneous effects of PAP and Fatigue (from Tillin and Bishop, 2009)](image-url)
CHAPTER TWO – METHODOLOGY
CHAPTER TWO - METHODOLOGY

Overall aims of the current research

The present research aimed to increase the understanding of application of PAP methodologies to warm-up, and to ensure that data generated could inform coaching practice by addressing the optimal application to the key warm-up aims. The studies were designed to address both elements of potential potentiation in warm-up design; namely the use of maximal intensity activities normally included in the warm-up (predominantly running and jumping), together with the potential to elicit PAP through the use of loaded activities.

Overall outline of experiments

To allow these aims to be effectively investigated a series of experiments were set up. These were carried out over the off-season phase of a single training year. All of the investigations gained ethical approval from the University of Glamorgan Ethics Committee prior to the commencement of the study. Each study is outlined below:

Study One: The effects of potentiated warm-ups on running speed

Warm-up has traditionally focussed on the general warm-up and stretching components (Jeffreys, 2007b; Faigenbaum, et al., 2005; Verstegen, 2004). A number of authors have outlined the need to include some exercises of increased intensity to provide a potentiation effect prior to performance (Jeffreys, 2008b; Jeffreys, 2007b; Faigenbaum et al., 2005; Burkett, et al., 2005). Faigenbaum, et al., (2005) and Burkett, et al., (2005) have also suggested that there exists a specificity element to the potentiated warm-up. The present study aimed to address both of the above issues, i.e. the need for a potentiated warm-up and the specific nature of potentiation. It investigated the effects on speed performance of two potentiation based warm-up protocols, a sprint potentiated warm-up and a jump
potentiated warm-up, and compared speed performance achieved following these protocols to that achieved via a general warm-up alone.

The study was a randomised protocol, with speed performance (10 metre sprint) measures taken following three different warm-up protocols. Subjects were randomly assigned to either a sprint potentiated group, a jump potentiated group or a general warm-up group for each day. All athletes were tested for speed over a ten metre distance following each of three different warm-up protocols carried out on three non consecutive days. The ten metre distance was selected as it best matched the sprint requirements of a large number of team sports (see later). The testing protocols were identical for each group, and rest periods between all activities and all tests were standardised.

Performance on each warm-up was analysed in order to answer the two following questions:

1. Does the inclusion of a maximal intensity exercise in a warm-up enhance maximal running performance?
2. Is maximal potentiation specific to the type of activity undertaken?

**Study two  The acute effects of assisted and resisted sprinting on running speed**

This study investigated the potential of using a sprint specific PAP based potentiation phase in the warm-up, and investigated whether the performance of a resisted run or an assisted run prior to running could acutely enhance speed performance. This was based on the conjecture that a loaded sprint protocol (resisted or assisted) may provide an additional level of potentiation over traditional sprints (Pearson, 2001).

The study was a randomised pre test/post test protocol, with speed performance measures taken pre and post three different protocols 1) a sprint assisted run 2) a sprint resisted run, and 3) an unloaded (control) run. All athletes were initially assessed for maximum speed over a 10 metre distance. They were then randomly allocated into one of the three groups,
a sprint assisted group, a sprint resisted group and a control group. Group sizes were allocated based upon equipment availability, and the logistics of ensuring the exact work/rest periods within the context of a training session. The sprint resisted group performed two resisted sprints using 10% of bodyweight. The sprint assisted group performed two assisted sprints, allowing for performance 10% faster than maximal speed. Both groups were then retested over the 10 metre distance. A rest of 4 minutes was allowed between the PAP inducing activities and the re test as this has been shown to allow for the effective expression of PAP (Jensen and Ebben, 2003). The control group performed all sprints tests but did not perform a potentiating activity, simply repeating the sprint potentiated protocol from study one, with an additional two sprints to equate for work volume. The comparison with the control group identified whether any increase in performance could be assigned to the resisted or assisted protocols.

This design addressed the following two key questions:

1. Can resisted or assisted running acutely enhance running speed?
2. Is any running speed enhancement over and above that achieved via maximal speed running?

**Study three  The acute effects of loaded countermovement jump performance on counter movement jump performance.**

This study was based on two key suppositions: one that jump performance is an important indicator of sport performance in a range of sports, and secondly that a specific jump potentiation protocol may provide an enhanced potentiation effect over a traditional unloaded jump protocol. This study therefore investigated whether a loaded counter movement jump (CMJ) would enhance performance on a subsequent, unloaded CMJ.

The study was a pre-test/post-test protocol, with CMJ performance measures taken pre and post a weighted CMJ. Ten athletes were randomly assigned to provide a control group, to isolate the effects of the weighted protocol. The control group performed both CMJ but did not perform the weighted jump. This isolated the effects of the load on subsequent jump performance.

This study therefore aimed at determining:
1. Does the performance of loaded countermovement jumps enhance jump performance?

2. Is this performance increase greater than that achieved with maximal intensity, unloaded CMJ?

**Study four  Identifying the optimal resistive load for inducing PAP**

The majority of research into PAP has focussed on the effects of PAP as elicited by a heavy resisted movement such as the squat. For this protocol to be optimally applied to training and warm-up situations, a key determinant for effective application is to elucidate the optimal load for eliciting PAP.

This study isolated the effects of three loadings of a parallel squat on subsequent jump performance, as measured by a counter-movement jump. The study was a randomised test retest protocol, measuring jump performance prior to, and subsequent to, the performance of parallel squats at three different loadings. All athletes were pretested to measure their 1RM performance. Testing then took place a week later, where a random order of resistances were allocated. Loads were set at 60%, 80% and 93% to replicate light, medium and heavy resistances (Baechle, et al., 2008).

This design aimed at determining

1. Can squats acutely enhance subsequent jump performance?

2. Do certain loads produce greater potentiation than others?

**Study five  Identifying the optimal rest interval for inducing PAP**

Building from the previous study on the optimal load application for eliciting PAP, the second key question for coaches involves the optimal time scale of PAP. This study looked at the effect of three different rest protocols on the effects of PAP initiated by parallel squats, and measured by counter movement jump performance.
The study was a randomised test-retest design, under three different treatment conditions. PAP was measured via the change in counter-movement jump performance pre and post the PAP inducing activity. PAP was induced via the use of parallel squats of 3 repetitions at 93% of 1 RM. Rest periods were set at 2 minutes (Chu 1996), 4 minutes (Jensen and Ebben, 2003) and eight minutes (Kilduff, et al., 2007). Jump performance was reassessed at each of these time scales. These timescales were chosen to represent short, medium and long rest periods.

This design aimed to elucidate whether PAP was a time dependent mechanisms and whether an optimal time period existed at which time performance was optimally enhanced.

In order to test this theory, the following null hypothesis was constructed.

1. Are changes in jump performance elicited by the performance of heavy squats affected by recovery timescales?

**Study six The acute effects of heavy squatting and maximal voluntary contractions on running speed.**

A key measure in elite sports performance is running speed. If PAP has the capacity to enhance power output, then, by design, it could also have the potential to increase running speed, which is positively related to power output (Ozolin, 1976).

This study looked at whether PAP, elicited by heavy parallel back squats or maximal voluntary contractions (MVC’s) could acutely enhance running speed. The study was a randomised pre test, post test protocol, with speed performance measures taken pre and post both a squat, and MVC. This procedure was selected as it allowed for the evaluation of sprint performance pre and post squat and MVC, allowing for the isolation of the independent variables i.e. the squat and MVC. Subjects were randomly assigned to either a squat group or a MVC group.

This study aimed to answer the following key questions
1. Can sprint performance be acutely enhanced by the prior performance of back squats?

2. Can sprint performance be enhanced by the prior performance of MVC’s?

3. Which of the two methodologies is superior?

**Selection of subjects**

PAP methodologies include the application of a range of potentiating protocols, ranging from assisted sprints through to high resistance squats. A key feature of the majority of these methodologies is that their use is advised only with trained athletes (Baechle, et al., 2008). Similarly, a number of the testing regimes, e.g. 1RM squats, are only advised for trained athletes. The design of the studies needed to ensure that all athletes recruited were extensively trained in the use of all methodologies. This required prior instruction and training in a range of strength and conditioning protocols including resistance training, plyometrics and speed training. This was potentially a confounding variable, as the protocols were specifically designed to augment performance, and their use is only advised for trained athletes. However, this selection increased the ecological validity of the studies, as the protocols would not be recommended to recreational athletes, and their effects on trained athletes could be evaluated. The recruitment from a regional sports academy pool of athletes, who were in their second year or above of training, ensured that all athletes had at least 18 months of instruction and experience in all of the protocols.

This selection of trained athletes also ensured that all subjects were experienced in the testing methods used in the studies. All athletes within the Academy programme were tested four times per year (September, December, March and June). In this way, all of the subjects had been through a minimum of six testing sessions (the research protocols were delivered in spring and summer) prior to the experiments. Their normal testing battery included all of the tests selected within these studies (1RM squat, 10 metre sprint, counter movement jump). Additionally, the physical performance associated with these tests (squats, sprints and jumping) were extensively used in their physical conditioning programmes. This extensive experience helped eliminate potential learning effects within
the repeated measures protocols utilised within the experiments (Thomas and Nelson, 2001).

However, the selection of athletes from a youth academy also had drawbacks. While they all had undertaken a period of at least 18 months training, their levels of physical development could be below those of professional athletes. A review of published papers on PAP suggested that PAP will be greatest in the strongest athletes (Ruben et al., 2010; Tillin and Bishop, 2009; Jeffreys, 2008b), and subjects in the sample selected may not be able to elicit the greatest amount of PAP. However, the subject group were trained athletes in the target age group of the study, again maximising ecological validity. This ecological validity was further maximised by ensuring that all protocols were conducted prior to scheduled training sessions, and within the athlete’s regular training environment.

Similarly, it could be argued that optimising warm-ups for academy athletes is not a priority. However, many young athletes are being selected for major teams in a range of sports, and with the concurrent emergence of major competitions in soccer, rugby etc at Under 20 and Under 21 level. Currently, large investments of both time and capital are being made in these groups, with many programmes evaluated against success in major competitions. It is logical that developing optimal warm-up protocols for these age groups can be warranted.

All subjects signed informed consent forms prior to their participation in the studies. Ethical approval was granted via the associated University of Glamorgan procedures.

**Selection of the dependent variable.**

The rationale underpinning the selection of the dependent variable was the selection of tests that demonstrated actual performance as it relates to sport. While direct measurement of performance in team sports is difficult, performance in specific parameters that directly influence sport performance can be identified. To take advantage of this, two key elements were chosen both of which have significant relevance to sports performance across a range of sports, namely jumping height and sprinting speed.
**Jump performance**

Jump height provided a potential test with which to investigate the performance enhancement potential of PAP, and the vertical jump test has been accepted as a valid measure of leg power (Eston and Reilly, 2001). In utilising vertical jumps two fundamental methods existed, namely the squat jump and the counter-movement jump. The squat jump test comprises jumping vertically from a static squatting position, normally with a 90 degree knee angle (Eston & Reilly, 2001), however, this jump eliminates the contribution of the stretch shorten cycle. However, power output in the majority of sports events involves the mechanical energy contributed by the elastic elements of the musculotendinous unit, in addition to the force generated by the muscles (Stone, et al., 2007). In this way, the counter movement jump, which involves, the utilisation of a pre stretch was more related to the type of performance seen in sport, as elimination of the SSC components as in the squat jump, remove an element that can both contribute to performance, and additionally provided a potential mechanism for PAP (Harrison, 2007). Markovic, et al., (2004) found that the countermovement jump showed the highest relationship with explosive power, compared to other jumping protocols ($r = 0.87$). For these reasons, a counter movement jump was the preferred method of analysing jump performance. Additionally, the use of the arms was allowed, as this again more closely replicates the performance of jumps in sport. This was helped by the fact that the study utilised trained athletes and so the skill learning element often associated with the use of the arms was negated.

**Speed performance**

In most field sports, average sprinting distance is relatively small. This is reported as being 10-15 metres in football (Reilly and Thomas, 1996), with speed over short distances being fundamental to success, being a significant feature of game deciding situations. (Taskin, 2008) Superior speed allows players to reach the ball first and to be in a position for the development of plays (Silvestre, et al., 2006). To support the important of acceleration over maximal speed, Cometti, et al., (2001) found that elite French footballers ran significantly
(p<0.05) faster over 10 metres than amateur players, but that there was no difference in 30 metre sprint speed.

In terms of rugby, similar results are reported. Baker & Nance, (1999) suggest that the average sprint distance in national league rugby may be ten – twenty metres, while Duthie, et al., (2006a) stress that the acceleration phase of running is more important to rugby union success than the maximal velocity, but no average distances were recorded. Duthie, et al., (2006a) stress that running speed over short distances was fundamental to success, with faster players more likely to reach and tackle an opponent when defending or evading a tackle when attacking. Accumulatively, enhanced speed has a dramatic effect on the outcome of individual passages of the game, and potentially on the game itself.

For the above reasons, together with the assertion that acceleration and maximal speed are separate and specific qualities (Cronin and Hansen, 2005) an acceleration distance was preferred over a maximal speed distance in these studies. This is in accordance with the advice of Duthie, et al., (2006a) who suggest that speed testing of team sport athletes should focus on the assessment of acceleration. This would allow conclusions drawn to be directly applied to game performance for all players. The ten metre test was therefore selected as the measure of sport speed, as it allowed for the evaluation of pure acceleration (McFarlane, 1993), and which is recommended by Bloomfield, et al., (1994) as an indicator of sport specific running speed, and recommended as the key speed test for both rugby union (Jenkins and Reaburn, 2000) and soccer (Tumilty, 2000). The data from the studies of McBride, et al., (2005) and Chatzopoulis, et al., (2007) demonstrate the complexity of running speed, where speed can be enhanced in one section of a 40 yard sprint and not another, resulting in an inability to relate the findings to performance without an analysis of the sport specific requirements. For this reason the research designs aimed to find one dependent variable that was indicative of sports performance across all playing positions, and which had the potential to be acutely enhanced via PAP.
Other considerations needed to be accounted for to ensure internal validity, the most important of which was the environmental effects on performance. As the experimental protocols either involved repeated measures, or measures taken across different days, environmental issues needed to be accounted for. Environmental conditions such as temperature, wind, track conditions etc all have the potential to impact on performance. (Tumilty, 2000) For this reason the decision was taken to ensure that all measurement was performed indoors. The 10 metre distance allowed all measurements to be taken indoors.

**Test Protocols**

A number of test protocols were utilised during the series of experiments, and each is outlined below. All protocols were undertaken at the same time each day to avoid circadian variation (Atkinson and Reilly, 1996). All sessions took place at 9.00 am as this correlated with the athlete’s normal strength and conditioning and team training periods. Additionally, all were undertaken in the spring and summer, which coincided with the off season for all participating subjects. In this way, the accumulated fatigue precipitated by the competitive season was avoided.

**10 metre sprint**

All timings utilised electronic timing gates (Newtest system – Newtest Oy, Oulu Finland see instruments section). Currently wide variations exist in the start protocols advised for timed sprints. As the aim was to determine acceleration time rather than reaction time, a self timed protocol was utilised. While many protocols recommend differing start distances behind the start line the current protocol utilised the start pad methodology, as utilised at formalised assessment events such as NFL combines, and the NSCA Performance Index (Epley, 2008). Here a start switch was placed immediately behind the start line, in a protocol similar to a 100 metre start where the hand must be placed behind the start line as per IAAF rules. Athletes placed their hand on the start pad, which started timing immediately the hand was released. Athletes were able to place the start pad on their preferred side, negating any advantage of right or left hand dominance. Athletes were advised to use a three point stance for each sprint, and used this extensively in their training. This stance and start switch protocol minimised any potential momentum
generated prior to activating a starting gate, which is the major source of variation when using photocells to assess sprint performance (Duthie, et al., 2006b).

Timing gates were placed ten metres from the start line. These were placed at hip height as recommended by Yeadon, et al., (1999). Testing was carried out on a rubberised floor, and indoors to minimise environmental variables (Duthie, et al., 2006b).

**Counter movement jump**

Counter movement jump (CMJ) performance was performed on a contact mat (Just Jump, Probiotics, Alabama). The test was carried out as per the protocols outlined by Harman and Garhammer, (2008). Athletes were asked to stand at the centre of the contact mat and instructed to jump as high as they could and land on the centre of the mat. They were allowed to utilise their preferred depth of countermovement and utilise their arm action. No preparatory or stutter steps were allowed. As these CMJ’s had been performed on a number of occasions any learning effect was negated, and the protocol allowed each athlete to achieve maximum performance. Performance was recorded in inches, and converted to cm.

**Instrumentation**

**Newtest Power system**

Given the small distance involved, and the resultant small changes in performance, accurate data were essential. Electronic timing, via infra red beams and linked to a central processing unit, was therefore essential for the collection of reliable data. The studies utilised the Newtest Powertimer (Newtest Oy, Oulu Finland). This consisted of a start pad and an infra-red gate (IP 40 - photocells IP 67), placed 10 metres from the start line. The photocells had a sensing range of 0.2 - 2 metres, and the system as a whole a reported accuracy of 0.001 seconds, and allowed times to be recorded to the nearest hundredth of a second.
Jump performance was a key variable in many of the experiments. A key aim of the studies was to develop protocols that would measure jump performance and also could be used by coaches. Though the direct measurement of leg power can be achieved via comprehensive biomechanical analyses (Burr, et al., 2007), these methods are expensive and impractical for most coaches (Burr, et al., 2007). Jump mats (contact mat) have been reported to be a valid measure of vertical jump performance. Markovic ,et al.,(2004) report that the use of a contact (jump) mat is the most reliable and valid field test for assessing jump height. The Just Jump mat (Probiotics, Huntsville Alabama) is a validated contact mat which has been proved to have an excellent correlation with jump performance measured by both Vertex and digital camera systems where Leard, et al., (2007) found a 0.967 correlation between jump height measured by the Just jump system and that measured via 3 camera video analysis. (p = 0.01). Prior to the commencement of the current studies, CMJ on the just jump system had previously been correlated with performance on a Kistler quattrojump system (Kistler Systems , Winterthur Wülflingen, Switzerland) (r = 0.89) and a vertex system (r = 0.91).

Given the relatively low cost and portability of the system, any methodologies developed via the experiments could be replicated by coaches without the need for expensive or time consuming laboratory equipment.

Quattro jump

For one experiment the aim was to measure both jump height and the key kinetic variables that contribute to jump height. While contact mats are able to effectively measure jump height, they cannot measure key variables that contribute to this including peak force, peak power and rate of force development. To elucidate these measures, a uni-directional force plate was utilised, Quattro Jump: 9292AD Portable Force Plate System, (Kistler Systems , Winterthur Wülflingen, Switzerland) which was linked to specific Software: OJ Software, Type 2822. Version 1.0.9.2. This system had previously been validated by Winchester, et al., (2008) as a valid and reliable system for measuring jump height, and peak power.
**Reliability**

Reliability is defined as the consistency of measurements, and can be considered as the amount of measurement error that has been deemed acceptable for the effective practical use as a measurement tool (Atkinson and Nevill, 1998).

Given the nature of speed and jump performance and the small worthwhile changes in performance, it was important that the tests and instruments utilised were sensitive enough to distinguish these small differences. Therefore, pilot studies on both sprint scores and jump scores were carried out prior to the commencement of the experiments. To ensure that reliability could be established within the protocols used, and within the athlete group, the pilot studies were carried out in the scheduled testing session prior to the commencement of the studies. The subjects utilised were the same subjects as used in study one (n = 59). This took place four weeks prior to the commencement of the studies. These tests used the same testing protocols that were utilised within all of the studies that measured speed. The warm-up utilised the sprint potentiated warm-up utilised in study one.

**Reliability of speed scores**

Reliability was established via an Intraclass correlation analysis and demonstrated excellent test/retest reliability ($r = 0.91$) of the Newtest system, and the protocols used in the studies. However, intraclass correlation, while a popular choice of reliability studies, only demonstrates relative reliability, or the degree to which individuals maintain their position within a sample (Atkinson and Nevill, 1998). While an important measure, it is also important to ascertain absolute reliability, or the degree to which repeated measures vary for individuals (Atkinson, and Nevill, 1998). The data was also analysed for the coefficient of variation, and showed a 0.8% variation in sprint time, which compares to that found by Duthie, et al.,(2003) where a 0.6% variation was found in elite rugby players, and indicated
low error scores. The speed scores were therefore, assumed to be reliable, both within the protocols used and within the specific subject group.

**Reliability of jump scores**

Reliability was established via an intraclass correlation analysis and demonstrated excellent test/retest reliability \((r = 0.93)\). To determine absolute reliability, analysis of CMJ scores calculated a 0.7% variation in jump height indicating low error scores and a high reliability of measures. The CMJ scores were therefore, assumed to be reliable, both within the protocols used and within the specific subject group.

**Smallest worthwhile change in performance**

Performance increments in sports are often small, and therefore, it was important to determine the magnitude of a worthwhile change in performance (Duthie, et al., 2006b). For sprint times, this can be calculated from using a small Cohen effect \((0.2)\) size multiplied by the between subject standard deviation within the specific population, multiplied by the mean sprint score (Duthie, et al., 2006b; Moir, et al., 2004). For the subjects tested, this results in a worthwhile change of speed performance of 0.03 seconds, based on a mean sprint time of 1.96 seconds. For jump scores, the pilot studies, calculated a 0.7% variation in jump height. This provides a worthwhile change in performance of 0.79 cm, based on a mean jump height of 57 cm.

