# The Effect of a Plyometric Protocol on Muscle Potentiation

by

Mariska Booyens

A thesis submitted in partial fulfillment of the requirements for the degree of

Master of Science

Physical Education and Recreation
University of Alberta

## Abstract

This thesis describes experiments designed to investigate whether a plyometric protocol consisting of drop jumps, induce PAP, and if so, assess the magnitude and time course of the induced PAP. Participants performed a standard warm-up followed by drop jumps or a low-pace walk. PAP induced by the drop jumps were assessed through electrically evoked isometric twitch torques. Peak twitch torque significantly increased with no change in M-wave peak-to-peak amplitude, indicating that the mechanism responsible for the augmented peak twitch torque was distal to the sarcolemma. The PAP dissipated within 6 minutes. By 11-16 minutes following the plyometric protocol, peak twitch torque was below baseline. These results have implications for determining whether a plyometric protocol would be beneficial for athletes to incorporate prior to performance, and if so, determine the optimal time to implement the plyometric protocol for maximal performance benefits. The present study provides evidence that drop jumps induce PAP and maximizes the force generating capacity of the muscle. Drop jumps can be implemented directly prior to athletic performance, lasting no longer than 6 minutes, to maximize the force generating capacity of the muscles

## Acknowledgments

I would like to thank my supervisor and committee member Dr. Dave Collins for helping and supporting me every step of the way. Thank you for challenging me, taking me out of my comfort zone and encouraging me to think critically. His constant support and motivation helped me to be successful and I am very grateful for the time and dedication he put in to help me complete my Masters.

I would like to thank my committee members, Dr. Pierre Baudin and Dr. Brian Maraj. Thank you Dr. Baudin for accepting me as your practicum student and supporting me to go on to pursue a Masters. Thank you for your wise insight and guidance and being a part of my research. Dr. Maraj, thank you for always surrounding me with positivity no matter what happens. Thank you for being a part of my committee and providing me with helpful feedback.

I would like to thank members of the Neurophysiology Lab for accepting me as one of their own and always being insightful and optimistic. I would like to thank Alex Ley for helping me with conducting my research and teaching me what I needed to know to be successful in collecting quality research. Thank you for always giving me helpful feedback and assisting me when I needed help.

Lastly, I would like to thank my fiancé Ryan Johnson, and my wonderful family for supporting me every step of the way. Your constant love and support has meant the world to me. Thank you for encouraging me to keep going even when times were tough and believing in me and my goals. Thank you for coming to my defense and sharing in my special moment.

## List of Figures

### Chapter 1



### Chapter 2

**List of Abbreviations**

| | |
|---|---|
| **ANOVA** | analysis of variance |
| **PAP** | post activation potentiation |
| **EMG** | electromyography |
| **RTD** | rate of torque development |
| **PTP** | post-tetanic potentiation |
| **M-wave** | motor wave |
| **$Ca^{2+}$** | calcium |
| **MVC** | maximal voluntary contraction |
| **RFD** | rate of force development |
| **PTT** | peak twitch torque |
| **TTPT** | time to peak twitch torque |
| **CMJ** | counter movement jump |

# TABLE OF CONTENTS

# CHAPTER 1: GENERAL INTRODUCTION

## 1.1 Preface

The majority of athletic performances rely on the ability of the athletes' sprinting performance (Guggenheimer, Dickin, Reyes, & Dolny, 2009). Guggenheimer and colleagues (2009) suggest that the enhancement of sprinting performance should be a goal for both sport scientists and athletes alike, therefore developing means of augmenting acute or chronic sprint performance should be a focus of training and competition. In order to improve performance, coaches and athletes need to explore different means of improving muscle performance beyond a basic pre-activity warm-up. This thesis includes a description of one project that investigated the temporal characteristics and augmenting effects of a muscle potentiating following a standard warm-up. The results of this study will provide evidence upon which to develop potentiating protocols to maximise performance.

Firstly, the general introduction of the thesis provides an overview of the muscular and neurological components involved in sprinting. Secondly, background information on traditional warm-up routines and the underlying mechanisms involved. Lastly, the importance of a phenomena known as post activation potentiation (PAP) and its role in improving performance, the integration of applied PAP protocols and how their affects are harnessed, the mechanisms responsible, factors affecting PAP, and how PAP is measured. This last section summarizes important factors pertaining to PAP and describes the objectives and hypotheses of this study.