**PAP Application protocols**

Another critical selection was the selection of the methods of inducing PAP. These methods needed to fulfil two main criteria. Firstly, they needed to utilise methods that had the potential to induce PAP, either by utilising heavy loading of mechanically similar exercises, loading mechanically identical exercises, (through the application of external loads or assistance), or utilising maximal voluntary contraction of the associated musculature. Secondly, they had to incorporate methods that could be potentially integrated into warm-up procedures. This second criterion also needed to consider the potential of the protocol
to induce fatigue. As team sports are played over an extended period (e.g. football 90 minutes, rugby 80 minutes), protocols needed to be selected that could induce potentiation, but which did not result in undue fatigue that may affect performance in the latter stages of the game. Therefore, the protocols selected aimed to induce potentiation but minimise fatigue, consisting of a controlled number of trials and controlled application duration. To investigate all of these potentially PAP inducing activities, the experiments involved the application of the following potentially PAP inducing activities on subsequent performance; namely:

1. Sprint resisted sprinting
2. Sprint assisted sprinting
3. Weighted counter movement jumps
4. Squats
5. Maximal Voluntary Contractions

The application of sprint resisted sprinting

Resisted sprint training has become a popular training method in many sports (Alcarez, et al., 2009; Alcarez, et al., 2008; Cronin and Hansen, 2006; Lockie, et al., 2003). It involves an external loading of sprint technique, and provides for a very specific form of loading, via maintaining similar characteristics to the act of sprinting (Alcarez, et al., 2009).

Sprint resistance can be provided in a number of ways, including elastic resistance, towing a variable resistance or uphill running (Dintiman and Ward, 2003). In this experimental design, a method was needed that could be standardised for all subjects, and could be applied in a range of situations, and for these reasons the towing method was chosen. This has previously been demonstrated to be an extremely consistent and effective method of providing sprint resisted application (Alcarez, et al., 2008; Cronin and Hansen, 2006; Lockie, et al., 2003)

To aid standardisation, a sled based resistance was selected, and so a key variable was to choose a suitable resistance. The resistance chosen needed to provide sufficient resistance to provide a potential potentiating effect, but not be too great as to cause a mechanical
alteration of sprint technique. Various studies have suggested that to maintain load specificity, horizontal velocity should not fall below 90% of maximal velocity (Alcarez, et al., 2009; Lockie, et al., 2003). The net effect of velocity will be dependent upon the load selected, and excessive load promotes increases in oscillations on the centre of gravity and significant reductions in stride length (Alcarez, et al., 2009). The load selected needed to provide sufficient stimulus to induce PAP, but at the same time not alter the kinematic pattern of the sprint. Maulder, et al., (2008) reported that a load of 10% of bodyweight had no negative effect on sprinting technique, whereas a load of 20% altered the kinematics of the sprint. Additionally, the 10% load also resulted in speed decrements within the 10% guidelines (90% of max velocity).

Within this design, the sprint resisted group performed a resisted sprint using 10% of bodyweight. This resistance allows for a biomechanically similar action to be used as in an un-resisted run (Maulder, et al., 2008; Plisk, 2008; Spinks, et al., 2007; Lockie, et al., 2003). Additionally, the use of a bodyweight dependent variable resistance allowed for differences in body mass to be catered for, providing a more uniform potentiating effect. The resisted run was performed over a distance of 10 metres to replicate the requirements of the test, and to match the sprint performed by the control group within the experiment. This distance would also minimise possible fatiguing elements of the run. The 10 metre distance would allow for the highest forces to be applied, due to the longer ground contact times, a factor which has previously been identified as a key component of PAP (Markovic, et al., 2008). It should be noted that the distance may not necessarily be optimal for development of PAP due to the changing physical requirements for sprinting over different distance, with an increasing reliance on SSC activity with increased distance (Ozolin, 1986).

The sled was attached to the waist of the athlete rather than via a shoulder harness to minimise the torque around the hips, thus minimising any changes in torso angle (Alcarez, et al., 2008). This was attached via a rope of 10 metres in length.
The application of sprint assisted training

Sprint assisted training involves towing runners to greater speed than they can achieve unassisted (Corn & Knudson, 2003). This type of training has many names including tow training, overspeed training supramaximal training, but for these studies the term sprint assisted training will be used. Traditionally, sprint assisted training has been suggested as a method of enhancing stride cadence. Studies to date do not support this, suggesting that changes in running speed are produced by changes in ground contact kinetics, and associated increases in stride length (Clark, et al., 2009; Corn & Knudson 2003; Mero & Komi, 1985). Kinetic and kinematic analysis has shown that the net effect of sprint assisted running is to increase horizontal momentum, resulting in changes in the kinetic pattern of the braking phase of sprinting, but no change in the propulsive phase (Corn & Knudson 2003; Mero & Komi, 1985). The net result of this is that the foot lands further in front of the centre of mass, increasing braking forces (Corn & Knudson 2003). This results in an increase in the resultant force and an increase in pre contact EMG (Mero and Komi, 1987), suggesting a change in neuromuscular activity prior to contact in an attempt to compensate for the greater contact forces. Total ground contact times tend to remain unchanged or decrease, indicating an increase in net force per unit time (Clark, et al., 2009). While sprint assisted running may not increase stride cadence, this increase in ground forces may be a suitable method of increasing PAP.

Similarly, a choice had to be made in the sprint assisted method used. This similarly had to provide potentiation but without altering mechanical technique. Downhill running at a slope of 3% is often quoted as the preferred method of providing assistance (Dintiman and Ward, 2003), but such a slope was unavailable (and could not be applied universally) and so an elastically aided system was used. This was an elastic rope of 10 metres long, and stretched to 2 times its resting length (Doubleman Overspeed - Extra Safety Sleeve Elastic Tube Perform Better, Cranston RI). Pilot studies had demonstrated that this protocol resulted in 10 metre sprint times that were a mean 9.3% (SD ± 1.2) faster than maximal time. This was congruent with recommendations proposed by Clark et al., (2009), Plisk (2008), Jeffreys
(2007) and Dintiman and Ward, (2003) and who suggest that sprint assisted runs should be no more than 10% faster than maximal levels. This protocol was therefore selected, to allow for biomechanical similarities between the assisted and unassisted protocols (Plisk, 2008). The assisted run was performed over a distance of 10 metres to replicate the requirements of the tests, and to match the sprint performed by the control group within the experiments. As for the sprint resisted methodology, again this distance may not necessarily optimise PAP, as SSC activity would not be maximised at this distance and the overall load may not be optimal to elicit maximal PAP. However the 10 metre distance would allow for the highest forces to be applied, which has previously been the key modifier of PAP (Markovic, et al., 2008), and due to its short duration (typically <2 seconds) result in minimal fatigue.

**Weighted Counter Movement Jumps**

Weighted jumps could be elicited in a number of ways including holding weights in the hand, holding weights across the shoulders (Barbell) or utilising a weighted vest. Given Yessis', (1995) assertion that the potentiating activity should replicate the movement as closely as possible, then the weighted vest was preferred as it allowed the arms to be utilised in the jumping action. In choosing a load, a number of factors were considered, namely, the effects on the power output of the jump and the kinematics of the jump. In terms of power output, Cormie, et al., (2008) found that power output in a CMJ is maximised at a low load, and often at body weight. Similarly, advice given as to the kinematics of performance with resistance a weight of no more than 10% is often recommended (Cormie, et al., 2008; Jeffreys, 2007). For these reasons a weight of 10% of bodyweight was selected as the resistance in these experiments.

**Resisted Exercise**

Squats have been the traditional method by which PAP has been elicited dynamically previously (Ruben, et al., 2010; Jeffreys, 2008b). To replicate these studies, and to provide a level of consistency across studies, the squat was chosen as the means of providing heavy
resisted exercise for this series of studies. This allowed for a more specific contraction mode than during open chain exercises or isokinetic applications, which bear little resemblance to the accelerative/decelerative motion present in sprinting (Cronin and Hansen, 2005). Additionally, as the squat was a mainstay of the academy athletes programmes the subjects were able to ensure excellent technique and maximise the loads they could utilise. A key methodological question was to determine the squat depth. Here a position of thighs parallel to the floor was chosen. This point was determined via the use of a goniometer that measured the angle of the femur to the floor. This angle was set via the use of elastic bands placed across a Power Rack (Bodysolid USA, Forest Park, IL). In this way a consistency of squat depth could be achieved for each athlete across all repetitions.

The thighs parallel position was preferred for two key reasons. First, it was the minimum depth used in training by all athletes, and secondly, a parallel squat maximises the involvement of the gluteus maximus and ensures maximal muscle recruitment through the exercise (Caterisano, et al., 2002). It can be hypothesised that by activating the greatest number of muscle fibres, the potential for PAP mechanisms to be stimulated is maximised. However, this does come with the proviso that technique is challenged to a greater degree with greater squat depth, and that technical proficiency must precede the addition of load.

Weight was applied via an International Weightlifting Federation approved weightlifting bar and discs (Werksan USA, Moorestown, NJ), which could be adjusted to the nearest kilogram.

**Maximal voluntary contractions**

Maximal voluntary contractions have previously been utilised to elicit PAP. They may also allow for a more time efficient method of eliciting PAP in warm-up situations, as they would negate the requirements for changing loads between individuals. Given these opportunities MVC’s were also investigated as to their potential to enhance subsequent performance. The methodology utilised a “Smith Machine” (Bodysolid USA, Forest Park, IL) with linear bearings. To ensure similar muscle recruitment patterns as for free weight squats, the Smith machine was set so that the individual achieved the same thighs parallel position as for the squats. The MVC was performed at this point, as this would equate to the most
mechanically inefficient part of the squat, a point at which muscle activation is at its
greatest (Caterisano et al., 2002).

**Statistical Analysis**

Previous reports on sprint testing suggest that the error associated with sprint protocols are
2% or 0.04 seconds (Moir, et al., 2004; Fitzimmons, et al., 1993). This is indicative of a good
test. However Duthie, et al., (2006b) indicated that this can be reduced to 1% or 0.02
seconds by using the same protocols utilised in this series of studies.

Given the small worthwhile changes in performance, it was important to calculate the
number of subjects required to achieve statistical power for each study. Statistical power
refers to the probability that a statistical test will indicate a significant difference when
there truly is one. (Eng, 2003). The greater the power, the less likelihood of committing a
type II error, where a difference does exist but the test lacks the power to detect it, thus
yielding a false negative result (Eng, 2003). Thus, the power required for each study was set
at 80%, and the appropriate subject number required was calculated for each study, based
on the typical error calculations and the estimated smallest meaningful change (Hopkins,
2006). Calculations on the required numbers to achieve power were carried out prior to the
studies, as power calculations are most appropriate when they incorporate a minimum
difference that is stated prospectively (Eng, 2003). Minimum subject numbers were
calculated for each study.

A study of a sample provides only an estimate of the true value of an outcome statistic
(Batterham and Hopkins, 2006). Given the relatively small magnitudes of worthwhile
performance it is important to evaluate the real world significance of an outcome. A non
significant result does not necessarily imply that there is no worthwhile effect and cannot
reflect the value for an individual within a population (Batterham and Hopkins, 2006). For
this reason, individual data was analysed, against the smallest worthwhile change in
performance. (Batterham and Hopkins, 2006)
All statistical analysis was carried out SPSS Version 15 (SPSS Inc Chicago III). Tests of normal distribution (Kolmogorov-Smirnov and Levene’s) were conducted on all data prior to analysis to ensure normality of distribution. On assumption of normality, appropriate statistical analysis were carried out in relation to the specific methodologies utilised.
CHAPTER THREE – THE STUDIES
STUDY ONE - THE EFFECTS OF POTENTIATED WARM-UPS ON RUNNING SPEED
STUDY ONE – THE EFFECTS OF POTENTIATED WARM-UPS ON RUNNING SPEED

Abstract

The present study investigated the application of three different warm-up procedures on sprint performance. Thirty-five male subjects undertook three different warm-up procedures, general warm-up (G), sprint potentiated warm-up (SP) and jump potentiated warm-up (JP), after which they were tested for running speed over 10 metres. General warm-up consisted of 5 minutes of movement followed by four dynamic stretches, SP warm-up consisted of the general warm-up but with five additional 10 metres sprints, while the JP warm-up consisted of the general warm-up followed by 5 sets of 3 vertical jumps. Warm-ups were randomly allocated on three non consecutive days. Mean 10 metre times for the G group was 1.99 sec ± 0.10, for the JP group 1.93 ± 0.08 and for the SP group 1.88 ± 0.08. Repeated measures ANOVA demonstrated significant differences between groups (p<0.05) whilst Tukey’s HSD demonstrated that these differences extended across all groups. The results demonstrate that a general warm-up may not fully prepare athletes for sprint performance, and that a potentiation phase comprising of maximal intensity activities is needed. The results also indicate a specificity of potentiation effect, with sprint activities more effectively preparing athletes for sprint performance than jump activities.

Background to the problem

Warm-up has traditionally focussed on the general warm-up and stretching components (Jeffreys, 2007b; Bishop, 2003a;), having as much of an emphasis on the injury reduction aim as on maximising performance. However, strength and conditioning coaches are now focussing their attention on the utilisation of warm-ups to maximise performance, (Jeffreys, 2007a, 2007b, Verstegen, 2004). To this end Jeffreys, (2007b) suggests that all warm-ups should contain a period of potentiation, to ensure that athletes are able to perform at maximal capacity at the onset of training/competition. Despite this trend, few studies currently exist to attest to the inclusion of potentiating activities into a warm-up, and whether these offer any advantages over general warm-up procedures, which themselves...
have become far more dynamic over the last decade with static stretching increasingly being replaced by dynamic mobilisation methods (Jeffreys, 2008a).

While the focus of many strength and conditioning experts is to view warm-up as performance preparation, and thus look at methods of using warm-up to maximise subsequent performance, there remains a great disparity in the application of warm-ups, especially in team sports. The majority of warm-ups consist of a period of general temperature raising, via the use of a period of light activity such as jogging or the carrying out of movement skills, followed by a period of mobility work. There is less uniformity about the use of potentiation exercises. Currently, the later phases of warm-up can vary considerably, with some warm-ups ending immediately after the general warm-up phase, others simply focussing on skill based actions, while others will progress to levels of maximum activity.

In recent work by Jeffreys (2007a) a RAMP methodology was proposed, via which warm-ups can be optimised. This outlined the need to include some exercises of maximal intensity to provide a potentiation effect prior to performance. In this context, the term potentiation simply refers to a phase where exercise intensities are progressed up to maximal levels, and does not necessarily include the supra-maximal potentiation aims possibly attainable via the application of PAP (although the potential that this may have to attain supra maximal performance is noted). The main reasons given for the potentiation element of a warm-up are:

- Faster muscle contraction and relaxation of both agonist and antagonist muscles. (Hoffman, 2002)
- Improvements in rate of force development and reaction time (Enoka, 2008; Asmussen, 1976)
- Improvements in muscle strength and power (Enoka, 2008; Bergh and Ekblom, 1979)
- Lowered viscous resistance in muscles (Enoka, 2008)

All of these adaptations should theoretically be able to enhance strength speed and power performance, and given this, should be a key element of any warm-up. Power sports such as sprints on the track, jumps and throws in field events together with events such as
weightlifting, will normally use a form of potentiation, by progressively increasing exercise intensity to high levels immediately before competition. However, the use of activities designed to specifically exploit PAP have not been investigated or utilised. Even the use of progressively intense types of activity is less universal in team sports. Given that the majority of team sports can involve high intensity exercise from the start, a warm-up needs to be able to ensure that athletes are capable of maximal performance at the outset of a game, and do not have to use the first minutes of a game to progress to a point where they are capable of maximal performance. Many team sport warm-ups may not currently be optimal in terms of optimising speed and power performance. The trend is currently for team sport warm-ups to become very skill based, and the inclusion of maximal intensity exercises may be on the decline rather than being increased. This assertion that current warm-ups may not be optimal is supported by a study of two warm-up protocols carried out by Skoff and Strojnik, (2007). Here, a general warm-up (slow running and stretching) was compared to a general warm-up but with the addition of bounding and sprinting. There were statistically significant (p<0.05) differences between the groups in peak knee extension torque and muscle activation level. Unfortunately, no measures of performance were taken, and therefore the results of the study cannot necessarily be extrapolated to enhanced sports performance. The differences do suggest that the general warm-up alone was insufficient to maximise performance and that a period of potentiation based exercise enhanced muscle function.

This approach is further supported by Faigenbaum, et al., (2005) and Burkett, et al., (2005) who also suggest a specificity element to the warm-up. Burkett, et al., (2005) in a study of warm-ups on the vertical jump, found that the use of a weighted jump warm-up resulted in vertical jump performance that was significantly (p<0.001) superior to that achieved with either a submaximal jump, a running and stretching warm-up or no warm-up. This again suggests that a period of exercise performed at maximal intensity is required to maximise subsequent performance. Additionally, this study, by using a performance measure, allows the extrapolation of the data to actual performance. The study does not confirm whether loaded jumps are superior to unloaded maximal intensity jumps as a potentiating factor. Neither of the control protocols included maximal activities, and therefore no delineation between loaded activities and maximal activities could be made. Faigenbaum, et al., (2005)
studied the effects of three warm-up procedures, (walking and stretching, dynamic exercises, dynamic exercise with 3 drop jumps from 15cm boxes) on vertical jump, long jump and shuttle run in children. They found that general warm-up resulted in significantly reduced scores in all tests (P<0.05) compared to the dynamic exercise with drop jumps protocol. The general warm-up also resulted in significantly lower scores in the vertical jump and shuttle test (p<0.05) against the dynamic exercise warm-up. This study suggests that the post warm-up performance is closely related to the intensity of work performed in the warm-up, and that maximal intensity efforts are required in order to elicit maximal performance. This again suggests that a general type warm-up does not fully prepare an athlete for performance, and suggests that some maximal intensity activities must be included in warm-up if subsequent performance is to be maximised.

Burkett, et al., (1995) and Faigenbaum, et al., (1995) suggest that the potentiating activity should replicate the sports movement as closely as possible, in terms of the type of movement, directions of movements, force of movements and speed of movements. If this is the case, then the potentiating exercise needs to be chosen carefully, to ensure optimal application. If a specificity effect of potentiation does exist, an exercise might only have the maximal capacity to affect the level of potentiating produced if it replicates the required sports action.

Given this divergence of application in warm-up and the trend towards skill based warm-ups in team sports it is important to determine whether potentiating type of activities need to be included in the warm-up. If a potentiation effect does exist, it is also crucial to determine whether or not a degree of specificity of activity affects the potentiating results.

**Study aims**

This study was set up to examine whether a potentiation phase, incorporating maximal intensity exercise, should be included in a warm-up, and secondly, whether there was a specificity element to the potentiation. This was achieved by comparing running speed following three different warm-up protocols, a general warm-up only, a general warm-up followed by a non specific potentiation phase (jumping) and a general warm-up followed by a specific potentiation phase (sprinting). Running speed was selected as the dependent
variable as it is fundamental to performance in the vast majority of team sports (including football and rugby).

**Experimental approach to the problem**

The study was a randomised protocol, with speed performance (10 metre sprint) measured immediately following three different warm-up protocols, on three non-consecutive days as per the Burkett, et al., (2005) protocols. The warm-up protocols were general warm-up, general warm-up followed by jumping potentiation, and general warm-up followed by sprint potentiation. In all three protocols, the general warm-up procedures were identical, to enable the isolation of the potentiation activities. The protocols were all performed on three separate days and subjects were randomly assigned to one warm-up protocol on each day. All athletes were tested for speed on a 10 metre sprint, immediately following each of three different warm-up protocols carried out on the three non-consecutive days. In this way, all athletes were tested for running speed having followed each of the three warm-up protocols.

**Hypothesis Generation**

The experiment had two key research questions to address:

1. Does the inclusion of a potentiation phase (incorporating maximal intensity exercise) in a warm-up enhance running performance?
2. Is maximal potentiation specific to the type of activity utilised?

**Subjects**

35 male subjects gave informed consent to participate in the study and their physical characteristics are outlined in see table 3.1-1. All were competing athletes and were experienced in sprint training. All subjects were competitive athletes across two sports (rugby n= 20 and football n=15). All were involved in an academy strength and conditioning programme, where they had been instructed in sprint training technique, and plyometric technique and had participated in at least one year’s sprint, plyometric and resistance
training. They were also experienced in speed testing, having been tested on a minimum of six occasions previously.

<table>
<thead>
<tr>
<th>Age</th>
<th>Height (cm)</th>
<th>Weight (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>18.1 (±0.6)</td>
<td>178 (±0.4)</td>
<td>71 (±9.8)</td>
</tr>
</tbody>
</table>

*Table 3.1-1  The physical characteristics of the participants*

**Instrumentation**

Speed scores were measured on a Newtest timing system Newtest Powertimer (Newtest Oy, Oulu Finland). This consisted of a start pad and an infra-red gate (IP 40 - photocells IP 67), placed 10 metres from the start line. The photocells had a sensing range of 0.2 - 2 metres, and the system as a whole had a reported accuracy of 0.001 seconds, and allowed times to be recorded to the nearest hundredth of a second. The light cells were laid out as per the protocol recommended by Yeadon et al (1999).

**Test procedures**

Testing took place over three sessions carried out on three non consecutive days (Monday, Wednesday, Friday) during the non competitive season. Athletes were randomly assigned to utilise one of three warm-up protocols on each day of testing. In this way, by day three of testing, all athletes had used all three protocols. The random allocation minimised the effects of daily undulations of performance, which may have been caused by athlete's activities etc.

All three protocols included a general warm-up phase, including a raising element, followed by an activation and mobilisation element (Jeffreys, 2007). A general raising period of five minutes was undertaken, using a ten metre distance with cones at both ends. Athletes performed three sets of four different movements between the two cones forward and
back, sideshuffle, carioca and track (Jeffreys, 2007b; Verstegen, 2004). This was followed by the performance of a series of dynamic mobilisation exercises. This consisted of five dynamic stretches (Inch worm, lunge with diagonal rotation, lateral lunge, free squat and calf walk with shoulder rotation (Jeffreys 2007b; Verstegen, 2004). This completed the general warm-up protocol. Dynamic exercises were selected for the mobilisation phase as these negated the possible deleterious effects on performance of static stretching (Jeffreys, 2008a), enabling the potentiation effects to be more effectively isolated.

For protocol two, the sprint potentiation protocol, the general warm-up was followed by a series of five 10 metre sprints of progressively increasing intensity, until sprints 4 and 5 were of maximum voluntary intensity. Athletes were encouraged to run at a percentage of their maximal level on each of sprints 1, 2 & 3, with the first being performed at an estimated 70%, the second at an estimated 80% and the third at an estimated 90%. Thirty seconds recovery was provided between each run. All athletes were highly experienced using this protocol.

Protocol three consisted of the general warm-up followed by a series of 5 sets of three continuous vertical jumps. These increased in intensity until set 4 and 5 were of maximal intensity. Three jumps were chosen to replicate the time of effort of the sprint protocol, in an attempt to equate the volume load of work. As per the sprint protocol, athletes were encouraged to jump at a percentage of their maximal level on each of jump sets 1, 2 & 3, with the first being performed at an estimated 70%, the second at an estimated 80% and the third at an estimated 90% of maximal effort.

Four minutes subsequent to each protocol (general warm-up, sprint potentiated warm-up and jump potentiated warm-up) athletes performed a single timed sprint of 10 metres. While traditionally, speed testing involves three sprint trials (Harman and Garhammer, 2008) with the best score being taken, in this instance a single sprint was measured. The rationale behind this decision was to avoid the possible potentiating effects of sprint performance on repeated trials. For example, if three trials were used, on trial three, both the jump potentiated group and the general warm-up group would have completed two maximal intensity sprints, providing a possible potentiating activity and thus, negating the legitimacy of the study.
Statistical Analysis

Statistical analysis was carried out on SPSS Version 15 (SPSS Inc Chicago III). Tests of normal distribution (Kolmogorov-Smirnov and Levene’s) were conducted on all data prior to analysis. Upon assumption of normality, scores from the three protocols were compared via a 1 x 3 repeated measures ANOVA, comparing each athlete’s times across the three warm-up protocols. This was the same statistical protocol as utilised by Burkett, et al. (2005). Statistical significance was set at p<0.05. Post hoc analysis was carried out via Tukey’s Honestly Significant Difference test (HSD). Power calculations were carried out prior to the study and to achieve a power of 80%, with a maximal rate of error of 20% (unlikely) and a typical error score of 0.8, and utilising a 95% confidence limit, (Hopkins, 2006) the number of subjects required to achieve power was 17 (N = 17).

Results and Analysis.

The results of the three warm-up protocols are Fig 3.1.1

Fig 3.1-1 10 metre sprint times following 3 warm-up protocols

Statistically significant difference (p<0.05) between: general and jump α, general and sprint β, jump and sprint γ
Analysis of the raw data demonstrated that sprint performance was poorest following general warm-up (1.99), greater following jump potentiated warm-up (1.93) and greatest following sprint potentiated warm-up (1.88). Repeated measures ANOVA demonstrated significant differences in sprint performance between the warm-up protocols (p<0.05) while Post Hoc analysis demonstrated that the statistically significant differences extended across all protocols. Therefore, potentiation based activities do result in enhanced sprint performance over a general warm-up alone. Additionally, a sprint potentiated warm-up has greater performance enhancing benefits than a jump potentiated warm-up, suggesting a specificity effect to potentiation.

Due to the nature of sports performance, and especially running speed, where small differences can be very important to competitive performance, it is also useful to look at the individual data produced via the experiments, as well as the statistical results. An analysis of the individual data demonstrated that all athletes had superior sprint performance following the sprint potentiating protocol than after general warm-up alone. These improvements ranged from 0.02 to 0.19 seconds. Indeed enhanced scores of 0.19 seconds are especially important given the distance of run, and the small increments by which performance improvements are reported. The smallest worthwhile change in performance value of 0.03 seconds reflects the potential importance of these individual changes.

Indeed, this trend to enhanced performance was also clear for the jump protocol, where 34 of the 35 athletes had superior times than they achieved with the general warm-up protocol (the other athlete had no change in performance). Individual improvements in this instance ranged from 0.0 to 0.12 seconds. Again performance enhancements of up to 0.12 seconds are extremely important to speed performance over such a short distance, and have the power to greatly impact the level of sports performance achieved, especially when compared to the smallest worthwhile change in performance of 0.03 seconds. The results of the statistical analysis, together with analysis of the individual data demonstrates clearly that no athletes were optimally prepared for speed performance via a general warm-up.

In terms of the individual data on sprint versus jump potentiating warm-ups, all athletes recorded faster times following the sprint potentiating protocol, with the range of difference varying between 0.01 to 0.12. Again scores of up to 0.12 seconds could be very
important in game performance. This clearly suggests a specificity of effect, with sprint potentiating warm-ups being preferred to jump potentiating warm-ups in terms of enhancing sprint performance.

**Discussion**

The results of this experiment clearly support the concept of incorporating a potentiation phase into all warm-up activities as proposed by Faigenbaum, et al., (2005) and Jeffreys (2007b). If the aim of warm-up is to maximise subsequent performance, then based on this evidence, all warm-up activities should incorporate a potentiation phase, over, and above a general warm-up. While general warm-up can facilitate subsequent performance, via lowering viscous resistance in muscles (Enoka 2008) improving oxygen delivery and blood flow to working muscles (McArdle et al 2007) and enhancing metabolic reactions (Enoka 2008). The present results would suggest that they are not sufficient to maximise the neuromuscular processes required for maximal speed performance. It would seem that warm-ups which only consist of general warm-up, and do not involve a short period of maximal intensity exercise, will not optimise performance in the early stages of competition or training, and will compromise an athlete’s ability to express speed in the early stages of a game. This could last until an appropriate series of activities can be initiated within the game situation, which in itself could last well into a game. This provides a compelling reason to include an appropriate potentiation phase in all warm-up activities. Additionally, a failure to prepare optimally for the physical demands of the sport could also heighten the potential for injury.

The potentiation phase of a warm-up is required to fully prepare an athlete for maximal performance. Without this phase, a warm-up will not be able to optimise the benefits of warm-up in relation to, muscle contraction and relaxation speeds (Hoffman, 2002), rate of force development (Asmussen, 1976) and improvements in muscle strength and power. Athletes involved in strength and power sports have always intuitively incorporated a potentiation phase into their warm-ups, sprinters for example will always perform a range
of starts and top speed work, and weightlifters will always use progressively heavier lifts prior to competing.

However, while a potentiation phase is an almost uniform feature of strength and power based warm-ups, it is far from uniform in team sports, and individual game sports such as tennis. While there has been a move away from the old jog and stretch approach in many of these games to a more skill based dynamic approach, a potentiation phase is still often omitted (Jeffreys 2007b). Often, while these warm-ups are dynamic in nature, maximal intensity exercises are not systematically included, and are dependent upon maximal application in the skill based areas, which is, at best, random in its application. Due to this, physical performance in the opening stages of play will be compromised, and a lack of maximal speed, and/or maximal force capacity at this time could be costly in terms of the game outcome. If speed and power is not potentiated in warm-up, then performance will be compromised until the game activities provide for the maximal intensity exercise which will provide potentiation. Due to the nature of sports performance, peak speed or power may be required immediately or some way into the game, and performance can be compromised until full potentiation is achieved. Given the small differences between winning and losing in elite sport, this failure to maximise performance from the start of a game needs to be rectified.

Examination of the individual data between the general warm-up protocol and the sprint potentiated protocol have clear implications for coaching practice. All athletes had superior sprint performance following the sprint potentiating protocol than after general warm-up alone. These improvements ranged from 0.02 to 0.19 seconds. This latter score reflects a large change in performance simply from adding five 10 metre sprints to the general warm-up protocol. Indeed, 24 athletes had improvements in performance of 0.1 seconds or more, which reflects a major change in improvement over 10 metres, especially when compared to the smallest worthwhile change in performance of 0.03 seconds. When changes in speed performance are measured in hundredths of a second, these types of changes from warm-up protocols reflect the clear need to re-examine many protocols in terms of their optimisation of performance. Many athletes spend hours of training trying to achieve 10 metre improvements in the region of 0.10 seconds, yet these could be compromised via the use of poor warm-up procedures. Five sprints of 10 metres can, easily, and time effectively,
be introduced into warm-up activities for team sports, and based on this data, it is recommended that all warm-ups for team sports incorporate a period of maximal intensity work.

Another key finding in this experiment is the specific nature of potentiation. While the jump potentiating protocol was significantly superior to the general warm-up only (p<0.05), demonstrating that even general potentiation is superior to general warm-up alone, this itself was significantly (p<0.05) less effective than the specific sprint potentiating protocol. This suggests that potentiation is a specific phenomenon, and when utilised, needs to conform to the requirements of the specific activity. In this way, athletes engaged in running based events need to ensure that potentiation is provided via sprint based activities. This has important implications for warm-ups in sports that have a range of performance patterns. Soccer players for example, will be required to accelerate, decelerate, move laterally jump and so on, and an effective potentiating warm-up may require activities that stress all of these movement patterns. Given this specificity of potentiation, it is highly unlikely that a general warm-up can optimally prepare an athlete for peak performance from the onset of competition. Similarly, potentiation is likely to be maximised if the preconditioning activity can replicate the subsequent activity.

**Implications for the results of previous PAP research**

The findings of the present study questions the results of previous PAP research. The vast majority of the studies utilised a general (jog and stretch) warm-up prior to the measurement of the dependent variable. Therefore, changes in performance previously associated with supra-maximal performance potential of PAP, may have been attributable to a failure of the control warm-up to optimally prepare athletes for performance, and changes in performance may not be attributable solely to the methodologies utilised in the study. In addition, studies that have previously associated the application of PAP with an acute enhancement of performance need to be re-evaluated to consider whether the control warm-ups utilised failed to adequately prepare athletes for performance, resulting in sub maximal scores against which subsequent scores were compared.
**Potential drawbacks in the study.**

A major factor to consider in this study is the effects of prior training. The athletes in question were accustomed to the potentiation based warm-up, with all of their training session preceded by such a warm-up, and with them being fully aware of the theoretical underpinnings of the warm-up structure. In this way, there may have been a subconscious inhibition on performance when preceded by a general warm-up and even a non specific potentiating warm-up. These factors need to be considered when interpreting the results. Indeed, this drawback could exist across all previous studies where athletes are utilised, especially where athletes were accustomed to more intense warm-up procedures and may not have performed maximally following general warm-ups. These factors have not been totally considered in previous published research.

**Future developments**

Despite giving clear evidence of the needs and benefits of a potentiating phase in warm-ups, a number of issues need to be addressed prior to being able to optimally apply potentiation based protocols in warm-ups for team sports.

The protocols utilised in this study were simply a graded series of sprints or jumps leading to a maximal effort over 10 metres. However, it is unlikely that these necessarily represent the optimal models or the optimal protocols for potentiation. For sprint based potentiation this needs to examine key issues such as whether 10 metre sprints are sufficient, or whether longer sprints, where greater stride cadences and shorter ground contact times are achieved (Plisk, 2008), offer even greater potential. In addition, logistical factors such as the number of repetitions, the rest between sets, etc, needs to be examined before optimal protocols can be authoritatively produced.

Another issue needs to examine which movement patterns in sport offer the potential to be facilitated by potentiation. While running speed can be facilitated, it has yet to be ascertained whether other movements, such as deceleration patterns, change of direction patterns, jumping patterns etc can also be facilitated via potentiation activities. Answers to
these questions will ultimately allow effective sport specific warm-up protocols to be produced.

**Practical Application to Coaching and Performance**

The results of this paper have some important implications for warm-up practice.

- All warm-ups for any sport involving the demonstration of speed and power will benefit from a potentiation phase, at least in the early phases of competition. This needs to involve a progressive series of activities that build up to maximal intensity. Warm-ups should be developed which maximise this effect.

- While skill based warm-ups are important, the fact that they focus on skill will often hinder an athlete reaching maximal intensity e.g. when running and dribbling a soccer ball, the player will never run at maximal speed. In this way activities need to be incorporated that differentiate the physical elements from the skill element to ensure maximal performance is attained. For example the performance of a series of sprints, without the inclusion of a ball etc is recommended.

- Where substitutes are used in a game, the use of potentiating activities is even less common, and specific protocols need to be adopted which facilitate potentiation for substitutes.

- Where breaks in performance are common e.g. rain breaks in tennis, lunch breaks in cricket, half time in soccer, a potentiation protocol should be set up, which facilitates optimal performance immediately upon the resumption of play. These need to be graded in terms of the length of the break, and the time available for a subsequent warm-up.
STUDY TWO - THE ACUTE EFFECTS OF ASSISTED AND RESISTED SPRINTING ON RUNNING SPEED
THE ACUTE EFFECTS OF ASSISTED AND RESISTED SPRINTING ON RUNNING SPEED

Abstract

This study investigated the acute effects on running speed of sprint resisted, and sprint assisted running in the warm-up of youth athletes. 59 male subjects were randomly allocated to one of three warm-up groups, a sprint assisted group (SA) n = 30, a sprint resisted group (SR) n = 21, and a control group (SP) n = 8. All athletes undertook a general warm-up consisting of five minutes of movement, four dynamic stretches, and followed by five 10 metre sprints of increasing intensity (70%, 80% 90%, 100%, 100%). They were then tested on a ten metre sprint test. The SR group then undertook two 10 metre resisted sprints against a resistance 10% of bodyweight, the SA group undertook two assisted sprints of 10 metres, while the control group undertook two 10 metre sprints. All groups were then retested on their 10 metre speed. Statistical analysis using ANOVA with repeated measures showed no significant differences (p>0.05) between the groups on performance pre or post application. The conclusions are that the addition of sprint resisted or sprint assisted methods in the warm-up of athletes offers no additional benefit from that achievable with traditional high speed running.

Background to the problem

Study one highlighted that speed performance is improved if it is preceded by maximal intensity sprint performance, and that sub maximal intensity warm-up activities are insufficient to elicit maximal speed performance. The conclusions recommended a potentiation phase to all warm-ups for speed and power sports, where activities progressing to maximal effort are utilised following a general warm-up phase. This potentiation phase of the warm-up has the capacity to enhance subsequent speed and power performance, and failure to utilise this phase can hinder performance.

A logical extension from this was to question whether this process could be further enhanced via the application of specific methods that provide for additional intensity of actions in the potentiation activity. Given the suggested specificity effects of potentiation evident in study one, then optimal potentiation of speed performance is more likely to be
elicited via running based activities. In this way, activities where sprint performance can be “loaded” may provide opportunities for post activation potentiation levels higher than those elicited by maximal speed running alone. Given that speed is the product of stride length and stride cadence (Plisk, 2008), methods that can overload these two mechanisms may provide an increased capacity for potentiation. Stride length is closely related to ground contact forces (Plisk, 2008; Weyand, et al., 2000), and methods that can maximise ground contact forces may provide for a possible potentiating activity. Similarly, activities where stride cadence can be enhanced, with its associated impact on rate of force development (RFD), could provide a possible avenue for potentiating activities.

Currently, the alternation of loaded and unloaded activities are the focus of a specific method aimed at the acute enhancement of running speed termed contrast training (Plisk, 2008, Jeffreys, 2007a). Authors have suggested that the use of contrast training, the use of a preloading exercise on subsequent unloaded exercise, can acutely enhance speed and power performance. (Pearson, 2001). Similarly, authors have suggested that contrast training can be utilised via the use of super-maximal running speeds to acutely enhance speed performance (Dintiman and Ward, 2003). However, no scientific data has been produced to ratify these claims. Current studies in contrast/complex training are limited to resistance training protocols, and/or explosive exercise protocols on subsequent strength or power output (Till and Cooke, 2009; Jeffreys 2007b). Despite the importance of running speed to sports performance, no research currently exists to determine whether or not it can be acutely enhanced via the prior application of either resisted or assisted runs.

**Sprint resisted/assisted training.**

Sprint resisted training, where sprint performance is resisted via the use of a mechanism which provides a resistance that the athlete needs to overcome while running, is postulated to increase ground reaction forces (Harrison and Bourke, 2009; Dintiman and Ward, 2003; Lockie, et al., 2003). Lockie, et al., (2003) utilising a load of 12.5% of bodyweight found a decrease in mean stride length of 10% and an increase in ground contact time. Harrison and Burke, (2009) postulate that these increases allow for an increase in force production in order to develop and maintain velocity, while increasing muscle stiffness and vertical force at each ground contact. This increase in force could potentially contribute to the generation
of PAP, especially given that Cronin and Hansen, (2006) suggest that sprint resisted training can increase neural activation.

Similarly, sprint assisted training, where an athlete is able to run at supra-maximal speed via the use of a range of assistance mechanisms, is postulated to increase stride cadence (Plisk, 2008; Dintiman and Ward, 2003). No definitive data is available to support either of these claims. While these methods have been used by athletes for a number of years, it is only recently that the concept of their application in a contrast training methodology has been proposed. However, while the use of contrast activities is postulated to enhance subsequent performance, without scientific data, these methods are little more than speculation, and no author currently proposing these methods has provided scientific data to support these claims. In addition, no paper currently exists which investigates the efficacy of these methods to the acute enhancement of running speed, and their inclusion in optimal warm-up procedures. This study was designed to investigate the claims of contrast training by elucidating whether a resisted run or an assisted run could enhance subsequent speed performance, and therefore focussed on two key questions.

1. Can resisted or assisted running acutely enhance running speed?
2. Is there any running speed enhancement over and above that achieved via maximal speed running?

**Experimental approach to the problem**

**Selection of the dependent variable.**

While speed is generally acknowledged as being important for sports performance (Plisk 2008; Dintiman and Ward, 2003; Counsilman, 1976), close examination of movement patterns in team sports emphasises that the vast majority of sprints are of a short distance and therefore acceleration is of far greater importance (Jeffreys, 2009). The ten metre test was selected as a specific measure of sport speed, as it allowed for the evaluation of pure acceleration (McFarlane, 1993) which is important in the vast majority of team sports, and which is recommended by Bloomfield et al., (1994) as an indicator of sport specific running speed. With the 10 metre sprint being able to be measured indoors, environmental elements that could affect performance (wind, temperature etc) could be controlled to a far
greater degree, and a major source of performance variation was removed. Additionally, 10 metre performance is closely related to the power characteristics of the athlete (Ozolin, 1976) and could be potentially enhanced by PAP mechanisms.

**Overall Study design**

The study was a randomised pre test/post test protocol. Following a standardised warm-up, all athletes were initially tested for running speed on a 10 metre sprint, using three trials with the best score recorded. They were then randomly allocated into one of two application groups, a sprint resisted group (SR) n = 21, and a sprint assisted group (SA) n = 30, with an additional control group (C) n = 8 to isolate the possible potentiation effects of maximum speed running. Numbers were allocated between the SA and SR groups in relation to equipment availability and the need to ensure athlete to equipment ratios ensured appropriate work/rest intervals within the confines of the athlete's training time allocation.

Each group undertook two potentiating activities, the sprint resisted group undertaking two resisted sprints towing a sled based resistance of 10% bodyweight. The sprint assisted group undertook two assisted sprints of 10 metres, using an elastic assistance mechanism, while the control group undertook two traditional sprints to equate the volume load of activity.

Subsequent to the interventions, all groups were then retested on the 10 metre sprint. A rest of 4 minutes was allowed between the PAP inducing activities and the re test as this has been shown to facilitate the expression of PAP previously (Jensen and Ebben, 2003). This was also a timeframe that could possibly be utilised within team sports warm-ups, being used immediately before competition started. The control group performed all sprint tests but did not perform a potentiating activity, simply performing two additional 10 metre sprints to equate the volume of work, and to equate rest intervals.

**Subjects**

59 male subjects gave informed consent to participate in the study, and whose physical characteristics are outlined in table 3.2-1. All were competing athletes in two intermittent sprint/power based sports, (rugby n = 24 and football n = 35) competing in Division 1.
College sport. As part of their athletic programme, all were active in a strength and conditioning programme, which included speed training for two days per week. Athletes had been in the programme between 18 months and 36 months. All had previously been tested for running speed on at least 6 occasions, and had been subjected to both sprint resisted and sprint assisted methods.

<table>
<thead>
<tr>
<th>Age (yrs)</th>
<th>Height (cm)</th>
<th>Weight (Kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>18.3 (± 0.7)</td>
<td>180 (± 6)</td>
<td>73 (±9.4)</td>
</tr>
</tbody>
</table>

*Table 3.2-1 Physical characteristics of the participants*

**The application of resisted and assisted running**

**The application of resisted training**

To aid standardisation, a sled based resistance device was selected (Perform Better, Cranston RI) using 10% of bodyweight, and attached to the waist via a 10 metre length of cord. This resistance was chosen for two reasons. The low resistance results in minimal alterations in running technique (Plisk, 2008), and the use of a bodyweight dependent variable resistance allowed for differences in body proportions to be catered for, allowing for a more uniform potentiating effect. The resisted run was performed over a distance of 10 metres to replicate the requirements of the test, and to match the sprint performed by the control group within the experiment. The 10 metre distance facilitates the highest forces being applied, because of the longer ground contact time in this phase of the sprint (Plisk, 2008). High forces have previously been suggested as being the key modifier of PAP (Markovic, et al., 2008).

**The application of sprint assisted training**

Sprint assisted running was provided by an elastic rope of 10 metres long, and stretched to 2 times its resting length (Doubleman Overspeed - Extra Safety Sleeve Elastic Tube Perform Better, Cranston RI). Pilot studies had demonstrated that this protocol resulted in 10 metre sprint times that were a mean 9.3% (SD ± 1.2) faster than maximal time. This was congruent with recommendations proposed by and Plisk, (2008), Jeffreys, (2007a) and Dintiman and
Ward, (2003) who suggests that sprint assisted runs should be in the region of 10% faster than maximal levels. This level of increase was selected to allow for biomechanical similarities between the assisted and unassisted protocols (Plisk ,2008). Speeds greater than 10% are suggested to alter running mechanics, via initiating the need to brake, resulting in postural and ground contact alterations in the running action (Plisk, 2008). The assisted runs were performed over a distance of 10 metres to replicate the requirements of the test, and to match the sprint performed by the control group. The kinetic profile of a sprint changes over time, with greater ground contact times in the initial stages, becoming shorter as a sprint progresses. This necessitates a shift in importance from concentric strength ability to SSC ability as distance increases (Plisk, 2008; Ozolin, 1976). 10 metres may not allow for each of these alterations to be manifested, and could potentially affect the capacity of assisted running to generate PAP. Therefore, as with the sprint resisted group, this distance may not necessarily be optimal for the exploitation of PAP, but at present no data has been generated on this issue. The distance does allow for a replication of the test involved (i.e. 10 metres) and does reduce the potential for fatigue.