## 1.2 Introduction to sprinting

Sprinting is a fundamental requirement for a majority of sports. In track competitions the sprint start and acceleration from the blocks are two important phases that directly affect the results in sprinting events, and account for more than 50% of the athletes sprint result (Tellez & Doolittle,

1984; Coh, Peharec, Bacic, & Kampmiller, 2009). Coh &Tomazin (2006) describe performance of the sprint start and block acceleration phase as specific motor problems that require the athlete to integrate, in terms of space and time, an acyclic movement into a cyclic movement. The maximal muscle force generated to initiate block clearance and transition to an optimal sprint is dependent on multiple physiological and neurological factors. These factors include motor neuron excitability, proportion of the available motor unit pool recruited, the type of fiber and cross-sectional area of the contracting muscles, contraction speed, and muscle, tendon, and joint stiffness and elasticity (Ross, Leveritt, & Riek, 2001). According to Coh and colleagues (2009, pg. 140) block velocity is defined as a sprinters' velocity at the moment of losing contact with the front starting block and is largely generated by the activation of erector spinae, gluteus maximus, vastus lateralis and medialis, gastrocnemius-medialis, and biceps femoris muscles.

The transition from block clearance to acceleration is a very complex sequence, requiring high muscle activation. During block clearance, sprinters can generate horizontal forces greater than a thousand Newtons (Mero, 1988; Coh et al., 2009). The muscles responsible for generating the reactive force are the gluteus maximus, rectus femoris, vastus medialis, vastus lateralis, biceps femoris, and the gastrocnemius-medialis muscle (Coh et al., 2009). An efficient transition depends on the execution of the first step, the length of the step, and positioning of the foot in the braking phase of the foot contacting the ground (Coh et al., 2009). According to Coh and colleagues (2006), acceleration is the phase during sprint races where the kinematic parameters of the stride are dramatically changing and the complex cyclic movement is defined predominantly by the duration of the contact and flight phases, the increase of the frequency and length of strides, and the position of the body's centre of mass at the moment of ground contact.

Performance in sprinting is determined by the ability of the athlete to accelerate out of the blocks, generate maximal velocity, and maintain maximal velocity against the onset of muscular fatigue (Ross et al., 2001). Adequate pre-activation of the muscle is important for the efficient execution of the ground contact phase to overcome ground reaction forces (Coh et al., 2009). Runners who are able to optimise timing of agonist and antagonist muscle activation are advantageously able to decrease co-contraction at an appropriate point of contraction and as a result can increase their speed (Ross et al., 2001). Dynamic protocols that change the temporal sequencing of muscle activation for movement efficiency, alter motor unit recruitment strategies, increase recruitment and firing rate of the muscle fibers, and increase joint stiffness could possibly create an advantageous potentiating effect in the muscles that has direct implications on sprinting performance (Ross et al., 2001).

## 1.3 Track and field warm-ups

One important factor that affects performance is warm-up. A warm-up is defined as a period of preparatory exercise to improve training or performance (Hedrick, 1992). Traditional activity specific warm-ups include a brief period of low intensity aerobic-type activities, followed by static stretching and activities that are sport specific (Safran, Seaber & Garrett, 1989; Schilling & Stone, 2000; Behm & Chaouachi, 2011). The main purpose of an activity specific warm-up is to acutely maximize performance, increase muscle and tendon suppleness, increase body temperature, stimulate peripheral blood flow, and prevent risk of injury (Gullich & Schmidtbleicher, 1996; Schilling & Stone, 2000; Smith, 2004; Behm & Chaouachi, 2011). However, moderate intensity standard warm-ups have shown to have no effect on performance, but plays a role in decreased joint resistance due to the viscoelastic nature of the muscle, and improved chemical reactions in the muscle due to increased peripheral blood flow (Shellock & Prentice, 1985; Smith, 2004;

Burkett, Phillips, Ziuraitis, 2005; Hilfiker, Hubner, Lorenz, & Marti, 2007; Altamirano, Coburn, Brown, & Judelson, 2012).