**Instrumentation**

Speed scores were measured on a Newtest timing system Newtest Powertimer (Newtest Oy, Oulu Finland). This consisted of a start pad and an infra-red gate (IP 40 - photocells IP 67), placed 10 metres from the start line The photocells had a sensing range of 0.2 - 2 metres, and the system as a whole a reported accuracy of 0.001 seconds, and allowed times to be recorded to the nearest hundredth of a second. The light cells were laid out as per the protocol recommended by Yeadon et al (1999). Athletes were able to place the start pad on their preferred side, negating any advantage of right or left hand dominance. All sprints were measured indoors on a rubberised gymnasium floor to minimise any environmental factors such as wind etc. (Tumilty, 2000) The ten metre sprint provides a valid test for accelerative ability (Bloomfield et al., 1994) , and is used by many sports organisations (Tumilty, 2000).
Test procedures

Testing took place over a single session preceded by a standard warm-up which consisted of 5 minutes of movement activities (forward/back, sideshuffle, Ickey shuffle and back track) with increasing intensity to provide for a general rise in body temperature (Jeffreys, 2007b; Verstegen, 2004) followed by five dynamic stretches (Inch worm, lunge with diagonal rotation, lateral lunge, free squat and calf walk with shoulder rotation (Jeffreys, 2007b; Verstegen, 2004). This was then followed by a series of five 10 metre sprints of increasing intensity, until repetition 5 was a maximum effort sprint. This was the same protocol that was utilised by the potentiation group in study 1, and which optimised sprint performance over general warm-up alone, or jump potentiated warm-up.

Subsequent to the standardised warm-up, all athletes performed two timed sprints of 10 metres, the best performance providing their baseline scores. The group was then randomly allocated into three groups, the sprint resisted group (SR) the sprint assisted group (SA) and the control group.

The resisted group then performed two resisted runs, with a resistance set at 10% of their bodyweight, four minutes after the initial test, with one minute separating each run. The assisted group performed two assisted runs, four minutes subsequent to the first test, and with one minute separating each run. To equate workload, the control group performed a further two sprints four minutes after the first, and with one minute separating each run.

All groups then performed a further two 10 metre tests, 4 minutes subsequent to the potentiating activity. The best score provided their post test score.

Statistical Analysis

Prior to undertaking the study, Power calculations were carried to ensure appropriate group size. To achieve a power of 80%, with a maximal rate of error of 20% (unlikely) and a typical error score of 0.8, and utilising a 95% confidence limit, (Hopkins, 2006) the number of
subjects required to achieve power was 17 (N=17). The study therefore achieved the statistical power required to minimise the likelihood of a type II error.

Statistical analysis was carried out via SPSS Version 15 (SPSS Inc Chicago III). Tests of normal distribution (Kolmogorov-Smirnov and Levene's) were conducted on all data prior to analysis. Upon assumption of normality, mean scores ± standard deviation were recorded for each protocol pre and post intervention. Scores pre and post application for each group were analysed via an analysis of variance (ANOVA) with repeated measures as utilised by Mangus, et al., (2006). Statistical significance was set at p<0.05.

To also determine whether initial speed capabilities affected the level of performance changes, both the sprint resisted and sprint assisted group were split into two, based on initial running speed capabilities. Groups were allocated based on accepted academy norms for the 10 metre sprint for good or superior performance. Athletes exceeding these scores were placed in the faster runner group, and athletes not achieving these scores were placed in the slower runners group. An independent t test was carried out on the performance changes between faster and slower runners in both the SA and SR groups. The statistical significance was set at p<0.05.

Results and analysis.

Pre and post intervention means for the three groups, together with change in performance means for the three groups are outlined are in Fig 3.2-1.
Fig 3.2.1- Changes in 10 metre sprint performance following three warm-up protocols.

An ANOVA with repeat measures demonstrated no significant differences between groups pre or post application. Therefore, neither sprint resisted running nor sprint assisted running offer any advantage over maximal speed running in acutely enhancing running speed, and their use in warm-ups is not warranted.

Analysis of the raw data.

While no statistical differences were found, and neither the SR or SA methods can be recommended as warm-up protocols, it is useful to analyse the raw data, as trends may emerge which can inform coaching practice and/or guide future research.

For the SR group, the range of performance change varied from an improvement of 0.193 seconds to a deterioration of 0.26 seconds. In terms of performance changes, 2 athletes showed no change, 9 athletes demonstrated an improvement in performance with ten showing a deterioration in performance. It should be noted that, while not statistically significant on a group basis, an improvement of 0.193 would have an impact on sports performance, and therefore warrants further investigation. Here, the smallest worthwhile change of performance of 0.03 seconds provides a useful comparison, with the value being well above this.
Analysis of the SA group showed the range of performance change varied between an improvement of 0.242 to a deterioration of 0.15. In terms of performance changes, 11 athletes showed an improvement while 19 showed a deterioration in performance. Again, while not statistically significant, the changes in performance, both positive and negative do warrant further investigation, especially when compared against the smallest worthwhile change in performance of 0.03 seconds.

Performance changes in the control group ranged from a deterioration of 0.128 to an improvement of 0.019. For this group the highest performance increases were lower than those for either the SR or SA group. This suggests that on an individual level the resisted and assisted methods had more of an effect on performance, albeit inconsistent.

Differences between faster and slower athletes

Findings of previous research has suggested that stronger athletes are more able to utilise PAP than less strong athletes (Chiu, et al., 2003). As concentric strength is related to acceleration ability (Ozolin, 1976), then theoretically, faster runners may be able to better utilise PAP than slower runners. The performance changes for slower versus faster runners for the sprint resisted and sprint assisted protocols are shown in table 3.2-2.

Sprint resisted group (N= 21)

<table>
<thead>
<tr>
<th></th>
<th>Faster (n=6)</th>
<th>Slower (n = 15)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean pre</td>
<td>1.821 ± 0.972</td>
<td>2.166 ± 0.117</td>
</tr>
<tr>
<td>Mean post</td>
<td>1.792 ± 0.073</td>
<td>2.166 ± 0.144</td>
</tr>
<tr>
<td>Mean change</td>
<td>0.029 ± 0.088</td>
<td>0.00 ± 0.102</td>
</tr>
</tbody>
</table>

Sprint assisted group (N=30)

<table>
<thead>
<tr>
<th></th>
<th>Faster (n=9)</th>
<th>Slower (n=21)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean pre</td>
<td>1.811 ± 0.074</td>
<td>2.18 ± 0.139</td>
</tr>
<tr>
<td>Mean post</td>
<td>1.848 ± 0.114</td>
<td>2.178 ± 0.139</td>
</tr>
<tr>
<td>Mean change</td>
<td>+ 0.037 ± 0.069</td>
<td>0.002 ± 0.968</td>
</tr>
</tbody>
</table>

Table 3.2-2: Analysis of performance change differences between Faster/slower runners
For the sprint resisted group, the results of an independent t-test on change in performance between faster and slower runners showed no significant differences between the groups (p>0.05). An analysis of the raw data showed that faster runners showed a mean improvement of 0.029 while no improvement was evidenced in the slower group.

The results of the independent t-test on change in performance between faster and slower runners showed no significant differences between the groups (p>0.05). Indeed, based purely on raw data, performance of the faster runners showed a greater deterioration in performance (0.037) than the slower runners (0.004).

In this instance initial running speed appears to have no influence on the potential impact of potentiating activities. If differences do exist that influence an athlete’s ability to potentiate performance, then other factors other than initial running speed need to be investigated.

**Discussion**

The conclusion drawn from this investigation is that neither sprint assisted running nor sprint resisted running appear to confer any potentiating benefits to running performance, over and above that achievable through normal maximal speed running in youth athletes. Therefore, their inclusion in warm-up procedures cannot be justified from a potentiation standpoint. The fact that these methods require the utilisation of specialist equipment, and can be time consuming in their application, further question their application to warm-up procedures.

Similarly, the application of sprint assisted and sprint resisted running in a contrast training paradigm needs to be questioned. The contrast training paradigm is based upon the premise that running speed is enhanced subsequent to the application of sprint resisted runs and/or sprint assisted runs. In this way, running sessions are recommended where a series of sprint assisted runs are followed by traditional high speed sprints, and where sprint performance is potentiated by the prior application of resisted/assisted methods (Pearson 2001). The fact that no potentiation is evident in the present study would question this
claim, and the application of contrast training needs to be further examined. This is especially the case as the method can be time consuming involving the application and then removal of the specialist assisted/resisted equipment. The fact that some individual performance is negated via these methods further questions that applicability of contrast based methods to group situations.

As a group there were no significant changes in performance. On an individual basis there were reported improvements of 0.193 seconds for the sprint resisted group and 0.242 seconds on the sprint assisted group. On a purely sports performance basis the level of performance change does warrant investigation, and supports the notion of an individuality to the response to these methods (Till and Cooke, 2009). If this is the case, then these methods could be evaluated on an individual basis as to whether they confer any performance benefit for each individual (Till and Cooke, 2009). However, based on this evidence the application of sprint resisted or assisted running within warm-ups for groups cannot be recommended, and similarly contrast training recommendations on a group basis are questionable. This is especially pertinent given that a number of athletes experienced performance decrements following application, and thus the use of these activities in warm-up or in contrast methodologies could compromise, rather than enhance, subsequent performance.

**Future developments**

While the results of the present study suggest that sprint assisted running and sprint resisted running confer no enhanced improvements over traditional high speed running, and seriously questions their application to warm-up procedures, a number of further studies needs to be carried out before their application can be completely ruled out.

Firstly, the current study utilised only two applications of the resisted/assisted protocol. Future studies need to determine whether a greater number of applications is necessary to induce any potentiation. However, caution needs to be taken when investigating this route in regard to warm-ups, in that it will require a greater time, which could hinder other elements of the warm-up and especially the skill based requirements. Similarly, a greater
volume of work will also elicit greater levels of fatigue, which may influence performance during a game.

The current study was based on collegiate/youth athletes. While this study demonstrated no potentiation difference between faster and slower athletes, previous research has demonstrated a strength based potentiation capacity (Chiu, et al., 2003). While the application of these methodologies to potentiation based warm-ups in age group teams cannot be advised based on the current evidence, future studies need to elicit whether potentiation can be elicited in senior competitors, who may have greater strength levels.

Additionally, other variables also need to be investigated before the concept of potentiating subsequent activity through the application of loading sprinting can be comprehensibly refuted. Given the rapid changes of ground contact times, ground reaction forces and stride cadences during any sprint activity, and the subsequent changes in the primary physical characteristics that dictate performance in these activities, a number of variables can be manipulated that aim to exploit different ratios of these factors. Variables such as sprint duration (distance), loads, rest periods etc all need to be investigated before the concept of potentiation through resisted or assisted sprinting can be totally refuted.

The current study was on the application of resisted and assisted methods over 10 metres. This distance is largely related to the strength characteristic of the major extensor muscles (Ozolin, 1976). As sprint distances increase, then the relative importance of the stretch shorten cycle correspondingly increases. If the potentiation effects are based on SSC activity, then perhaps greater distances of application are required to maximise any potentiating effects. Again, while this factor needs to be investigated, it does come with the proviso that greater distances will elicit greater fatigue. In a similar vein, if the greatest impact on performance involves elements of the SSC, then it could be that improvements in speed will only be seen over longer distances. Care here must be taken in ensuring that any distances tested, are indicative of the performance needs of any given sport. For example for players in sports such as basketball, tennis etc, even if 40 metre times can be improved, they will have no functional relevance given the restraints of court size in these sports.

The current study utilised loads/resistances that aimed for change in performance of no greater than 10%. While these recommendations are made in a number of texts, (Dintiman
and Ward, 2003, Jeffreys, 2007b, Plisk, 2008), these relate to mechanical issues, where loads are chosen that do not alter running mechanics. It has yet to be determined whether these are the optimal loads for potentiation. There is a current trend amongst some coaches to utilise much heavier loads in sprint resisted training, and future studies need to determine whether these may confer acute potentiation benefits to speed performance. As the analysis of the raw data of this study suggest that sprint resisted running appears to confer greater potentiation potential than assisted running, then investigation into the application of higher resistances may be warranted.

The current study utilised a rest period of four minutes between the potentiating activity and the post test. According to the fitness fatigue model, peak potentiation will occur immediately post activity, and slowly dissipate, whilst peak fatigue will similarly peak post activity and dissipate more rapidly (Zatsiorsky and Kraemer, 2008). Given the relatively low loads utilised in this study, then perhaps the four minute rest may not have maximised the PAP effects on performance. Four minutes is the recommended timescale following resistance based activities of a much higher intensity (Jensen and Ebben, 2003), but for lower intensities a shorter rest period may be more applicable. This would move closer to the point of peak potentiation, as fatigue is less likely with lower loads. However, as the studies aim is to investigate the application of PAP to sports based warm-ups, even if potentiation can occur in very short time frames, then given the logistics of applying this in these short time period before activity, and of the rapid dissipation of performance, then the potential to utilise this in sports based warm-ups is limited.

**Practical applications to coaching performance**

Including assisted and/or resisted running in warm-ups can be time consuming, and requires the provision of specialist equipment. As it does not confer benefit to subsequent performance, their use in warm-ups procedures cannot currently be recommended. Once maximal speed running is achieved during the warm-up, the use of either assisted or resisted runs appears to confer no further potentiation benefits, and will therefore add
additional fatigue, but without conveying additional potentiating benefits. Based on the current study, the application of sprint assisted or sprint resisted training cannot be advised.

Additionally, the utilisation of these methods via the use of contrast training methodologies (where they are interspersed with normal running, with the idea that they enhance subsequent performance) cannot be justified on a purely performance potentiating basis. While they may offer variability in drill application, and may confer advantages to motor learning (Schmidt and Wrisberg, 2004), their use on a potentiating basis cannot be justified.

In this way, guidelines given as to the application of contrast methodologies based on a potentiatio basis need to be revisited.
STUDY THREE- THE ACUTE EFFECTS OF LOADED COUNTER MOVEMENT JUMPS ON COUNTER MOVEMENT JUMP PERFORMANCE
THE ACUTE EFFECTS OF LOADED COUNTERMOVEMENT JUMPS ON COUNTERMOVEMENT JUMP PERFORMANCE

Abstract

This study investigated the acute effects of loaded counter movement jump performance on subsequent counter movement jump performance. 25 male subjects, all competitive youth athletes, were randomly allocated into one of two groups; a weighted jump potentiated group (WJ) n = 15, or a jump potentiated group that acted as a control (C) n = 10. All athletes undertook a general warm-up consisting of five minutes of movement followed by five dynamic stretches after which they carried out five 10 metre sprints of increasing intensity. They were then tested for counter-movement jump height (CMJ) using a Just Jump contact mat. Following this, the WJ group performed two resisted jumps with a weight of 10% of bodyweight, while the C group undertook a further two un-resisted jumps. CMJ height was retested 1 minute and 4 minutes subsequent to the last jump, and the change in performance recorded. ANOVA with repeated measures demonstrated no significant differences (p>0.05) between the groups performance at either baseline, 1 minute or 4 minutes. The application of resisted jumps seems to offer no advantage in potentiating performance, and based on this evidence, their use in contrast training methodologies needs to be questioned.

Background to the problem

Study one demonstrated the need for a potentiating phase in the warm-up of strength and power athletes. It also demonstrated that there is a specificity element to this and that a jump based protocol did not result in as great a degree of potentiation as a sprint protocol in terms of enhanced sprint performance. However, the fact that a jump protocol did provide for a significant (p<0.05) level of potentiation over a general warm-up suggests that jumps could have a potential for providing suitable potentiation activities, especially in situations where limited space is available. While experiment two found no enhancement of sprint performance from assisted and resisted running via a contrast training type protocol using running methods, jumping based methods also utilise this contrast philosophy. According to the proponents of contrast training, loading jump performance results in an
enhanced subsequent jump performance (Pearson, 2001), although, again, no data is presented to support their claims, and no papers have been produced which directly investigate these claims. Burkett, et al., (2005) in a study of warm-ups on vertical jump performance, found that the use of a weighted jump warm-up resulted in vertical jump performance that was significantly (p<0.001) superior to that achieved with either a submaximal jump, a running and stretching warm-up or no warm-up. However, this study did not distinguish between the effects of loaded jumps against maximal effort unloaded jumps, as the control protocols all involved submaximal activities. In this way the direct effects of load could not be ascertained.

Study three therefore set out to investigate whether a loaded counter movement jump (CMJ) would enhance performance on a subsequent unloaded CMJ, and directly compared this to the results achieved with maximal unloaded jumps.

Various authors have suggested that the use of contrast training (the use of a heavier preloading exercise on subsequent unloaded exercise), can enhance power performance (Pearson 2001). However, study two found that neither a sprint resisted, nor a sprint assisted protocol, enhanced subsequent sprint performance. Like sprint performance, CMJ performance is closely linked to the strength and rate of force development characteristics of the major extensor muscle of the hip and leg (Eston and Reilly, 2001). As these have been previously demonstrated to be able to utilise PAP, in the form of either MVC or heavy squats (Sale 2002), then the potential to utilise loaded CMJ warrants investigation, as these could be effectively integrated into warm-up routines without the need for heavy resistance based equipment. Additionally, jump protocols with little or no resistance, utilise resistances that are at or near to those that maximise power output (Cormie, et al., 2008), via having to overcome the system mass. Therefore, they may offer a viable method of eliciting PAP, and one that could be incorporated into the warm-up routines of teams.

Vertical jump performance has been linked with elite performance in a number of sports such as American Football (McGee and Burkett, 2003), Volleyball, (Barnes et al., 2007), and Ice Hockey (Burr et al., 2007), and is a key element of many combine tests. This role in combine testing provided another important aspect to optimal warm-up, in that the ability to enhance jump performance could mean significant improvements in an athlete’s capacity
to be drafted etc. In this way, the use of activities that can enhance jump performance needed to be carefully investigated.

This study therefore aimed at determining:

1. Whether the performance of loaded countermovement jumps (CMJ) enhanced subsequent jump performance.

**Experimental approach to the problem**

The study was a randomised pre-test/post-test protocol, with CMJ performance compared pre and post weighted CMJ. To eradicate the confounding potentiating effects of the jump activity itself, ten athletes were randomly selected to provide a control group, who undertook the same protocol, except that the potentiating jumps were unloaded. This removed the issues with the Burkett, et al.,(2005) study, where the control jumps were sub-maximal. The control group performed both CMJ tests but did not perform the weighted jump, instead performing an un-resisted jump in order to equate total work performed between both groups. This isolated whether any increase in performance was due to the initial CMJ rather than the weighted jump.

Resistance for the weighted jump was set at 10% of bodyweight. This is a resistance that was within the range that optimised power output, but without affecting the kinematics of jump performance (Cormie, et al., 2008).

Post tests were performed one minute and four minutes subsequent to the performance of the potentiating activity. This was to ensure that any potentiation effect was noted. Four minutes had been suggested as the optimal rest period post potentiation for enhanced performance (Jensen and Ebben 2004). However, Chatzopoulis et al., (2007) suggest that the magnitude of PAP is protocol dependent, and therefore for lighter potentiating activities, the rate of decay of potentiation may be faster and that peak potentiation may occur at a much earlier period. For this reason a rest period of one minute was measured in addition to the four minutes.
Subjects

25 male subjects gave informed consent to participate in the study, and their physical characteristics are outlined in Table 3.3-1. All were competing athletes in National Collegiate Division 1 competition. They were drawn from two sports, rugby and football. All had participated in a formal strength and conditioning programme for at least 18 months and were experienced in countermovement jumps, both as a testing and a training modality.

<table>
<thead>
<tr>
<th>Age</th>
<th>Height (cm)</th>
<th>Weight (kgs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>18.1 ± 0.6</td>
<td>178 ± 4</td>
<td>71 ± 9.8</td>
</tr>
</tbody>
</table>

Table 3.3-1: Physical characteristics of the participants

Instrumentation

Countermovement jumps were performed on a contact mat (Just Jump, Probiotics Alabama), with jump height being calculated from flight time using the formula Jump height = 9.81 m/s² x flight time(s)²/8). The formula is based upon the assumption that the time spent in the jump phase is the same as that spent during the return back to the mat from the position of maximal vertical displacement (Rixon et al., 2007).

Test procedures

Testing took place over a single session preceded by a standard warm up which consisted of 3 minutes of skipping to provide for a general raise in body temperature followed by five dynamic stretches (Inch worm, lunge with diagonal rotation, lateral lunge, free squat and calf walk with shoulder rotation (Jeffreys, 2007a). This was then followed by a series of five 10 metre sprints of increasing intensity, until set 4 was a maximum effort sprint (the same protocol utilised in study one). The sprint activities were included to ensure that a potentiation phase of warm up was included. Study one had shown that a general warm-up
only was unable to fully potentiate performance, and that maximal effort sprinting would result in a level of potentiation over and above that provided by general warm up alone. As this experiment aimed to investigate the supramaximal potential of resisted jumps, then a potentiating activity was needed, but one that would not include a jumping activity. For this reason the sprint protocol that had demonstrated potentiation in experiment one was selected.

Following the warm-up, both groups performed two countermovement jumps, one minute apart, with the best score being recorded as the baseline score. The group was then randomly allocated into two groups, the resisted jump group (n = 15) and the control group (n=10).

Following the initial performance test, the resisted jump group performed two maximal effort CMJ’s with a weight 10% of their body weight, one minute after the second baseline test. They were then retested on their maximal CMJ performance, one minute after the weighted jump, with a further CMJ three minutes later.

The control group performed a further two CMJ’s, one minute after the second trial. They then performed two further CMJ’s tests, the first, one minute after the application jump, and the next a further three minutes later. This acted as the control equating the volume of jumping, and isolating the load as the independent variable.

Statistical Analysis

Power calculations were carried out prior to the study and to achieve a power of 80%, with a maximal rate of error of 20% (unlikely) and a typical error score of 0.7, and utilising a 95% confidence limit, (Hopkins, 2006) the number of subjects required to achieve power was 19 (N=19). The study therefore achieved the statistical power required to minimise the likelihood of a type II error.

Statistical analysis was carried out on SPSS Version 15 (SPSS Inc Chicago III). Tests of normal distribution (Kolmogorov-Smirnov and Levene’s) were conducted on all data prior to analysis. On assumption of normality, baseline (pre weighted jump) scores were compared.
to the scores after the weighted jump for both the weighted jump group (WJ) and the control group (C). Statistical analysis on CMJ performance between the WJ and the control group was carried out via Analysis of Variance (ANOVA) with repeat measures, with baseline performance and performance 1 minute and 4 minutes post, analysed. Statistical significance was set at p<0.05.