In track and field, athletes usually complete a warm-up that consists of four integral parts. In the first part the athlete starts with an easy jog for several minutes followed by surges (Derse, Hansen, O'Rourke, & Stolley, 1995). Surges are defined as bursts of running at faster tempos preceded by a light jog (Derse et al., 1995). In the second part, the athlete completes a controlled static stretching routine. The third part includes dynamic stretching that consists of arm and leg movements through wide ranges of motion. The last part includes the athlete completing a basic set of rhythmic drills that are specific to the sport movement (e.g. high knees, high skipping or skipping kicks; Derse et al., 1995). The majority of studies investigating potentiating protocols, have utilized a standard warm-up consisting of moderate cycling or jogging followed by static stretching (Bazzet-Jones, 2004; Burkett, Phillips, & Zuiraitis, 2005; Gilbert & Lees, 2005; Lima et al., 2011; Byrne, Kenny, & O'Rourke, 2014). The present study will investigate the potentiation induced by a standard warm-up and dynamic protocol (drop jumps) and asses the magnitude and time course of potentiation to determine whether it is beneficial for performance.

## 1.4 Muscle Potentiation

Sprinting speed and the ability to out accelerate your opponent are crucial components in explosive sports, considering the limited time to gain distance over your opponent. The contractile history of a muscle can affect the ability of an individual to athletically perform (Robins, 2005). To maximize athletic performance, warm-up procedures that involve dynamic movements have become increasingly popular and are designed to potentiate the muscle, elevate body temperatures, and maximize dynamic ranges of motion (Mann & Jones, 1999; Faigenbaum et al., 2006). Dynamic warm-ups may enhance neuromuscular function which creates an optimal environment

for power production (Faigenbaum et al., 2006). Although track competitions are strictly regulated, there are multiple factors that the coaches and athletes cannot control, such as the exact time that the performance is initiated. Thus, a particular challenge for competitors is the time delay between warm-up and performance that could possibly deteriorate the enhanced neuromuscular state of the muscle, therefore a short effective muscle potentiation protocol could be beneficial. The use of a brief potentiation protocol that can be implemented during the time between the warm-up and the performance could provide an optimal level of muscle potentiation.

### 1.4.1 Post activation potentiation

Post activation potentiation (PAP) has become a topic of investigation in recent years since it is thought to be an effective means for maximizing acute power development (Lorenz, 2011). The term "PAP" was defined by Robbins (2005) as: "The phenomenon by which acute muscle force output is enhanced as a result of contractile history" (pg. 453). For example, the execution of a set of high-intensity squats or drop jumps prior to performance of a vertical or horizontal jump enhanced jumping performance by 2.39% and 5.5%, respectively (Gourgoulis et al., 2003; Lima et al., 2011). Robins (2005) proposed that loading of the neuromuscular could enhance performance since it elicits a "sensitive" or "excited" state in the muscle (pg. 453).

There is some confusion within PAP literature when referring to PAP and post-tetanic potentiation (PTP) and the mechanisms responsible for the potentiated effects. The terms PAP and PTP have been used interchangeably in the sport science literature. PTP is defined as: "A brief period of repetitive stimulation that results in an enhanced contractile response" (Rassier & MacIntosh, pg. 499, 2000), whereas PAP is referred to as twitch potentiation that is induced by voluntary contraction (O'Leary, Hope, & Sale, 1997; Rassier & MacIntosh, 2000). To induce potentiation the conditioning activity most commonly includes a sustained maximal voluntary

contraction (MVC), or concentric-eccentric type movements (weighted back squats or jump squats; Sale, 2002). An illustration of how the amplitude of an electrically evoked twitch is enhanced due to PAP following a maximal voluntary contraction (MVC) is shown in Figure 1-1 (Sale, 2002). Throughout this thesis any reference to PTP will be excluded since PTP is induced through electrical stimulation; is affected by the duration, intensity, and frequency of the conditioning stimulus; and is associated with higher excitatory post-synaptic potentials at a neuronal level which is not within the scope of this study (Güllich & Schmidtbleicher, 1996; O'Leary, Hope, & Sale, 1997). Therefore this present study will only refer to PAP through means of voluntary induction and its effects at a muscular level.