To isolate the effect of potential potentiation independent of time, a dependent t test was carried out on baseline performance and maximal post potentiation jump height for the resisted jump group.

**Results and Analysis**

The results for each group are outlined in Fig 3.3-1.

![CMJ height for control and weighted jump group](image)

*Fig 3.3-1 – CMJ performance at baseline, 1 minute and 4 minutes post application*

ANOVA with repeat measures showed no change in CMJ performance between the weighted jump group (WJ) and the Control group (C) at either baseline, 1 minute or 4 minutes post.

The results show that loaded countermovement jumps do not enhance jump performance, and that there is no difference between performance increases subsequent to loaded CMJ’s than following unloaded CMJ’s.
Change in CMJ height 1 minute post application

<table>
<thead>
<tr>
<th>CMJ height (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>1.5</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>0.5</td>
</tr>
</tbody>
</table>

Fig 3.3-2 Change in CMJ performance 1 minute post application.

<table>
<thead>
<tr>
<th>Weighted</th>
<th>Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Series1</td>
<td>-0.45</td>
</tr>
</tbody>
</table>

Even when time was removed as a variable, and the maximum potentiation at either 1 or 4 minutes calculated (table 3.3-2), and subjected to a dependent t test, no significant (p>0.05) potentiation effects were demonstrated.

Change in CMJ height 4 minute post application

<table>
<thead>
<tr>
<th>CMJ height (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-0.4</td>
</tr>
<tr>
<td>-0.8</td>
</tr>
<tr>
<td>-1.2</td>
</tr>
<tr>
<td>-1.4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Weighted</th>
<th>Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Series1</td>
<td>-1.03</td>
</tr>
</tbody>
</table>

Fig 3.3-3 Change in CMJ performance 4 minute post application.
<table>
<thead>
<tr>
<th></th>
<th>Pre (cm)</th>
<th>Post (cm)</th>
<th>Change cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resisted jump group</td>
<td>59.62 ± 9.47</td>
<td>59.75 ± 9.38</td>
<td>0.12 ± 2.24</td>
</tr>
</tbody>
</table>

* Denotes significant difference (p<0.05)

Table 3.3-2 Maximal performance change post potentiation

Analysis of the raw data.

While no statistical differences were found, it was useful to analyse the raw data, as trends may emerge which can inform coaching practice and/or guide future research (Till and Cooke, 2009). It must be noted however, that no statistical differences were found and therefore no changes were found in performance.

Analysis of the raw data showed that at both one and four minutes the jump performance in the WJ group actually decreased. At one minute post application, performance was depressed by 0.49 cm, and at 4 minutes this was 0.115 cm.

In the WJ group, at 1 minute post application, only 4 athletes demonstrated an increase in performance, while 9 demonstrated a decrement in performance. This performance change ranged from an increase of 4.25 cm to a decrease of 2.5 cm. At 4 minutes post application, the same 4 athletes demonstrated potentiation while the same 9 demonstrated performance decrements, the range here was a potentiation of 5.25 cm to a decrease of 2.75 cm. While on a group basis no significant changes in performance were found, on an individual basis these performance changes do warrant investigation, especially when compared to the smallest worthwhile change in performance of 0.79 cm.

Discussion

Despite claims by various authors (Pearson, 2001) describing the potentiating benefits of loaded jumps on subsequent unloaded jump performance the results of this study contradict these claims. The results of the present study demonstrate that loading a jump does not enhance performance.
Previous research has indicated large loads are required in order to maximally induce PAP. The current study only utilised the 10% of bodyweight load advised by proponents of contrast training methodologies. The load may have been insufficient to adequately potentiate subsequent performance, although it was close to the load that maximised power output (Cormie, et al., 2008). Before the use of explosive based exercises can be ruled out in terms of their ability to enhance performance through PAP, a greater range of loads needs to be examined, along with a greater range of applications such as jump squats, and olympic lifts. However, greater jump loads will affect the kinetic performance of the jump, with greater loads requiring greater time for force application. It needs to be determined whether these changes in the kinetic profile of the jump will affect subsequent jump performance. Similarly, in terms of standardising warm-up routines for sports, the use of specialist equipment will limit application. Availability of specialist equipment cannot always be guaranteed, especially at away venues, and unless equipment is easily portable, its practical application to warm-up is limited.

Comyns, (2007) suggested that the timeframe of PAP is not uniform and varies between individuals. In this way the effects of PAP may be hidden in research where performance effects are measured at a given time frame. This research initially suggests that while there may be an amplitude effect; athletes who demonstrate PAP will do this over a range of timescales. When time was removed from the equation, and the maximum potentiation irrespective of time was analysed, no significant changes were reported. It should be noted however, as only two time frames were measured in this current study, these conclusions need to be treated with some caution.

The analysis of raw data does produce an important point to note. Four individuals demonstrated a potentiation effect, with one individual having a peak potentiation of 5.25 cm. For this individual, peak score changed from 73.75 cm to 79 cm. While overall group differences were insignificant, in terms of individual performance, this increase needs to be noted. From an already impressive score, this athlete produced a performance that would indicate great potential and would have been impressive in combines. In this way, loaded jumps may have performance enhancement potential in certain individuals, and could warrant further research. This also throws up an important implication for PAP application, that of individual differences in capacity to benefit from PAP. As PAP is dependent upon the
subtle interaction of potentiation and fatigue (Tillin and Bishop, 2009; Hodgson, et al., 2005; Rassier and Macintosh, 2000), the relative impact of any PAP application on these elements could be highly individual. In this way, they would be related to the individual’s capacity to both utilise the PAP inducing elements of any activity, but also to withstand the fatigue inducing effects of any application. It could be that, as with medical interventions, there exist groups of responders and non-responders to PAP interventions.

Similarly, Robbins, (2005) highlighted that the precise mechanisms of PAP have yet to be determined, and to date two major mechanisms have been proposed (Comyns et al., 2007). The first an enhancement of neural excitability (Gullich and Schmidtbleicher, 1996) is not a single mechanism, and a number of physiological mechanisms will contribute to this. PAP may have a number of contributory factors, that affect both the potentiation element along with the fatigue element. With a number of contributory factors, the full effects of PAP will be closely related to the capacity of the individual to utilise these mechanisms, which itself may be related to various inherent and trained capacities of each individual. Similarly, the capacity of an individual to optimise the second proposed mechanism of PAP, namely the phosphorylation of myosin light chains, will be closely related to both inherited and trained capacities of an individual. To add further complexity to this situation, an athlete’s capacity at any time will vary, and the utilisation of PAP may have a temporal element to it, and be related to the athlete’s capacity at a given time. This is likely to depend upon the complex interrelationships between potentiation and fatigue (Tillin and Bishop, 2009; Jeffreys 2008c), and could well depend upon a number of contributory physiological mechanisms, that could vary between individuals, but also, more challengingly, vary temporally within individuals, thus making definitive conclusions as to the mechanisms of PAP, and also definitive guidelines as to its application extremely difficult.

**Future research implications**

While the current study suggests that weighted jumps confer no performance enhancing effects, it is important to investigate a number of factors prior to completely discounting this mechanism:
Firstly the use of heavier loads needs to be investigated as these may confer a greater PAP inducing capacity, although again this would need to be balanced with a greater fatigue inducing potential. This may require the application of different timeframes of application and subsequent testing.

A variety of exercises to provide application of the PAP inducing exercise need to be investigated which allow for heavier loads. These need to include jump squats and olympic lifts. However, it needs to be noted that these methods may provide for limited application potential for standardised warm-ups with their reliance on specialist equipment.

Where individuals display enhanced performance, research needs to establish the consistency of this effect. Only when this is established should any form of individualisation of protocols take place.

**Implications for coaching practice.**

The results of the present study suggest that loaded jumps of 10% of bodyweight have no acute effect on subsequent jump performance. Their use in warm-up procedures is therefore not advised.

The study also suggests that contrast training methodologies, utilising loaded jumps prior to unloaded jumps offer no benefit to subsequent performance. When investigating individual differences, in certain individuals they also have the potential to hinder subsequent performance and therefore should be used with caution. Contrast training methodologies should therefore not be used on a group basis.

Where certain individuals demonstrate consistent potentiating effects, individualised warm-up procedures may be utilised which maximise the benefit from this protocol. This would likely be more applicable in individual sports, or in team sports where time can be allocated to individual warm-ups. Similarly, contrast training methodologies, if utilised, should be constructed on an individual basis, and broad general programmes should be avoided. However, this should only be attempted when a consistency of effect is demonstrated.
Additionally, if individual modalities are developed, these need to investigate any temporal patterns, and consider the interaction between fatigue and potentiation.
STUDY FOUR- IDENTIFYING THE OPTIMAL RESISTIVE LOAD FOR INDUCING PAP
IDENTIFYING THE OPTIMAL RESISTIVE LOAD FOR INDUCING PAP

Abstract

If heavy resisted exercises such as the squat are to be utilised in warm-ups with the aim of enhancing power output, then determining the optimal load that elicits PAP is critical. This study looked at the effects of three different loads on subsequent jump height. 14 male subjects participated in the study and 1RM was determined for each. On three separate testing days, each subject undertook a general and sprint potentiated warm-up followed by three trials of a CMJ, with maximum height recorded (JH), along with peak power (PP), peak force (PF) and rate of force development (RFD). They were randomly allocated three different squats loads on three non consecutive days 60% 1RM,(60), 80% 1RM (80) and 93% 1RM (93). 4 minutes subsequent to the performance of the squat, CMJ height was re-measured. ANOVA with repeated measures on jump height showed no significant differences between pre and post height across all loads. Similarly, ANOVA with repeated measures on RFD, PP, and PF for the 93 group, showed no difference pre and post squat across all groups. The results demonstrate that squatting has no affect on CMJ performance, regardless of the load utilised.

Background to the problem

Studies two and three investigated the potential for the use of highly specific additional loadings to create possible PAP initiating opportunities in enhancing sprint and jump performance, and concluded that these do not provide the capacity to enhance performance. A limitation of these methods could be that while these would logically work on a kinematic basis, much of the current literature on PAP suggest that they may not provide the kinetic requirements of PAP generation (Docherty and Hodgson, 2007). In order to preserve the kinematic parameters of running and jumping techniques, resistances in all of the previous methodologies were, by design, low. However, the majority of studies where PAP has been evidenced have used high resistances, and the application of the previous studies may have been limited by the inability to utilise high loads in kinematically similar movements (Docherty and Hodgson, 2007).
While the capacity to provide high loads via the previous methods (sprint resisted runs, sprint assisted runs or weighted jumps) is limited, high resistances can be provided via the use of traditional weight training exercises such as the squat. Anecdotal evidence suggests that the use of heavy squats prior to sprint performance has been used by top sprinters, but without scientific evidence this can be no more than conjecture. However, it does highlight a potential utilisation of the PAP phenomenon in the warm-up protocols of power athletes.

Previous research has suggested that power performance can be enhanced via the performance of a prior potentiating exercise. (Ruben, 2010; Comyns et al., 2007; Kilduff, et al., 2007; Rixon et al., 2007; Comyns et al., 2006; Chiu, et al., 2003; Baker, 2003; Jensen and Ebben, 2003; Ebben et al., 2002; Hamada et al., 2000; Jenson et al., 1999; Young et al., 1998; Radcliffe and Radcliffe, 1996; Gullich and Schmidtbleicher, 1996). In the use of dynamic exercise such as the squat to induce PAP, a key factor is the selection of an optimal resistance that maximises PAP. The identification of an optimal load is essential if coaches are to integrate this methodology into effective sport warm-ups.

However, despite the importance of determining the optimal load that induces PAP, currently great ambiguity exists regarding the optimal load to maximise the benefits of PAP. While 5RM loads have been used in the majority of studies (Comyns et al., 2007) the results from this resistance have been mixed. In a number of studies, significant increases in subsequent performances were found (Rixon, et al., 2007; Evans, et al., 2000; Young, et al., 1998; Radcliffe and Radcliffe, 1996), while in others no significant differences were noted (Scott and Docherty, 2004; Jones and Lees, 2003; Jensen and Ebben, 2003; Hrysomallis and Kidgell, 2001).

Research into other loads is sparse (Comyns, 2007). Baker, (2003) found an increase in an explosive bench throw with a load of 65% of 1RM, suggesting that PAP can be induced with a relatively light load. Chiu, et al., (2003) found an increase in PAP with a load of 90% of 1RM but only found significant differences in strength trained athletes, while Gilbert et. al. (2001), found potentiation to be elicited at 100% of 1RM loads. Chatzopoulos, et al., (2007) found a significant improvement in sprint performance following 10 single repetitions of 90% 1RM on 0-10 metre and 0-30 metre sprint time, but only after 5 minutes recovery, no change was seen at 3 minutes.
Therefore, any attempt by coaches to utilise a resistance exercise such as the squat into any warm-up protocol with the aim of utilising PAP requires a clear knowledge of the load that is required to stimulate PAP. Study four attempted to identify the optimal load for the generation of PAP for subsequent power performance (as measured by a counter-movement jump) by comparing a number of loads that have previously been utilised to induce PAP.

This study aimed to answer two main questions

1. Can jump height be enhanced via the use of heavy squats
2. Do any loads produce better results than others.

**Experimental approach to the problem**

This study isolated the effects of three loadings on subsequent sports performance, as measured by a counter-movement jump. Performance during the CMJ was analysed primarily in terms of jump height to ensure application of the results to performance. However, to enable further analysis, performance was also assessed in terms of peak power, peak force and rate of force development, as these three variables have been reported to be closely related to jump height performance (Stone, et al., 2007). Via this data, not only can the effect on jump height be analysed, but also the effect on the key kinetic variables that determine jump height.

The study was a randomised test/retest protocol, measuring jump performance prior to, and subsequent to, the performance of parallel squats at three different loadings. Testing took place over four sessions, each preceded by a standard warm up which consisted of 5 minutes of movement of increasing intensity to provide for a general raise in body temperature followed by five dynamic stretches (Inch worm, lunge with diagonal rotation, lateral lunge, free squat and calf walk with shoulder rotation (Jeffreys, 2007a). This was then followed by a series of five 10 metre sprints of increasing intensity, until set five was a maximum effort sprint.
Session one then involved a series of squats at increasing weights to determine 1RM. This was estimated from a final set, where athletes chose a resistance that they could lift for 1-5 repetitions. 1RM was then calculated from the tables in Baechle, et al., (2008). All squats were taken to a thighs parallel position. The thighs parallel position was preferred on two key factors. First it was the minimum depth used by all athletes in their training and secondly based upon muscle activation patterns. A parallel squat maximises the involvement of the gluteus maximus, ensuring maximal muscle recruitment through the exercise (Caterisano, et al., 2002). It can be hypothesised that by activating the greatest number of muscle fibres, the potential for PAP mechanisms to be stimulated is maximised.

Testing then took place a week later, over three non consecutive days. Athletes were tested for CMJ performance on a force plate (Quattrojump -9292AD Portable Force Plate System, (Kistler Systems, Winterthur Wüelfingen, Switzerland) which was linked to specific Software: OJ Software, Type 2822. Version 1.0.9.2.), and then randomly allocated to one of three resistances on each day, so that after three days of testing all had been measured on jump potentiation at each load. Loads were set at 60%, 80% and 93% to replicate light, medium and heavy resistances (Baechle, et al., 2008). Four minutes was set as the rest time between squat and jump as this has previously been found to elicit a PAP response (Young et al., 1998).

Subjects

14 male subjects gave informed consent to participate in the study, and whose physical characteristics are outlined in table 3.4-1. All were competing athletes at Division 1 College level in rugby (n=10) and football (n=4). All had been active in a formal strength and conditioning programme that involved resistance and plyometric training for a minimum of 18 months. In this way, all had experience and proficiency in the back squat. Additionally, they were experienced in countermovement jumps. They had all been tested in the back squat on at least four previous occasions and in the CMJ on at least six previous occasions, and so were familiar with all protocols.
### Table 3.4-1 Physical characteristics of the participants

<table>
<thead>
<tr>
<th>Age (±)</th>
<th>Height (cm)</th>
<th>Weight (kg)</th>
<th>1 RM (kgs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>18.8 (+0.7)</td>
<td>180 ±5</td>
<td>82.6 ±9.8</td>
<td>135 ±25</td>
</tr>
</tbody>
</table>

**Instrumentation**

Countermovement jumps were performed on an uni-directional force plate, Quattro Jump: 9292AD Portable Force Plate System, (Kistler Systems, Winterthur Wülfingen, Switzerland) which was linked to specific Software: OJ Software, Type 2822. Version 1.0.9.2. Jump performance was measured along with peak force, peak power and rate of force development.

**Test procedures**

Testing took place over a single initial testing session and three application sessions, a week apart. The three application sessions were on non consecutive days, (Monday, Wednesday, Friday) where each individual was randomly allocated to a specific load on each day. Each application session was preceded by a day’s rest to minimise the effects of fatigue (Gullich and Schmidtbleicher,1996). All sessions were performed at the same time to minimise circadian variation (Atkinson and Reilly, 1996).

All sessions were preceded by a standard warm up which consisted of 3 minutes of rope skipping to provide for a general raise in body temperature followed by five dynamic stretches (Inch worm, lunge with diagonal rotation, lateral lunge, free squat and calf walk with shoulder rotation (Jeffreys, 2007a; Verstegen, 2004). This was then followed by five ten metre sprints of increasing intensity (70%, 80%, 90%, 100%, 100% of maximum), with a walk back recovery.
Session one aimed at determining each subjects 1RM for the back squat. Each back squat was taken to a thighs parallel position (Baechle, et al., 2008). Following the warm-up subjects performed a squat specific warm up consisting of three repetitions at 40 and 50 % of 1 RM, and one repetition at 70% (with three minutes recovery between each set) prior to choosing an appropriate weight for their maximum test. They then performed a maximal number of repetitions with this weight, with the subjects 1 RM being determined using the tables outlined by Baechle, et al., (2008). Thighs parallel position was determined via the use of a goniometer set against the femur. This was measured utilising a light load, but with the athlete utilising the same technique as for heavier loads. To indicate the position to athletes during performance, elastic bands were set across a power rack (Bodysolid USA) for each athlete to indicate the thighs parallel position for 1RM testing and for the subsequent application sessions.

On the first day of the application sessions, the group was then randomly allocated a squat resistance for each day. The application sessions were preceded by the exact same warm-up as described above, but were followed by three countermovement jump trials, with the best score recorded and used for data analysis. This provided the baseline figures against which the effects of PAP was measured. To determine the measures of peak force, peak power and RFD, these measures were recorded in the trial that elucidated peak jump performance, as this was the main performance variable to impact on coach decisions. This allowed for the impact of these variables on jump height to be analysed.

Following the allocation of a set load, the group immediately performed a squat warm up consisting of three repetitions at 40 and 50 % of 1 RM, with three minutes recovery between each. All participants then undertook a set of 3 repetitions of the squat at a randomised percentage of 1RM (60, 80 or 93%) on each day. This was followed four minutes later by a further set of 3 countermovement jumps. The best jump height was recorded, along with the peak force, peak power and RFD parameters that related to that jump.
Statistical Analysis

Power calculations were carried out prior to the study and to achieve a power of 80%, with a maximal rate of error of 20% (unlikely) and a typical error score of 0.7, and utilising a 95% confidence limit, (Hopkins, 2006) the number of subjects required to achieve power was 13 (N=13). The study therefore achieved the statistical power required to minimise the likelihood of a type II error.

Statistical analysis was carried out via SPSS version 15. Tests of normal distribution (Kolmogorov-Smirnov and Levene’s) were conducted on all data prior to analysis. On assumption of normality, baseline (pre squat) jump scores were compared to the scores after the different squat loadings. This was carried out via a two way analysis of variance (ANOVA) with repeated measures. Two within individual factors were present, these were condition at four levels (initial, 60%, 80% and 93%), and trials with one level (jump height).

A further repeated measures ANOVA was carried out on the other parameters associated with peak jump height at the 93% load, as this reported the greatest change in performance. Here, two within individual factors were present, these were condition at two levels (initial, 93%), and trials with three levels (peak power, peak force and rate of force development).

To further investigate the mechanisms of PAP, peak power, peak force and rate of force development were analysed pre and post squat for all athletes who demonstrated PAP. However, due to the small sample size these were carried out via analysis of the raw data rather than by statistical methods.

Results and Analysis.

The results of the CMJ scores are outlined in Fig 3.4-1. The ANOVA with repeat measures showed that there was no statistically significant difference (p>0.05) in CMJ height pre and post squat at any load. Therefore, it must be concluded that squat performance does not
enhance CMJ performance. Additionally there is no difference in the changes in CMJ height across 3 different resistances.

**Fig 3.4-1 CMJ height pre and post squat at three different loads.**

**Analysis of the raw data.**

While no statistical differences were found, it is useful to analyse the raw data, as trends may emerge which can inform coaching practice and/or guide future research. It must be noted however, that no statistical differences were found and therefore no changes were found in performance.

An analysis of the raw data demonstrates that only the 93% 1RM loads demonstrated any increase in performance (1.48 cm) whereas the 60% loads showed a negligible decline (-0.05 cm) in performance and 80% loads showed a similar negligible performance decline of -0.028 cm. The greatest increase in performance at the higher loads (93% 1RM) does lend a little credence to the notion that PAP requires high loads if it is to be initiated. Previous studies (Chatzopoulis, et al., 2007; Rixon, et al., 2007; Evans et al., 2000; Young et al., 1998; Radcliffe and Radcliffe, 1996) have demonstrated significant performance changes at similar loads, it must be noted that the performance changes in this study were non-significant.

On an individual basis, eight of the 14 athletes demonstrated performance increases at 93% load varying from 0.01 cm to 11.3 cm. These large individual performance changes warrant investigation, as they have the capacity to significantly impact on sports performance (Till
and Cooke, 2009). Given the smallest worthwhile change in performance of 0.79 cm, heavy load squats may offer a method of acutely enhancing jump performance in certain individuals. Additionally, it should be noted that the individual performance decrements were also greater at this load, reflecting the critical balance between fatigue and potentiation when evaluating net performance effects of any PAP methodology.

As the 93% protocol demonstrated the greatest increase in performance, albeit non-significant, more detailed analysis was carried out on the performance profile of this group in terms of the peak force, peak power, and RFD date. This is shown in table 3.4-2. Repeat measures ANOVA demonstrated that no significant (P>0.05) differences were found across any factors, and therefore the squat protocol did not significantly change PF, PP or RFD. Therefore, squats do not have the potential to enhance jump performance, peak power, peak force or rate of force development. This supports the findings of a number of studies (Scott and Docherty, 2004; Jones and Lees, 2003; Jensen and Ebben, 2003; Hrysomallis and Kidgell, 2001) where no increased performance following heavy squats was found at this load.

<table>
<thead>
<tr>
<th></th>
<th>Jump height (cm)</th>
<th>Peak power (W)</th>
<th>Peak force (N)</th>
<th>Rate of Force Development</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline pre 93%</td>
<td>52.33 (6.307)</td>
<td>2094 (717.89)</td>
<td>111.031 (50.396)</td>
<td>1057 (28.35)</td>
</tr>
<tr>
<td>Post 93%</td>
<td>53.82 (4.25)</td>
<td>2138 (522.38)</td>
<td>109.311 (29.77)</td>
<td>1158 (33.22)</td>
</tr>
<tr>
<td>Change</td>
<td>1.48 (6.85)</td>
<td>44 (267.55)</td>
<td>1.72 (0.368)</td>
<td>101 (10.14)</td>
</tr>
</tbody>
</table>

**Table 3.4-2:** Peak force, peak power and RD scores following squatting at 93% load

Previous research has suggested a strength based effect on the ability to utilise PAP. However, when the group was median split into stronger (n=7) and weaker (n=7) athletes, based on predicted 1RM; independent t-tests on the change in jump performance demonstrated no significant (p>0.05) differences between stronger and weaker athletes in
the change in jump height at this load. The results for this group are found presented in Fig 3.4-2.

![Figure 3.4-2](image)

**Fig 3.4-2 Pre and post CMJ scores of stronger and weaker athletes.**

While the group data did not demonstrate performance enhancing effects of PAP, the raw data did demonstrate 8 athletes who did improve performance at 93% loads. An analysis of the force platform data on athletes who demonstrated PAP (n = 8) demonstrated some interesting features. Athletes who demonstrated PAP showed a mean increase of 6.42 cm (± 4.01 cm) representing a 13.45 percentage change in jump performance. Therefore, a sub group of individuals may exist who can utilise PAP to enhance jump performance. The results for these athletes are outlined in table 3.4-3. Further research could be warranted to examine the characteristics of athletes who are able to exploit PAP.
Table 3.4-3 Analvsis of athletes demonstratina improved jump performance at 93% load (n=8)

For this sub group (n=8), of the variables recorded, only rate of force development showed an increase (3.24%), suggesting that PAP, while enhancing overall jump performance changes the kinetics of the jump. PAP appeared to have little effect on peak power, had little effect on, or actually reduced force output, but increased the rate of force development. As power, depends upon both force and velocity the effect on this variable will differ greatly with any kinetic changes on these variables. This supports the notion of Tillin and Bishop, (2009) that PAP is multifactorial, and its effects on performance will differ between individuals. This also supports the concept of Harrison, (2007) who suggests that the major influence of PAP on human performance is on stretch shorten cycle (SSC) performance rather than force output. Additionally, it also supports the decisions taken in these studies to focus on actual performance measures and not indicators of performance.

An analysis of each individual showed that the force power profile varied between pre and post squat performance for each individual, with a range of parameter changes. This suggests both individual kinematic profiles of jumps and also different kinematic profiles of
subsequent PAP. There was no uniform pattern of improvement/reduction in the jump profiles.

Discussion

Study four produced a number of key findings that have a major implication for the use of PAP based protocols in warm-up and for analysis of the mechanisms that produce PAP. Based on these results some important conclusions need to be drawn:

1) Squats do not elicit PAP on a group basis at any load. Where individual’s changes in performance are evident, these are not elicited at low loads. Of the loads measured only the 93% load had any alteration in performance, and this was non-significant on a whole group basis. Lower loads resulted in little change either positive or negative, either on a group basis or during individual analysis. If PAP squat based protocols are to be utilised then it is likely that loads need to be sufficiently high in order to stimulate PAP. Conversely, the greater the intensity of stimulus, the greater the potential for fatigue to develop, and the intra-complex rest interval therefore needs to be carefully selected.

2) PAP is highly individual, and needs to be evaluated on an individual basis if it is to be effectively utilised in warm-up or training. This variation seems greatest at higher loads, where it is likely that both potentiation and associated fatigue are more affected. The great variation in performance changes across individuals suggests that group based protocols may never be optimal, especially as the extent of fatiguing effects of PAP based protocols will be individual in nature and have the potential to negatively affect performance in some individuals. In this way, PAP based protocols, while potentially enhancing performance in some individuals, could indeed result in a deterioration of performance in others. It must be noted that if individualisation of protocols is to be attempted, this must only be carried out once a consistency of effect is demonstrated. Further research is necessary to determine this consistency.

3) While jump performance for the group demonstrating PAP improved, changes were inconsistent across the other variables (PP, PF or RFD), with only RFD showing a net improvement. This suggests that the kinematic profiles of enhanced performance
varies between individuals, and the individual nature of PAP may be related to the force/power profiles of specific performance. This is further emphasised by the fact that strength levels alone did not predict PAP enhancement. Given the delicate balance between potentiation and fatigue, and the complex interaction of factors that affect both performance and fatigue, it could be that PAP is not a single phenomenon, but instead is a balance between a number of neuro-muscular mechanisms which both potentiate and cause fatigue. If this is the case, then the individuality of PAP would seem logical. Additionally, it then becomes likely that PAP will be a context specific factor dependent upon the characteristics of the pre-conditioning activity, the characteristics of the individual (both fixed and temporal) and the characteristics of the subsequent activity. This would tie in with the conclusions of Tillin and Bishop, (2009) who attest to PAP being a multi-factorial phenomenon and suggest a context based relationship. Given this, the quest for fixed warm-up or complex training protocols utilising PAP protocols may be fatally flawed.

4) The results of this study emphasise that enhanced performance on a single profile of performance e.g. peak power does not necessarily infer improved performance. Some individuals demonstrated reductions in peak power with improvements in jump performance, others reductions in peak force with improvements in performance and vice versa. For coaches looking at performance enhancement, performance scores are far more relevant than individual profile scores. While scientific analysis can benefit from enhanced levels of data, these must not necessarily be extrapolated to infer performance changes.

5) Strength may not be the key determinant of whether or not an athlete is able to utilise PAP. Instead, it may be linked to the specific kinematic profiles of performance, and may be related to other neuromuscular factors such as SSC ability, motor co-ordination patterns etc. In this way, the ability to utilise PAP may be both genetic and learned, and related to the motor programs utilised when performing a movement. Jump profiles, for example, differ between individuals with each individual utilising a method that optimises their performance e.g. some athlete’s jump emphasising concentric force, using a slower SSC, while others utilise SSC
components with a jump profile where the amortisation phase is shorter (Turner and Jeffreys, 2010). The differing effects of PAP on these elements will confer differences in the potential of PAP to enhance performance.

6) Due to the kinematic patterns utilised, and their relationship to PAP, the ability to utilise PAP may not be general. Instead, it may be related to the movement pattern with athletes theoretically able to utilise PAP in one instance e.g. sprinting and not in another e.g. jumping. This would further add complexity to its application in warm-ups for performance enhancement. This again supports the conclusions of Tillin and Bishop, (2009) who suggest a mode and context specificity to PAP.

7) The mechanisms of PAP may not be a single mechanisms. While a number of different physiological mechanisms have been proposed, the hunt for a single cause may be flawed. Given the complexity of neuro-muscular activity, and the close relationship between potentiation and fatigue, it is highly likely that different mechanisms will determine the precise relationship between potentiation and fatigue. The possibility of different mechanisms contributing to PAP would help explain the great differences found between studies, and the lack of unequivocal data as to the type of athletes able to benefit from PAP.

This last conclusion dramatically changes the focus of physiological research into PAP, as the search may now need to focus on a number of contributory mechanisms, rather than on a single mechanism. In this way, the effects of PAP on performance are likely to be varied, and related to a large number of individual characteristics rather than on a single characteristic e.g. strength.

**Implications for future research.**

In order to maximise performance, future research needs to focus on identifying optimal application of PAP methodologies. The results of the current study indicates that PAP cannot be generated via squats. However when individual performance was analysed, the
results suggest that if PAP can be initiated, it may only occur with heavy loads and a number of issues still need to be addressed.

It is important to determine whether a single bout of activity is sufficient to elicit PAP or whether a series of bouts is needed. Given the conclusions drawn to date it is likely that this will be an individual feature, as while potentiation may increase so will associated fatigue, and again, all of the complex factors affecting PAP will need to be considered. Future research also needs to focus upon the consistency of any PAP effects within individuals, and determine any temporal changes in this effects.

Optimal intra-complex rest periods need to be determined to enable optimal application of PAP methodologies. This was the focus of study five.

As PAP seems to be context related, future studies need to reflect this. They need to investigate PAP as a whole phenomenon, and research design needs to integrate the conditioning activity, the protocol, the subject group and the subsequent activity. Additionally, based on the individual nature of PAP, further research needs to focus on identifying the characteristics of athletes who can benefit from PAP. This also needs to investigate any intra-individual fluctuations in the ability of PAP to enhance performance.

**Implications for coaching practice**

As the aim of these studies was to guide coaching practice, then it was important to relate the findings to such practice. The results of this study suggest that:

- These findings do not provide any evidence to support the use of PAP based protocols (including squatting) in group based warm-ups. If PAP is to be utilised on an individual basis, it is likely that heavy loads will need to be utilised.
- Some athletes may gain great benefit from PAP inducing squats, other athletes will show a decline in performance. If utilised, these protocols should be used on an individual basis and not in a team situation, and only when a consistency of effect has been demonstrated. Coaches need to determine these individual variations before integrating these activities in warm-up.
• Potentiation may not occur in all activities, and again the impact on performance such as sprinting, jumping needs to be evaluated on an individual basis. Coaches need to assess warm-up protocols on an activity by activity basis, and use data to evaluate the impact of these protocols. Only where data suggests that performance is consistently enhanced should the protocols be utilised on a regular basis.
STUDY FIVE - IDENTIFYING THE OPTIMAL REST INTERVAL FOR INDUCING PAP
IDENTIFYING THE OPTIMAL REST INTERVAL FOR INDUCING PAP

Abstract

Intra-complex rest interval, the time period between the application of a pre-conditioning activity and subsequent dynamic performance, is an important element in the construction of optimal PAP protocols. This study investigated the acute effects of squats (3 reps at 93% 1RM) on countermovement jump (CMJ) performance at three different intra complex rest intervals. Thirteen male trained subjects undertook a general warm-up followed by five 10 metre sprints of increasing intensity. They were subsequently tested for CMJ height after which they performed 3 repetitions of parallel squats at a load of 93% of 1RM. They were then retested for CMJ height, 2 minutes, 4 minutes and 8 minutes post squat. An analysis of Variance (ANOVA) with repeat measures showed no significant differences (p>0.05) between CMJ height at baseline (pre squat) (53.30 cm ± 11.02), 2 minute post squat (54.01 cm ± 10.17), 4 minute post squat (53.80 ± 10.25) and 8 minutes post squat (53.25 ± 10.97). When baseline scores were compared to maximum post squat scores, via a dependent t-test, no significant differences (P>0.05) were found. These results indicate that no optimal timeframe exists for PAP, as induced by heavy load back squats, and even when time is removed as a factor, heavy load squats did not produce a significant increase in CMJ performance. Their application to team warm-up protocols is not recommended.

Background to the problem

Following on from the determination of optimal loads, the second key question for coaches hoping to apply resistance-based PAP generating protocols in warm-up is the timescale of the PAP (Jeffreys, 2008b). Only when this is determined can the optimal rest interval between the strength stimulus and any subsequent peak performance be calculated. This rest period is termed the intra-complex rest interval (Jensen & Ebben, 2003), and is crucial if coaches wish to integrate potentiating activities into warm-up. Indeed, it may be that the timescale of PAP will determine whether or not it can be effectively incorporated into warm-up procedures. As well as the performance implications the timescale will also determine the logistical efficacy of utilising this methodology in pre performance
preparation. Therefore the determination of the timescale of PAP is crucial if the phenomenon is to be of any benefit to warm-up protocols.

As noted in the literature review the actual timescale of optimal PAP is a delicate trade-off between potentiation and fatigue, and as such, will be dependent upon a range of factors (Tillin and Bishop, 2009). The traditional view is that this time period should be minimal (Ebben & Watts, 1998) to maximise the heightened neural stimulation provided by the strength exercise (Comyns, 2006). This focuses on the peak potentiation side of the equation, and may make sense when potentiation is provided by a low intensity stimulus and where associated fatigue is low (Tillin and Bishop, 2009).

However, PAP appears to require a high intensity of stimulus (Chiu, et al., 2003) and given the complex interactions between potentiation and fatigue, this thinking could be flawed. While potentiation may peak immediately post exercise, accumulated fatigue may mask this effect on subsequent performance. Indeed, fatigue seems more dominant in the early stages of recovery, and consequently, performance at this time can be diminished (Tillin and Bishop, 2009). This train of thought has led to a number of rest periods being suggested.

Recommendations for rest periods between exercises within the complex pair range from 30 seconds to five minutes (Chu, 1996). Empirical research has investigated rest intervals of between 10 seconds (Jensen & Ebben, 2003) and 20 minutes (Jones & Lees, 2003). Empirical studies to date suggest that shorter rest periods (less than 4 minutes) may not be optimal, and that fatigue may mask any potentiation effects, although the results are equivocal. Jensen and Ebben, (2003) found non-significant improvements in performance following 5RM squats at 1, 2, 3 and 4 minutes, while performance at 10 seconds was non-significantly reduced. They concluded that short rest periods are less effective at enhancing performance than longer rest periods. This work supports the concept that potentiation and fatigue can co-exist, and that subsequent performance will depend upon the interaction between these factors. Jones and Lees (2003) found no significant performance changes at 3, 10 and 20 minutes post 5RM squats. However, the current equivocal nature of present studies is clear where Gilbert, et al., (2001) suggest that potentiation peaks at 20 minutes post-activity.
The practical application of PAP relies greatly on the timescale, and the current findings are ambiguous and do not provide the coach with the required degree of accuracy with which to develop optimal protocols. Study five was aimed at enhancing the knowledge in this area, allowing coaches to make more accurate decisions and build more effective warm-up protocols.

**Experimental approach to the problem**

This study looked at the effect of three different rest protocols on the effects of PAP, as measured by counter movement jump performance. The study was a randomised test-retest design, using three intra-complex rest intervals. PAP was measured via the change in counter-movement jump height, pre and post the PAP inducing activity. PAP was induced via the use of parallel squats of 3 repetitions at 93% of 1 RM. CMJ height was subsequently measured at four different rest intervals namely, 2 minutes, 4 minutes and 8 minutes. These were chosen to represent short, medium and long rest periods.

**Subjects**

13 male subjects gave informed consent to participate in the study and whose physical characteristics are outlined in table 3.5-1. All were competing athletes (rugby) with experience and proficiency in the back squat. Additionally, they were experienced in performance of countermovement jumps. This removed the learning effect on jump performance which could have occurred with inexperienced jumpers.

<table>
<thead>
<tr>
<th>Age (yrs)</th>
<th>Height (m)</th>
<th>Weight (kg)</th>
<th>1 RM (kgs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>18.8 ± 0.7</td>
<td>1.82 ± 4</td>
<td>80.9 ±9.5</td>
<td>138 ± 25</td>
</tr>
</tbody>
</table>

*Table 3.5-1: Physical characteristics of the participants*

**Instrumentation**

Countermovement jumps were performed on a contact mat ("Just Jump" - Probiotics, Huntsville Alabama), with jump height being calculated from flight time using the formula:
Jump height = $9.81 \text{ m/s}^2 \times \text{flight time(s)}^2/8$). The formula is based upon the assumption that the time spent in the jump phase is the same as that spent during the return back to the mat from the position of maximal vertical displacement (Rixon, et al., 2007).

**Test procedures**

Testing took place over two sessions one week apart. All subjects had undertaken an initial session to determine each subject’s 1RM for the back squat. Each back squat was taken to a thighs parallel position (Baechle, et al., 2008), with the subjects 1 RM being determined using the procedures outlined by Baechle, et al., (2008).

All sessions were preceded by a standardised warm-up which consisted of 3 minutes of skipping to provide for a general raise in body temperature followed by five dynamic stretches (Inch worm, lunge with diagonal rotation, lateral lunge, free squat and calf walk with shoulder rotation (Jeffreys 2007). This was then followed by a series of five 10 metre sprints of increasing intensity, until sprints 4 and 5 were of maximum intensity. This ensured a potentiation phase was included in response to the findings of study one.

The warm-up on each day was then followed by three countermovement jump trials, with the best score recorded and used for data analysis. This provided the baseline figure against which the effects of PAP were measured.

The group then performed a squat warm-up consisting of three repetitions at 50 % and 70 % of 1 RM. All participants then undertook a set of 3 repetitions of the squat at 93% of 1RM. Further CMJ were measured, 2 minutes, 4 minutes, and 8 minutes post squat. The best score of two trials at each time interval was recorded.

**Statistical Analysis**

Power calculations were carried out prior to the study. To achieve a power of 80%, with a maximal rate of error of 20% (unlikely) and a typical error score of 0.7, and utilising a 95% confidence limit, (Hopkins, 2006) the number of subjects required to achieve power was 13. The study therefore achieved the statistical power required to minimise the likelihood of a type II error.
Statistical analysis was carried out via SPSS Version 15 (SPSS Inc Chicago Ill). Tests of normal distribution (Kolmogorov-Smirnov and Levene’s) were conducted on all data prior to analysis. On assumption of normality, CMJ scores from the four time periods protocols were compared via a 1 x 4 repeated measures ANOVA, comparing each athletes CMJ scores across the four time intervals. This was the same analysis as carried out by Burkett, et al., (2005). Statistical significance was set at p<0.05.

As individuals may differ in terms of the time duration for PAP, a further analysis was carried out between the baseline score and the peak post squat jump performance. A dependent t test was used to compare pre test scores with peak post potentiation scores. Statistical significance was set at p<0.05.

Results and Analysis

The CMJ scores for each time period are presented in Fig 3.5-1.

![CMJ height baseline and 2,4, & 8 minutes post squat](image)

Fig 3.5-1 CMJ scores at baseline and post squat at 2,4 and 8 minutes.
Analysis of Variance demonstrated no significant (p>0.05) differences between the jump scores at any time of measurement baseline, 2 minutes, 4 minutes or 8 minutes. This indicates that no single timescale results in a change of CMJ performance from baseline scores. The results show that heavy squats do not enhance CMJ height at any of the measured timescales.

In terms of an analysis between baseline scores and maximal score (Fig 3.5-2), while the mean increase was larger than for any single time frame, this change was not significant (p>0.05), and therefore no change in performance was recorded.

![Baseline and Maximum CMJ height - Pre and post squat](image)

**Fig 3.5-2 Analysis of baseline score and peak post score**

Analysis of the raw data

In terms of analysis of the individual data, there was no consistent pattern, with maximum performance occurring at all intra-complex rest intervals, but with 2 and 4 minutes proving the most efficacious time frame for the majority of individuals (83.6%). There was similarly no regular temporal pattern, with some individuals showing potentiation across all time frames, others no potentiation across all time frames, some early potentiators, some late potentiators and others who only potentiated at one given rest interval.
When the raw data was analysed irrespective of time, the highest degree of improvement occurred at 2 minutes, followed by 4 minutes. Performance showed a slight decrease at eight minutes, suggesting that any possible potentiating benefit had dissipated by this time.

Discussion

In terms of determining the optimal time frame, there were no significant differences between any scores. In this way, no potentiation was evident at any of the different intra-complex rest intervals. This suggests that potentiation is not produced via the completion of heavy squats (93% 1RM) and that, even where individual athletes demonstrate PAP, no one timeframe is optimal to elicit potentiation across a group of athletes. This has considerable implications for warm-up in team sports, where due to logistical issues it would be likely that a single time frame would need to be applied. This further supports the notion that PAP is a multi-factorial phenomenon, and will depend upon a range of factors including subject characteristics (Tillin and Bishop 2009)

A study of the raw data demonstrated that for some individuals, potentiation occurred at 2 minutes and 4 minutes post squat, while performance deteriorated below baseline at 8 minutes, although it must be remembered that all of these differences were insignificant on a group basis. The greatest potentiation occurred at 2 minutes post squat, suggesting that this time frame may be the intra-complex rest period that optimises performance within this group of athletes, this contradicts Jensen and Ebben, (2003) who suggest that at least four minutes is required to elicit performance potentiation. However, all changes were insignificant and relatively small, indicating that PAP is not present in this group of athletes. The differences between the optimal timeframes of potentiation for different individuals means that in team sport settings, the utilisation of PAP procedures prior to performance is fraught with complications which could even have negative effects on performance if the incorrect timescale is selected.

However, while mean performance changes were insignificant, the range of performance changes was from a decline of 5.5 cm to an increase of 4.25 cm, which could have an effect on guiding coaching practice, and warrants investigations based on the smallest worthwhile change in performance score of 0.79 cm. At the reduction end, a reduced performance of
5.5 cm is a large performance decrement, and this has implications where complex training methodologies are used with athletes, or where group warm-ups are developed. These results suggest that all PAP methodologies must be evaluated on an individual basis, and cannot be applied in group settings. However, where complex training methodologies are utilised this is often carried out in a group context. Where these are used with athletes, it is likely that these will have positive effects, negative effects and no effects on different individuals within the group.

Similarly, on the performance enhancement side, an increase of 4.25 cm is a large performance increase, and must be evaluated on a performance basis as well as a statistical basis. In situations where jump performances are important (e.g. combines) this level of increase can be important for an athlete. In this way, warm-up procedures need to be investigated on an individual basis. In terms of utilising PAP inducing methodologies for athletes, this should only be attempted by those who are consistently able to utilise this phenomenon, and should not be used across all athletes. In this way their application to team sports would appear to be very limited.