The most widely accepted mechanism of PAP is the phosphorylation of myosin regulatory light chains. This translates to an increase in actin-myosin cross-bridge sensitivity to calcium released from the sarcoplasmic reticulum (Sweeney, Bowman, & Stull, 1993). According to Gardiner (2001) the dominant role of the myosin regulatory light chains is to alter the function of actin-myosin cross-bridges through their state of phosphorylation. The phosphorylation of the myosin regulatory light chains augments the rate by which actin-myosin cross-bridges move from a non-force to a force producing state and increases the sensitivity of the contractile elements (actin-myosin cross-bridges) to calcium (Gardiner, 2001). The result is an increase in contraction force and increase in the rate of force development (Sweeny et al., 1993). This mechanism has been confirmed by analyzing human muscle biopsies and remains the most widely accepted mechanism in PAP literature (Houstan, Green, & Stull, 1985; O'Leary et al., 1997; Palmer & Moore, 1989; Hamada, Sale, MacDougall, & Tarnopolsky, 2000). Houston and colleagues (1985) extracted four muscle biopsies from the right lateralis muscle of six healthy males. The four biopsies were taken when the participants were relaxed in the chair, immediately following a

MVC, ~20 seconds post MVC, and ~120 seconds post MVC. The frozen specimens were homogenized and diluted and underwent a chemical and electrophoresis procedure (Houston et al., 1985). Houston and colleagues (1985) found a significant increase from resting value of 0.28mol phosphate/mol of phosphorylatable light chains to 0.32 mol immediately following the MVC. There was a significant correlation ($r=0.85$, $p<0.05$) between individual potentiation increase and increased phosphate incorporation in light chains of fast myosin 20 seconds following a voluntary contraction (Houston et al., 1985, pg.351)

According to Robins (2005) muscle contractions produce both fatigue and PAP, and it is the balance between these two factors that determine whether the muscle force is augmented or attenuated as illustrated in Figure 1-2. Robins (2005) describes the relationship between fatigue and PAP as a coexistence, resulting in a net attenuated state, a net potentiated state, or a constant state compared to the state of the muscle prior to the potentiating activity. Docherty and colleagues (2007) proposed that there are multiple factors that can influence induced potentiation that need to be considered when applying the principles of PAP. These factors include fatigue, fiber type of the individual, recovery window, training status of the individual, and the type of the potentiating activity (Hamada et al., 2000; Docherty & Hodgson, 2007).

### 1.4.3 Factors affecting PAP

#### *1.4.3.1 Fatigue*

When assessing the interaction between fatigue and PAP on performance it is important to consider the potentiating protocol used since this is an important determinant of the mechanisms involved (Westerblad et al., 1991; Rassier & MacIntosh, 2000). Fatigue is defined as: "The depression of contractile response, which can be attributed to prior activity" (Rassier et al., 2000, pg.500). Peripheral fatigue is located at the level of active muscle and effects multiple muscular

mechanisms such as excitation-contraction coupling, propagation of action potentials, metabolite accumulation, muscle structural integrity, and glycogen depletion (Allen, Lee, & Westerblad, 1989; Allen, Lannergren, & Westerblad, 1995; Proske & Morgan, 2001; Bowers, Morgan, & Proske, 2004; Place et al., 2010; Chaubet et al., 2013; Fernandez-del-Olmo et al., 2013). According to Place and colleagues (2010) electrically evoked contractions can be coupled with surface electromyography (EMG) to localize the potential sites of fatigue and distinguish whether peripheral or central mechanisms are involved. A greater reduction in the peak torque generated, with a consistent measure of M-wave amplitude indicates that contractile changes are distal to the sarcolemma and pertain to changes in force produced by metabolic and structural perturbations that alter active cross-bridges, $Ca2^{+}$ release and myofibrillar $Ca2^{+}$ sensitivity (Place et al., 2010; Allen et al., 1995). The decreased ability to generate force following continuous muscle contractions due to reduced $Ca2^{+}$ sensitivity is affected by factors such as decreased pH and increased inorganic phosphate content (Rassier & MacIntosh, 2000). Nuclear magnetic resonance, muscle biopsies, and blood samples have been used to identify peripheral mechanisms responsible for fatigue (Place et al., 2010). Following induced fatigue, single muscle fibers or skinned mammalian and human muscle fibers that are coated with fluorescent indicators can provide important measures ion and molecular content (Place et al., 2010). Fatigue and PAP both have $Ca^{2+}$ related mechanisms. PAP is due to phosphorylation of the regulatory light chains of myosin whereas fatigue is due to structural and metabolic perturbations that affect $Ca^{2+}$ activity, and it is the coexistence of these mechanisms that determine if the force is attenuated, enhanced or unchanged (Rassier & McIntosh, 2000).