Analysis of the optimal timescale for optimal potentiation for each individual demonstrated, 6 athletes peaked at two minutes, 4 at four minutes and 3 at eight minutes, while two athletes demonstrated a drop in performance post squat. For the two athletes who demonstrated a drop in performance, this was found at all time periods. This demonstrates that optimal intra-complex rest period, if it exists, is likely to be highly individual, and indeed may have a temporal variance. This likely relates to the complex interaction of potentiation mechanisms and fatigue mechanisms, and that, as these co-exist, the relative impact of each will change over time. These are likely to be related not only to the type of potentiating activity, but additionally the unique physiological characteristics of the athlete including the accumulated fatigue an athlete experiences. In this way, the extent of PAP, and the athlete’s ability to utilise the phenomenon may change across various phases of the annual macrocycle, as well as varying with the type of pre-conditioning activity and the type of subsequent activity.

Another interesting finding was that the lowest changes in performance were found after eight minutes. This is in contrast to the findings of Gilbert, et al., (2001) who suggest that
potentiation peaks after 20 minutes. Given the logistics of utilising PAP in warm-ups, and the likelihood that if heavy resistance training is to be used, these activities will have to be carried out before the final skill and tactical elements of team preparation, then if potentiation dissipates after 8 minutes, then these methodologies are likely to offer little advantage in competitive situations and therefore are of limited value to warm-ups in the training environment. It is imperative to note here that even if a physiological phenomenon does exist, it is foolhardy to pursue it if it cannot be effectively integrated into coaching practice. The strength and conditioning professional needs to take a multidimensional approach to the problem, and not necessarily chase one phenomenon at the expense of other factors (Jeffreys, 2008b).

When PAP was looked at across all time ranges there was a non significant change of 2.09 cm ±2.68, (p>0.05). This supports Comyns, (2006) conclusion as to the individual timeframe of PAP. Again re-emphasising the above point, the logistical complexities of designing PAP based warm-ups for groups of athletes may be flawed, and based on this evidence the coach simply needs to ensure a potentiation phase is included in the warm-up without recourse to additional PAP inducing activities.

However, if this individuality of PAP is the case, then it causes a problem in evaluating previous research into PAP. Any study that utilised a single intra-complex rest period may not have accurately reported the full extent of PAP, as the timescale chosen could never be optimal for each athlete. Thus, conclusions drawn as to the lack of evidence for PAP, rather than not finding PAP via the mechanisms utilised, may simply not have identified PAP at the timescale chosen. In this way, previous studies need to be revisited and re-evaluated in terms of their ability to prove/disprove the existence of PAP.

**Future research.**

Future research needs to integrate the application of optimal loads against optimal time frames, and in relation to the subsequent activity. In other words, research needs to be protocol specific. These designs need to ensure that conditioning activity, volume and recovery and subsequent activity need to be assessed together (Tillin and Bishop, 2009)
Previous research may need to be re-evaluated against the variable timeframe effects of PAP. It is likely that research into optimal loads that only utilised a single timeframe may have failed to identify PAP, not because it doesn’t exist, but simply due to the fact that it was not present at the time of subsequent testing. However, even where PAP is evident, if the dependent variable did not reflect sports performance, conclusions cannot be extrapolated to performance. However, this does need to be balanced against the flaws in many of the research designs highlighted in the reviews.

To fully address the individuality issue, additional research needs to be carried out to identify causes for the individualisation of PAP, and to identify the characteristics of athletes who are likely to benefit from PAP against those who are not likely to demonstrate PAP.

Future research also needs to look at the repeatability of the scores. While this type of study looked at PAP as a uniform phenomenon, if work is to be carried out at individualising warm-up routines, then the repeatability of the phenomenon needs to be investigated. Key questions need to focus on whether or not a degree of adaptation to the phenomenon occurs, and whether or not the phenomenon is always optimised at the same loads and rest periods. Given that fatigue and PAP co-exist, and are affected by prior contractile activity, then these may not be consistent effects. The degree of fatigue will be influenced by the accumulated training load (Jeffreys, 2008c), and not solely by the pre contractile fatigue. In this way, the optimal PAP inducing capacity may vary over time and excessive time spent individualising warm-up routines may not be warranted.

**Implications for coaching practice**

To further complicate the fact that the existence of PAP is highly individual in terms of optimal loading, then similarly optimal rest periods are also highly individual. If PAP mechanisms elicited from heavy resistance training are to be utilised in warm-ups, optimal application will require the utilisation of optimal timeframes for each and every athlete. They may not be logistically feasible given the range of timeframes found in the present study 2 minute to 8 minutes, and in previous studies where timescales of up to 20 minutes are recommended (Gilbert et al., 2001). Even if this is established, there is no evidence as to
the consistency of response. Until consistency can be established in individual response, the application of PAP to warm-up cannot be recommended, even on an individual basis.

If PAP is to be utilised in warm-up, then it is likely to be more easily assimilated into warm-ups for individual sports rather than team sports, where specific protocols can be set up for each individual athlete. This will require the identification of optimal PAP inducing protocols, in regards to loads, methodologies and intra-complex rest periods for each individual. This identification of optimal PAP protocols will assist in the development of individual optimising warm-up procedures. These would need to be set up in relation to additional research into the temporal variability of PAP across a competitive season. However, this again is subject to the establishment of a consistent response.

If PAP is to be optimally utilised into complex training methodologies, then sessions will need to be individualised to ensure that intra-complex time rest periods are optimal for each athlete. Again, this is likely to be logistically more feasible when small groups of athletes are involved. At all times where complex methodologies are utilised, the benefits to be gained from utilising complex pairings need to be evaluated against the logistical issues involved in the complex time frame, and its effect on volume load per session. Where long intra-complex rest periods need to be utilised, the requirements for optimising PAP may be outweighed by the effect on total work performed in the session. In these situations while jump performance may be enhanced, the volume of work carried out in the session may become so low that other key training aims may be compromised. It would appear that application of PAP into training modalities will also need to be evaluated on a cost benefit analysis, an analysis which needs to be done on an individual basis. Where generalisations in application are advised, these need to be seriously questioned.
STUDY SIX - THE ACUTE EFFECTS OF HEAVY SQUATTING AND MAXIMAL VOLUNTARY CONTRACTIONS ON RUNNING SPEED
THE ACUTE EFFECTS OF HEAVY SQUATTING AND MAXIMAL VOLUNTARY CONTRACTIONS ON RUNNING SPEED

Abstract

Running speed is fundamental to elite performance in the majority of team sports, and warm-up protocols that can maximise running speed warrant investigation. The present study investigated the effects of heavy parallel squats (3 repetitions at 93% 1RM) and Maximal Voluntary Contractions (3 MVC's of 3 seconds) in a parallel squat position on 10 metre sprint performance. 35 male trained subjects were tested for 10 metre sprint performance and then randomly allocated to one of two groups, squat protocol (S) n =17, MVC protocol (MVC) n = 18. The squat protocol carried out one set of squats for 3 repetitions at 93% of 1 RM. The MVC group carried out 3 maximal 3 second isometric contractions in a parallel squat position. Following each protocol 10 metre sprint performance was measured and the changes in performance compared across all groups. An ANOVA with repeat measures found no significant differences (p>0.05) in performance pre and post intervention between groups, demonstrating that no protocol resulted in significantly different performance.. These results demonstrate that neither MVC's nor squats are able to enhance running speed over 10 metres, and their use in warm-up procedures cannot be recommended.

Background to the problem

Running speed is generally accepted to be a major determinant of performance levels in a large number of team sports (Dintiman and Ward, 2003 ), and is a key in the testing and selection processes of many team sports (Plisk, 2008). Therefore, any warm-up protocol that could acutely enhance running speed has the potential to improve sports performance directly, and could also enhance performance in testing situations where performance on the test is a crucial selection indicator e.g. the NFL combine. As players in team sports will often have to display high running speeds from the onset of performance, any warm-up protocol that can directly enhance this has the capacity to improve performance, and could be a major contributor to team success. Teams able to display maximum speed immediately may be able to capitalise on scoring opportunities or make critical defensive plays that
prevent opponents from scoring. In this way, results of games can be directly affected by warm-up procedures, whereby speed is maximised from the onset of play.

Running speed is determined by the product of running stride length and running stride cadence (Plisk, 2008; Weyand, et al., 2000), with effective stride length (through the production of ground forces) being the major factor (Weyand, et al., 2000). Stride length is largely dependent upon the power characteristics of the hip and knee extensor muscles (Weyand, et al., 2000; Ozolin, 1986), and, being power based, could theoretically be influenced by PAP. However, despite this logic, while PAP has previously been demonstrated to provide an increase in power performance (normally jump performance) its effects on running speed has only recently started to be researched (Till and Cooke, 2009; Yetter and Moir, 2008; Chatzopoulis, et al., 2007; McBride, et al., 2005). With speed playing such an important role in sport, then mechanisms by which it could potentially be improved need to be investigated.

Despite the potential for improved speed performance through the utilisation of PAP, only four previous studies have investigated this phenomenon. McBride, et al., (2005) investigated the effects of three sets of squats at 90% IRM on running speed at 0-10 metres and 30-40 metres. These distances reflected initial acceleration which is largely dependent upon strength characteristics of the major extensor muscles (Ozolin, 1986), and late acceleration/maximum speed which is more dependent upon the stretch shorten cycle characteristics of the major extensor muscles of the lower body (Ozolin, 1986). McBride, et al., (2005) used a five minute rest interval and found no improvement in performance between 0-10 metres but a significant improvement at 30-40 metres. This suggests that PAP could have a greater effect on SSC characteristics than strength based characteristics. However, McBride, et al., (2005) suggest that a more intense pre activation protocol may have the capacity to enhance acceleration performance. It is important to note that the pre testing warm up protocol was of a general nature and, based on the findings of study one may not have optimally prepared athletes for subsequent performance.

Chatzopoulis, et al., (2007) investigated the effects of 10 sets of 1 repetition on running speed at 0-10 metres and 0-30 metres. Using fifteen trained sportsmen (basketball, volleyball, handball and soccer) they found no improvement in performance after three
minutes recovery, but significant improvements at both distances after five minutes recovery. This is likely due to the volume of pre-conditioning activity, and the associated requirement for fatigue dissipation. While this does demonstrate the potential for enhanced running performance via PAP, the protocol used in the Chatzopoulis, et al., (2007) study would be very difficult to integrate into an effective warm-up procedure in team sports. The time required for completion of 10 single repetitions at 90%1RM would make the protocol totally unrealistic in team sport environments, both on a logistical and a compliance basis. Again, the use of a general warm-up protocol prior to the initial testing, questions the findings of the study, potentially suppressing pre-application performance.

Yetter and Moir, (2008) found significant improvements in the 10-20 metre section of a 40 metre sprint following back squats, but not front squats. Again, supporting the variations found in the results of other studies, no differences were found at the final 20 m section of a 40 metre sprint. This suggests that there may be differences in the potentiation potential of differing exercises, and that potentiation can affect different aspects of speed performance to varying degrees. Again the flaws in the study highlighted in the review mean that the results need to be treated with caution.

Smith, et al., (2001) also postulated that PAP may be able to increase running speed, following their findings of enhanced 10 second sprint cycling performance following 10 x 1 repetition 1RM back squats. However as there is no direct correlation between running speed and cycling speed, then these suggestions have to be treated with caution. Till and Cooke, (2009) found no changes in sprint performance (10 and 20 metres) following three different potentiating activities (1 x 5RM deadlift, 5 tuck jumps and MVC’s (3 repetitions for 3 seconds) on a leg extension.

Previous studies have suggested that PAP can be elicited via the use of maximal voluntary contractions (Sale, 2002), but, no work has been carried out into its ability to enhance running performance. As the key aim of this series of papers is to enable coaches to utilise effective warm-up protocols, then MVC’s may provide for a more easily assimilated protocol than heavy squats. Utilising MVC’s would remove the requirements of varying loads and as muscular contractions are isometric, then less emphasis would need to be placed on technique that is imperative when working through the range of movement required in a
isotonic based squat. However, it needs to be noted that isometric contractions may differ in their potential to induce PAP and indeed on the mechanisms by which they potentially enhance performance (Tillin and Bishop, 2009). This can result in differences in subsequent performance (Rixon, et al., 2007), whereby some elements of performance can be enhanced by isometric contractions and not by dynamic contractions and vice versa, although the evidence of this is inconclusive (Rixon, et al., 2007). Differences in fatigue responses have been previously reported, and it is fair to assume that they might also have different effects on the mechanisms of PAP (Tillin and Bishop, 2009). Early fatigue during dynamic contractions is primarily peripheral in nature, (failure of muscle contraction mechanisms) with central fatigue (reduction in neural drive) developing later; while for isometric protocols the reverse is the case (Babault, et al., 2006). This is postulated to be due to dynamic contractions facilitating blood flow, aiding the removal of metabolites, and their effect of muscle force production capabilities (Babault, et al., 2006).

Study six aimed to examine whether running speed could be enhanced by the use of either heavy squats or maximal voluntary contractions, both of which have previously been demonstrated to be able to increase subsequent power output (Sale, 2002). The study utilised single applications of the exercises to ensure that any protocols utilised in the research could effectively be integrated into warm-up procedures.

This study aimed to answer the following key questions

1. Can sprint performance be acutely enhanced by the performance of squats

2. Can sprint performance be enhanced by the performance of MVC's

Experimental approach to the problem

The study was a randomised pre test/post test protocol, with speed performance over 10 metres measured pre and post a squat or MVC. Subjects were randomly assigned to either a squat group or a MVC group. All athletes were tested indoors for speed on a 10 metre sprint. The indoor protocol allowed for the removal of external influences such as wind, a wet track, temperature etc, which would affect performance measures (Harman and
Garhammer, 2008). Additionally, given that power performance is most likely to be enhanced by PAP (Sale 2002), the ten metre distance is more likely to be affected by PAP, as longer distances are more affected by stretch shorten cycle performance (Ozolin 1986). Similarly, as most sprints in sports are short, and in the order of ten metres it was a very sport specific measure of performance, that relates to a host of team sports, and to the playing positions within that sport.

Testing took place over two days separated by a week. The initial session aimed at determining each subject’s 1RM for the back squat. Each back squat was taken to a thighs parallel position (Baechle, et al., 2008). Following the warm-up, subjects performed a squat specific warm up consisting of three repetitions at 40 and 50 % of 1 RM, and one repetition at 70% (with three minutes recovery between each set) prior to choosing an appropriate weight for their maximum test. They then performed a maximal number of repetitions with this weight, with the subjects 1 RM being determined using the tables outlined by Baechle, et al., (2008). Thighs parallel position was determined via the use of a goniometer set against the tibia. This was measured utilising a light load, but with the athlete utilising the same technique as for heavier loads. To indicate the position to athletes during performance, elastic bands were set across a power rack (Bodysolid USA) for each athlete to indicate the thighs parallel position for 1RM testing and for the subsequent application sessions.

This was determined for each athlete using a goniometer based upon the angle of the femur to the floor. The MVC's were elicited via the use of a Smith machine set to allow MVC's to be produced at a thighs parallel position for each athlete, as determined by a goniometer set against femur angle. A protocol of 3 repetitions of 3 seconds duration was chosen, as this had both been demonstrated as efficacious in eliciting PAP previously (French, et al. 2003), and it also equated to the load of 3 repetitions used in the squat where a 2 and 1 cadence was used (i.e. 2 seconds to lower the bar and 1 second to raise the bar). An intracomplex rest interval of 4 minutes was allowed between both the performance of the squat or MVC and the sprint retest as this has been shown to allow for the expression of PAP previously (Jensen and Ebben, 2003).
**Subjects**

35 male subjects gave informed consent to participate in the study, and whose physical characteristics are outlined in table 3.6-1. All were competing athletes in Division 1 College sports (rugby n = 17 and football n = 18). All were participating in a formal strength and conditioning programme for at least 18 months, and this involved both strength and speed training. All were experienced in the squat and sprint activities, removing any potential learning effects. Each athlete had been tested for both maximum squat and speed previously on at least four previous occasions for the squat and six for the speed.

<table>
<thead>
<tr>
<th>Age (yrs)</th>
<th>Height (cm)</th>
<th>Weight (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>18.6 ± 0.7</td>
<td>179 ± 8</td>
<td>71.3 ±12.6</td>
</tr>
</tbody>
</table>

*Table 3.6-1: Physical characteristics of the participants*

**Instrumentation**

Speed scores were measured on a Newtest Powertimer (Newtest Oy, Oulu Finland). This consisted of a start pad and an infra-red gate (IP 40 - photocells IP 67), placed 10 metres from the start line. The photocells had a sensing range of 0.2 - 2 metres, and the system as a whole a reported accuracy of 0.001 seconds, and allowed times to be recorded to the nearest hundredth of a second. The light cells were laid out as per the protocol recommended by Yeadon et al (1999). Squats were performed in a power rack (Bodysolid USA, Forest Park, IL) utilising an olympic weightlifting set (Werksan USA). MVC's were performed on a Smith Machine (Bodysolid USA, Forest Park, IL.) with the bar set at a position corresponding to the athlete's thighs parallel position.

**Test procedures**

Testing took place over two sessions, each preceded by a standard warm up which consisted of 5 minutes of movement of increasing intensity to provide for a general raise in body temperature, followed by five dynamic stretches (Inch worm, lunge with diagonal rotation, lateral lunge, free squat and calf walk with shoulder rotation (Jeffreys, 2007a, 211)}
Verstegen, 2004). This was then followed by a series of five 10 metre sprints of increasing intensity, until set five was a maximum effort sprint.

Session 1 involved a series of squats at increasing weights to determine 1RM. This was estimated from a final set where athletes chose a resistance that they could lift for 1-5 repetitions. 1RM was then calculated from the conversion tables in Baechle, et al., (2008).

Session 2 involved the same standard warm up, except that after the sprint activities, all athletes then performed three timed sprints of 10 metres, with the best score recorded as the baseline score.

For the timed sprint, subjects placed their lead hand on a start pad, which was placed on the start line. Using a self start system, the timing started when the hand released pressure on the start pad. Using the start pad removed the variations in performance which can be caused by differing start protocols (Duthie, et al., 2006b). The timing was stopped when the athlete broke a beam at the finish gate. The self start system removed the influence of reaction time, and thus directly measured running speed. Subsequent to the sprint, the athletes were randomly allocated into two groups, the squat group (n = 17) and the MVC group (n = 18).

Subsequent to the initial speed test, the squat group performed a squat specific warm up of a set of 2 repetitions at 50 and 70% of 1 RM. They then performed a squat of three repetitions at 93% of their previously measured 1RM. The MVC group performed 2 sets of 2 repetitions of submaximal isometric contractions of 2 seconds durations, at increasing intensity, followed by a set of 3 MVC’s of 3 seconds duration. This 3 repetition protocol aimed to equate the work volume of the MVC and squat groups, as the average time for the performance of each squat was previously determined at 3.1 seconds (± 0.72). (Both groups then performed three further 10 metre tests, with the best score recorded as the post application score. The first sprint was timed at 4 minutes subsequent to the potentiating activity, with each subsequent sprint two minutes apart.
Statistical Analysis

Power calculations were carried out prior to the study and to achieve a power of 80%, with a maximal rate of error of 20% (unlikely) and a typical error score of 0.8, and utilising a 95% confidence limit, (Hopkins, 2006) the number of subjects required to achieve power was 19 (N=19). The study therefore achieved the statistical power required to minimise the likelihood of a type II error.

Statistical analysis was carried out on SPSS version 15. Tests of normal distribution (Kolmogorov-Smirnov and Levene’s) were conducted on all data prior to analysis. On assumption of normality, baseline scores were compared to the scores after the activity. Pre and post application scores were compared via an analysis of variance (ANOVA) with repeat measures as used by Baker (2003).

Results and Analysis.

The sprint score results for the squat and MVC group are shown in Fig 3.6-1.

![10 metre sprint times pre and post squat and MVC](image)

*Fig 3.6-1 10 metre sprint times pre and post squat and MVC*
The results of an AVOVA with repeat measures on the scores pre and post application for both groups, demonstrated that no significant differences (P>0.05) exist between all scores. In this way MVC’s or squats offer no sprint performance benefits over that achievable with a standard sprint warm-up.

Analysis of the raw data

While no statistical differences were found, it is useful to analyse the raw data, as trends may emerge which can inform coaching practice and/or guide future research. It must be noted however, that no statistical differences were found and therefore no changes were found in performance on a group basis.

An analysis of the raw data demonstrates that in the squat group, 5 athletes showed a performance increase, the largest of which was -0.18 seconds, 10 showed a performance deterioration the largest of which was 0.12 seconds, while 2 showed no change in performance. For the MVC group, 10 athletes showed a performance gain, the largest of which was -0.07 seconds, 5 showed a performance deterioration, the largest of which was 0.08 seconds, while 3 showed no change. In this way the MVC methodology showed an improvement in the largest number of athletes but this was of a very small amount. The squat methodology showed the greatest single gain -0.18 seconds, but was only able to improve performance in a very small number of subjects. However, given the extent of gain compared to the smallest worthwhile change in performance of 0.03 seconds, this method may be the protocol that warrants further investigation. Again, this demonstrates the highly individual nature of PAP, and the massive challenge a coach would have in attempting to integrate these methodologies into team sport warm up procedures.

Given the very small increases in performance through MVC’s this would not appear to be a suitable method of eliciting PAP to enhance running performance. Any changes were of such small magnitude that these could not be differentiated from error scores. Given the logistical factors required to incorporate this methodology in warm-up the limited potential for enhancement make this method redundant.
**Discussion**

The results of the present study clearly show that speed performance over 10 metres is not acutely enhanced via the performance of either resisted squats or MVC’s. This supports the findings of Till and Cooke, 2009; Yetter and Moir 2008; Chatzapoulis, et al., 2007 and McBride, et al., 2005, none of whom found significant improvements in performance in 10 metre running speed. Thus, it would appear that initial acceleration, which is the critical speed factor for performance in the majority of team sports (Jeffreys, 2009; Plisk, 2008), is not impacted by PAP methodologies. Where improvements have been found previously (Yetter and Moir, 2008; Chatzapoulis, et al., 2007; McBride, et al., 2005), these have been found at longer distances, and may reflect a greater impact on SSC performance rather than initial acceleration with its greater dependence on concentric force production (Plisk, 2008; Ozolin, 1976). While this study would question the use of these methods in team sports, the fact that longer distance speed may be positively affected by PAP may offer potential application in sports or specific positions where these capacities are important. This opens the opportunity for more research in this area.