*1.4.3.2 Fiber type*

One notable feature of PAP is that it is greater in fast, type II muscle fibers, because type II fibers undergo greater phosphorylation of myosin regulatory light chains in response to a conditioning activity, and contain higher levels of the kinase needed for phosphorylation (Moore & Stull, 1984; Sweeney, Bowman, & Stull, 1993). Hamada and colleagues (2000) found that muscles with a higher percentage of type II fibers demonstrate greater levels of PAP than muscles with predominantly slow type I fibers. Sale (2002) suggests PAP may offer the greatest potential for performance enhancement in brief maximal intensity activities requiring maximal strength and speed that are dependent on type II fibers (pg. 139). Another appealing characteristic of PAP is the ability to increase rate of force development (RFD). This appealing characteristic of PAP is beneficial for speed and power performance, and is most prominent in type II fibers (Docherty & Hodgson, 2007; Morana & Perrey, 2009). Morana and Perrey (2009) found significantly higher rates of torque development for power trained athletes than endurance athletes, following a submaximal PAP protocol. Therefore performance of power athletes who are involved in activities such as jumping, sprinting, and throwing, that require fast reactive movements and high rates of force development can be improved, if PAP is elicited (Sale, 2002).

Researchers might argue that endurance athletes would have a greater magnitude of PAP, since they typically have a higher proportion of type I muscle fiber composition that are more fatigue resistant (Tesch & Karlsson, 1985; Schluter & Fitts, 1994; Widrick et al., 1996; Hamada et al., 2000). However results from Morana and Perrey (2009) provides evidence that power trained athletes who have predominantly higher proportion of type II muscle fibers demonstrated higher levels of potentiation than endurance athletes with predominantly higher proportion of type I muscle fibers, following a submaximal PAP protocol (43.4±9.5Nm vs. 30±5.9Nm, respectively).

The induced PAP dissipated at a quicker rate for the power athletes than the endurance athletes, therefore one benefit of type I muscle fiber composition seems to be fatigue resistance, since the induced PAP dissipated at a slower rate (Morana & Perrey, 2009). However, athletes with predominantly type II fiber composition will generate significantly larger amounts of force and at a faster rate than endurance athletes, and therefore PAP would be beneficial for explosive activities of short duration. It should be noted that a person's fiber-type distribution is determined primarily by genetic factors, age and activity level (Güllich & Schmidtbleicher, 1996). Therefore, when observing the effects of a PAP protocol, one must consider choice of athletes, as power athletes will exhibit different results than endurance athletes (Hamada et al., 2000).

*1.4.3.3 Balance between PAP and fatigue*

The state of potentiation following a PAP protocol depends on the relationship between PAP and fatigue (Robins, 2005). Both PAP and fatigue may increase immediately following the PAP protocol and then gradually return to pre-potentiating levels and it is the balance between both states that determine the performance outcomes (Rassier & MacIntosh, 2000). There is a general consensus that PAP is maximal immediately after a brief conditioning stimulus (Vandervoort, Quinlan, McComas, 1983; Hamada et al., 2000; Comyns, Harrison, Hennessy, & Jensen, 2006; Baudry & Duchateau, 2007; Paasuke et al., 2007; Requena & Gapayeva, 2008; Moran & Perrey, 2009). The potentiation rapidly declines, but some researchers have reported that PAP is still evident for ~10-15 minutes (Lima et al., 2011). Robins (2005) describes the optimal recovery time, which depends on the rate of decline of PAP and the dissipation of fatigue. Exploitation of the enhanced benefits of PAP requires resolving two dilemmas as shown in Figure 1-2. Firstly, a greater PAP stimulus may produce greater onset of fatigue. Secondly, the longer the time between the PAP protocol and performance, the greater the recovery from fatigue, but the