**Implications for future research.**

While no methodology achieved statistical significance, the capacity for squat protocols to increase performance in certain individuals may warrant further investigation, given the results of previous studies suggesting its capacity to enhance speed over longer distances. This needs to involve the following areas:

- Determination of the individual factors that may allow certain individuals to benefit from PAP in terms of running speed. This will need to involve investigations across gender, strength levels, training status, and the role of SSC performance in determining the propensity of individuals to utilise PAP.

- As previous methodologies that demonstrated improved speed following PAP based applications (Yetter and Moir, 2008; Chatzapoulis, et al., 2007; McBride, et al., 2005) utilised multiple rather than single sets, future research needs to focus on the accumulation of PAP stimulus, rather than single dose stimulus. However, this must
also come with the proviso that a greater volume of activity will induce greater fatigue, which may affect both PAP, and overall fatigue in the coming activity. Additionally, greater application numbers produce logistical challenges, especially in a team based scenario.

- Future studies need to investigate the role of PAP on performance over longer distances, where its effect on SSC performance may be more marked. However, the power of this to impact performance must come with a proviso, namely that speed over the distance measured must be an important indicator of performance in the sports measured. For example while 40 metre speed may be improved, this would have no benefit for sports such as basketball, tennis, badminton netball etc where court restrictions limit running distances. Similarly, even in field sports, its application may be limited to positions which utilise this type of distance, as the majority of distances run are shorter in these sports.

**Implications for coaching practice.**

The results of the present study suggest that the performance of squats or MVC’s during warm-up present no additional benefits over a well structured general and sprint potentiated warm-up. Given the logistical challenges that incorporating these methodologies provide, and the mixed performance effects on different individuals, the results of the present study suggest that coaches should not employ these methods in the warm-ups for team sports.

The squat methodology would seem to confer greater potential benefits to certain individuals than the MVC methodology. However, this methodology also has the greatest potential for performance decrements post application. If this is to be employed it needs to be employed on an individual basis, with individual investigation into the application of optimal loads, optimal loading protocols, optimal intra complex rest intervals together with investigation into the consistency of performance.

Where sprint training is incorporated into resistance training within the same session, care has to be taken to ensure that sprint performance is not negatively affected by previously
performed resistance work. Again, to add confusion to the scenario, this is likely to happen at an individual level.
CHAPTER FOUR - REALISATION OF AIMS
REALISATION OF AIMS

**Study One**
Study one investigated whether the inclusion of a potentiation phase in a warm-up enhances running performance over and above that achievable with a general warm-up alone, and secondly whether there is a specificity element involved with this potentiation.

**Study two**
Study two aimed to ascertain whether resisted or assisted running could acutely enhance running speed, and whether any running speed enhancement was over and above that achieved via maximal speed running.

**Study three**
Study three investigated whether the performance of loaded countermovement jumps could enhance jump performance, and whether this performance increase is greater than that achieved with maximal intensity unloaded CMJ.

**Study four**
Study four investigated whether jump height could be enhanced via the use of heavy squats, and determined which loads optimised this effect.

**Study five**
Study five aimed to elucidate whether PAP was a time dependent mechanism and whether an optimal time period existed at which time performance was optimally enhanced.

**Study six**
Study six investigated whether sprint performance could be acutely enhanced by the performance of squats or maximal voluntary contractions. It also considered whether either of the methods conveyed superior results in acute speed enhancement.

Examination of the Research Questions

The following section will examine the research question associated with each experiment, and draw final conclusions on each.
Study One

This study investigated the application of three different warm-up procedures on sprint performance. 35 male subjects undertook, three different warm up procedures, general warm-up (G), sprint potentiated warm up (SP) and jump potentiated warm-up (JP), after which they were tested for running speed over 10 metres. General warm-up consisted of 5 minutes of movement followed by four dynamic stretches, SP warm-up consisted of the general warm up but with five additional 10 metres sprints, while the JP warm up consisted of the general warm-up followed by 5 sets of 3 vertical jumps. Warm-ups were randomly allocated on three non consecutive days. Mean 10 metres times for the G group was 1.99 ± 0.10, for the JP group 1.93 ± 0.08 and for the SP group 1.88 ± 0.08. Repeated measures ANOVA demonstrated significant differences between groups (p<0.05) whilst Tukey’s HSD demonstrated that these differences extended across all groups. The results demonstrate that a general warm-up may not fully prepare athletes for sprint performance, and that a specificity of potentiation effect may exist with sprint activities more effectively preparing athletes for sprint performance than jump activities.

Study Two

This study investigated the acute effects on running speed of sprint resisted, and sprint assisted running in the warm up of collegiate athletes. 59 male subjects were randomly allocated to one of three warm up groups, a sprint assisted group (SA) n = 30 sprint resisted group (SR) n = 21, and a sprint potentiated group (SP) n = 8. All athletes undertook a general warm up consisting of five minutes of movement followed by four dynamic stretches, and followed by five 10 metre sprints of increasing intensity. They were then tested on a ten metre sprint test. The SR group then undertook two 10 metre resisted sprints against a resistance 10% of bodyweight; the SA group undertook two assisted sprints of 10 metres, while the SP group undertook two 10 metre sprints. All groups were then retested on their 10 metre speed, and the changes in performance recorded. ANOVA with repeated measures showed no significant differences (p>0.05) between performance pre and post all applications. This study concludes that the addition of sprint resisted or sprint assisted
methods in the warm-up of athletes offers no additional benefit from that achievable with traditional high speed running.

**Study Three**

This study investigated the acute effects of loaded jump performance on subsequent jump performance. 25 male subjects, all competitive athletes, were randomly allocated into one of two groups a weighted jump potentiated group (WJ) n = 15 or a jump potentiated group that acted as a control (C) n = 10. All athletes undertook a general warm-up consisting of five minutes of movement followed by five dynamic stretches after which they carried out five 10 metre sprints of increasing intensity. They were then tested for counter-movement jump height (CMJ) using a Just Jump contact mat. Following this, the WJ group performed two resisted jumps with a weight of 10% of bodyweight, while the C group undertook a further two un-resisted jumps. CMJ height was retested 1 minute and 4 minutes subsequent to the last jump, and the change in performance recorded. ANOVA with repeat measures showed no significant difference (p>0.05) between the groups at either baseline, 1 minute or 4 minutes post application. This study concludes that the application of resisted jumps offers no advantage over un-resisted jumps in potentiating performance, and based on this evidence, their use in contract training methodologies needs to be questioned.

**Study Four**

This study looked at the effects of three different loads on subsequent jump height. 14 male subjects participated in the study and 1RM was determined for each. On three separate testing days, each subject undertook a general and sprint potentiated warm-up followed by three trials of a CMJ, with maximum height recorded (JH), along with peak power (PP), peak force (PF) and rate of force development (RFD). They were then randomly allocated three different squats loads on three non consecutive days 60% 1RM, 80% 1RM and 93% 1RM. 4 minutes subsequent to the performance of the squat, CMJ height was measured. ANOVA with repeated measures on CMJ height showed no significant differences between pre and post performance across all groups. Similarly ANOVA with repeated
measures on RFD, PP, and PF for the 93 group showed no difference pre and post squat. This study concludes that squatting has no affect on CMJ performance regardless of the load utilised.

**Study five**

Intra-complex rest interval, the time period between the application of a pre-conditioning activity and subsequent dynamic performance, is a critical element in the construction of optimal PAP protocols. This study investigated the acute effects of squats (3 reps at 93% 1RM) on countermovement jump (CMJ) performance at three different intra complex rest intervals. 13 male trained subjects undertook a general warm-up followed by five 10 metre sprints of increasing intensity. They were subsequently tested for CMJ height after which they performed 3 repetitions of parallel squats at a load of 93% of 1RM. They were then retested for CMJ height 2 minutes, 4 minutes and 8 minutes post squat. An analysis of Variance (ANOVA) with repeat measures showed no significant differences (p>0.05) between CMJ height at baseline (pre squat) (53.30 cm ± 11.02), 2 minute post squat (54.01 cm ± 10.17), 4 minute post squat (53.80 ± 10.25) and 8 minutes post squat (53.25 ± 10.97). When baseline scores were compared to maximum post squat scores, via a dependent t-test, no significant differences (P>0.05) were found. This study concludes that no optimal timeframe exists for PAP, as induced by heavy load back squats, and even when time is removed as a factor heavy load squats did not produce a significant increase in CMJ performance. Their application to team warm-up protocols is not recommended.

**Study six**

This study investigated the effects of heavy squats parallel (3 repetitions at 93% 1RM) and Maximal Voluntary Contractions (3 MVC’s of 3 seconds) in a parallel squat position on 10 metre sprint performance. 35 male trained subjects were tested for 10 metre sprint performance and then randomly allocated to one of two groups, squat protocol (S) n =17, MVC protocol (MVC) n = 18. Following each protocol, 10 metre sprint performance was measured and the changes in performance compared across all groups. ANOVA with repeat
measures found no differences (p>0.05) between groups, pre or post application, demonstrating that no protocol resulted in significantly different performance. This study concludes that neither MVC’s nor Squats are able to enhance running speed over 10 metres, and their use in warm-up procedures cannot be recommended.
CHAPTER FIVE - FINAL CONCLUSIONS
FINAL CONCLUSIONS

As warm-up procedures become increasingly focussed on performance, as well as on injury prevention (Jeffreys, 2007b; Verstegen, 2004), a number of elements need to be examined or re-examined. The issue of potentiation is one such topic, given the potential of pre-conditioning activities, to enhance subsequent performance (Tillin and Bishop, 2009). One important element that needs to underpin this process is to ensure that research focuses on measures of actual performance rather than on any indirect measures that may infer changes in performance, such as peak power. The critical feature underpinning all of the studies was the aspiration that the studies should guide practice. For this reason key performance measures were always chosen as the dependent variable, ensuring the extrapolation of any data generated directly to performance.

The results of this series of studies indicate two key findings:

1. Firstly a general warm-up alone may be insufficient to maximise performance, and that a period of high intensity activity needs to be undertaken prior to performance. This high intensity activity needs to be as specific as possible to the subsequent activity.

2. Secondly, on a group basis, the use of methods aiming to enhance subsequent performance via the utilisation of PAP confer no benefits over a well constructed warm-up, where potentiation is provided by a maximal intensity intervention of unloaded exercise.

However, further research needs to be carried out before these conclusions can be substantiated across all subject groups, and in all performance scenarios. Similarly, given the substantial complexity of PAP, further issues need to be investigated before final conclusions can be drawn, and optimal application suggested.

In terms of PAP itself, the results of this series of studies supports the conclusions of Tillin and Bishop, (2009) that PAP is a multi-factorial phenomenon. The net effects of any PAP on performance will depend upon the balance between the fatigue, and potentiation from a given pre-conditioning activity. The unique interaction between these variables in any given
situation will determine the net balance between fatigue and potentiation, and the subsequent effect on performance. For this phenomenon to be utilised to improve sports performance, then attention has to be paid to all of the modulating factors that will determine the net performance effect. Tillin and Bishop, (2009) recommend that if future research intends to confer ideal warm-up or training protocols for optimising PAP, then all of the elements associated with PAP including the preconditioning activity, the recovery and the subsequent activity should be assessed together. The six studies completed complied with this requirement. Ensuring that future research is similarly able to address these requirements will necessitate a firm understanding of the issues that will affect the entire process from input to output. This can be facilitated by the production of a model of PAP application.

The following model (Fig 5.1-1) has been developed based upon the findings of the current studies, together with those from previous studies. It utilises a systems model where the PAP process is described in terms of inputs to the system (the pre-conditioning activity), the processes within the system (in this case the athlete) and the outputs from the system (in terms of performance). This model provides for a systematic analysis of the factors that are likely to influence the net effects on acute performance of any given input. This model will provide the basis for the final evaluations of these studies.
PAP – A PERFORMANCE MODEL

Fig 5.1  PAP: A systems model
**Inputs to the system**

A key decision a coach will need to make is on the type of input (activity) they intend to use to elicit PAP. This will revolve around three key factors:

1. The type of activity
2. The intensity of the activity
3. The volume of the activity.

**Activity type**

In terms of the type of activity, the coach needs to assess whether the activity will provide the kinetic (force based) or kinematic (movement based) parameters required for optimising performance. The results of the current studies suggest that as part of a warm-up potentiation phase, maximal intensities using the exact same activity is likely to yield the best results, and that additional loadings of this activity will elicit no further gains in performance.

In terms of attempting to elicit PAP, then the kinetic variables may give greater potential than the kinematic variables. The suggestion by Gilbert and Lees, (2005) that methods which focus on power and speed development, such as plyometrics, resisted sprints and assisted sprints etc. may be able to induce PAP would be questioned on the basis of these studies, despite the fact that they may be more functional in sport specific settings. Although no methods utilised in any of the current studies achieved significant improvements in performance, dynamic squats achieved bigger raw performance increases than any other method. As the squat exercise includes both eccentric and concentric action, then this would support the conclusions of Hilfiker, et al., (2007) who suggest that eccentric muscle action appear to influence subsequent muscle performance more than isometric action, suggesting that dynamic exercise would have a greater effect on PAP than isometric activity.

**Activity intensity**
While no methodology resulted in significant performance improvements through PAP, the raw data did demonstrate that some athletes showed greater gains when using higher (93% 1RM) intensities, than low (80% 1RM and 60%1RM). Similarly, study one showed that sprint performance was enhanced when preceded by a series of maximal sprints. The results therefore suggest that whichever activity is used in an attempt to elicit PAP, intensities need to be high. This is based on the fact that, as PAP is most associated with Type II muscle fibres, (Hamada, et al., 2000) then the pre-conditioning activity needs to ensure that an appropriate number of Type II fibres are stimulated, whether through high resistance or high velocity. Indeed, future studies on dynamic protocols could focus on the optimal methods of achieving high intensities and whether the protocols are load or velocity based. However, these always come with the proviso that increased intensity will induce greater fatigue.

**Activity volume**

PAP is modulated by the volumes of the pre-conditioning stimulus (Hodgson, et al., 2005), and so, in addition to the nature of the PAP inducing exercise and its intensity, another important element to consider is the duration of the activity. Activity intensity and activity volume are inversely related and as intensity rises then volume needs to be correspondingly reduced. As each activity will have both potentiating and fatiguing effects, then the duration of exercise becomes a critical question. Hilfiker, et al., (2007) suggest that total contraction time should be less than 10 seconds to avoid undue fatigue. As intensity of activity required for PAP appears to be high, then the volume of activity will necessarily be low to avoid undue fatigue. Again, further research is needed to validate an optimal duration of any PAP inducing activity, and here again, the individual response characteristics will further complicate the quest (Jeffreys, 2008b). The vast majority of studies have used traditional “sets” of consecutive MVC’s or resistance exercises to induce PAP, where the overall duration of the exercise is largely determined by the number of repetitions. Batista, et al., (2007) found that PAP could be elicited via intermittent exercise, and this may be another option whereby PAP can be elicited whilst controlling fatigue. While the results of these studies do not directly address the notion of volume, it does need to be considered in
any PAP application protocol. Tillin and Robins, (2009) conclude that as the volume of pre-
conditioning activity increases, then fatigue becomes the dominant factor in the
potentiation fatigue relationship, and subsequently, it is likely that potentiation based
protocols need to be low in volume. This low volume requirement also reflects the fact that
the volume of activity in the subsequent sport following warm-up also needs to be
considered.

**The Process**

The inputs alone will not determine the extent of PAP. The results of these studies attest to
the highly individual nature of PAP, a fact further substantiated by reviews by Tillin and
Bishop, (2009) and Docherty and Hodgson, (2007). Analysis of the system itself, in this case
the athlete, needs to be a critical factor in designing PAP protocols. This analysis needs to
focus on three key areas:

1. The subject’s physiological characteristics
2. The physiological mechanisms of potentiation
3. The physiological mechanisms of fatigue.

A critical aspect of this analysis is that these systems are constantly in flux, and cannot be
assumed to be fixed. The net effect of any conditioning activity will be dependent upon the
interaction of these three elements at any one time. Given that these will also be both
input and output dependent, can help explain the great disparity in results of previous
studies, both within individuals, and between groups given the same protocols. Results of
the studies to date attest to the massive divergence in individual response to any given
stimulus, and are key to the findings that PAP based warm-ups cannot be advised on a
group basis.

As the aim of the studies was to examine the net effect on performance rather than on the
physiological causes of PAP, the analysis of the latter factors, i.e. the physiological
mechanisms of fatigue and potentiation, will be limited. However, the divergence in
individual performance results, and also in the underpinning mechanisms of performance
outlined in study four, where changes in peak power, peak force and rate of force production varied between individuals, suggests that PAP may be caused by the contribution of a number of factors, each balanced by associated fatigue effects. The net influence of each factor will be affected by the parameters of the input, and the output, in addition to the net characteristics of the subject at that given time.

In terms of subject variations, previous authors have attested to the importance of strength levels (Gourgoulis, et al., 2003), and training state (Chiu, et al., 2003). These in themselves are, to a degree, transient factors, and also do not differentiate between genetic characteristics (e.g. muscle fibre type) and training effects. Although it has been consistently proposed that PAP is closely related to Type II fibres, only one previous study (Hamada, et al., 2003) has directly compared PAP to muscle fibre type, finding significant differences in performance on a 3 second MVC between subjects with predominantly fast-twitch and those with slow twitch fibre types. However, the results of the present studies demonstrated no difference between performance changes between stronger and weaker athletes (study four) or faster and slower athletes (study two) on the ability to potentiate performance. In itself, strength may be too simple a construct, as it is not a time restricted construct, as is performance in the majority of team sports. Additionally, as RFD change seems to be the main aspect affected by PAP (study four), a more power based athlete evaluation that takes into account the stretch shortening cycle may be a better predictor than strength alone. Future studies need to focus on aspects such as the explosive strength deficit or reactive strength ratio as better indicators of the ability to utilise PAP. This importance of power is supported by Tillin and Bishop, (2009) but in a very different way. They suggest that athletes less able to convert strength into power benefitted more from PAP, and suggest that a ratio between strength and power may exist above which PAP cannot be exploited. As the majority of team sports aim to enhance power, this would contradict the claim by Chiu, et al., (2003) that training status is a positive indicator of PAP potential. The use in previous studies of untrained or moderately trained subjects, who are unlikely to be efficient at expressing power, further clouds this area. If Tillin and Bishop, (2009) are correct, then PAP may only be applicable to athletes who are unable to effectively exploit key aspects of power performance such as RFD, or SSC activity, and may therefore only be applicable to a small range of individuals who may not necessarily
represent the elite performers in the majority of team sports in which the ability to apply force rapidly is a key indicator (Stone, et al., 2007). Given this lack of uniform response it could be that, as with responses to treatments whether they be medical or training, that there exist responders and non responders to PAP. Therefore, the search for a single predictor may be flawed, and similarly, the search for group based applications unfounded.

A factor that has not been addressed in any previous studies is the transitory effects of accumulated fatigue. In athletes, a single training stress is superimposed upon accumulated training stress, as well as on non training stress (Jeffreys 2008c). Thus, the influence of a single activity may not be able to be taken in isolation, and must be related to elements such as timing of the activity, total daily activity, weekly training distribution, mesocycle training distribution and macrocycle training distribution. Performance has consistently been show to vary in response to these training factors (Jeffreys 2008c) and the taper itself is an attempt to balance overall training potentiation and fatigue in order to elicit maximal performance (Bompa and Haff, 2009; Mujika, 2009). Given this ever changing tapestry upon which PAP is exploited, it would appear logical to conclude, based on the processing systems of the athlete, that the extent of potentiation will demonstrate a temporal effect within each individual. Additionally, given the potential variants from both the inputs and outputs of the system, the likelihood of producing a protocol that consistently produces results within an individual will be difficult. To do this across a group of athletes could simply be impossible.

Output analysis

One of the reasons for the inconsistencies of past research into PAP is the range of subsequent activities that have been analysed (Tillin and Bishop, 2009). These have ranged from activities including sprints of different distances, maximal isometric contractions, loaded ballistic activities and CMJs. Given the different physiological and biomechanical parameters that underpin these activities, then it is possible that a given pre-conditioning activity will not have the same effect on different explosive activities.
This activity dependence is demonstrated by McBride, et al., (2005) who found that athletes ran 0.87% faster in a 40 yard sprint, (p<0.05) when preceded by a set of heavy squats (1 set or 3 repetitions at 90% of 1 RM), but found no statistical differences in the split times at 10 or 30 metres. Just as the pre-conditioning activity is likely to have a specific effect, then similarly, the subsequent activity may demonstrate a specificity effect. Additionally, this effect may be specific to the pre-conditioning activity or the athlete interactions or both, as previously discussed.

While French, et al., (2003) suggest that PAP is only effective in explosive muscle actions, other studies have indicated improvements in CMJ height, which can be characterised as a slow SSC activity (Turner and Jeffreys, 2010). Babault, et al., (2008) suggest that PAP is greatest during the eccentric portion of a movement, and this may enhance performance in SSC activities and for individuals with a propensity for SSC activity (although this would contradict the claims of Tillin and Bishop, (2009) of an upper limit of a strength/power ratio.

**Final Conclusions**

The results of these studies demonstrate clearly that PAP is a highly complex multi-factorial phenomenon, which needs a great amount of programming and analysis if it is to be used in performance. Based on the findings of study one the inclusion of a potentiation phase in a warm-up, where specific activities are taken to maximal intensity is highly recommended in team sports. General warm-up alone would appear to be inadequate to maximise speed performance.

However, based on studies 2-6, the use of PAP based activities, in an aim to further enhance performance, cannot be recommended on the basis of these studies. If it is to be used, it should be undertaken on an individual basis, and based on extensive prior analysis that is protocol, individual and outcome specific.
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