PAP effects will have diminished (Sale, 2002). Gilbert and Lees (2005) reported an increase in maximal force, but the temporal profile of PAP was dependent on the protocol used to induce it. Gilbert and Lees (2005) had participants perform five back squats with either their 1-repetition maximum or maximal power loads with 5 minutes of rest in between repetitions. The last repetition was followed directly by a maximal voluntary contraction (MVC) and counter movement jump test measures that were taken for 1 hour. RFD of the MVC test values changed significantly following both protocols. The RFD for 1-repetition maximum load peaked between 15-20 minutes with an increase of 11.8%, whereas RFD of maximal power loads showed a peak at 2 minutes following the MVC test and was characterized by an increase of 6.7% (Gilbert & Lees, 2005). Significant increases for the counter movement jump were observed following both protocols and peaked around the 20 minute mark (2005). It was evident that in both protocols there is an immediate depression of force following the PAP protocol, followed by a period of potentiation, and then the values return back to baseline by the 60 minute mark (Gullich & Schmidtbleicher, 1996; Gilbert & Lees, 2005). The results are consistent with other findings (Jensen, & Ebben, 2003; Gossen & Sale, 2000; Comyns et al., 2006, Lima et al., 2011). However, Gossen and colleagues (2000) reported that the leg extensions that were utilized as a performance measure potentiated the muscle, resulting in a slower dissipation of PAP. Therefore test design of the aforementioned studies make interpretation of adequate recovery windows complex, since the enhanced PAP is not due to the recovery time itself, but could possibly be due to the PAP induced by the measure used to assess the effects of PAP.

The optimal recovery window is determined by trial and error and needs to take into account factors such as training status of the individual, fiber-type, performance, and design of PAP protocol (Sale, 2002; Gullich & Schmidtbleicher, 1996). More research is needed to

determine whether a recovery window is necessary by assessing the temporal characteristics of a PAP protocol, through the use of electrical stimulation. Thus, the majority of studies that reported improvements in performance were based on measures that could possibly prolong the effects of PAP, making interpretation of results fairly complex. My thesis research described in Chapter 2 will assess the temporal characteristics of PAP induced by a plyometric protocol, through the use of electrical stimulation.

*1.4.3.4 Training status and gender*

Training level of the athlete affects the presence and amount of PAP (Behm et al., 2004). High level athletes exhibit more PAP than those who participate in recreational resistance training (Schmidtbleicher, 1987; Young, 1993; Gourgoulis & Aggeloussis, 2003). Since the trained participants are familiar with explosive strength movements, they are believed to have more efficient synchronized motor unit recruitment and greater activation, therefore, are able to contract a greater number of muscle fibers in a shorter period of time (Schmidtbleicher et al., 1987; Chiu et al., 2003). Also, power trained athletes are be able to achieve greater amounts of force since they have a higher expression of type II muscle fibers and therefore can generate higher levels of force (Hamada et al., 2000; Chiu et al., 2003; Morana & Perrey, 2009). The greater activation of musculature will result in increased degree of phosphorylation due to increased sensitivity to calcium (Moore & Stull, 1984; Chiu et al., 2003). The increased phosphorylation results in quicker contraction and higher levels of force production (Moore & Stull, 1984; Palmer & Moore, 1989; Rassier & MacIntosh, 2000).

Although training status of the individual affects PAP, gender has shown to have no effect on PAP (Jensen & Ebben, 2003). Although women produced a lower maximal ground reaction force and maximal height during jumping than men, there was no effect of gender when 5 trials of

CMJs were performed at different time intervals following a PAP protocol. Therefore the induced PAP is not dependent on the gender of the individual (Jensen & Ebben, 2003). These findings were confirmed by a meta-analysis performed on 32 studies, which met the appropriate required criteria (Wilson et al., 2013). Wilson and colleagues (2013) reported that training status does significantly affect the magnitude of PAP following a PAP protocol, however there were no significant differences between genders.

*1.4.3.5 Type of PAP protocol*

PAP has previously been applied to training through the use of complex-training strategies that are considered superior to other training methods for improving athletic performance (Docherty & Hodgson, 2007). Complex training involves the alternation of biomechanically comparable high-load weight training with plyometric exercises, which is essentially pairing a high force activity with a high power activity (Lorenz, 2011). Traditionally PAP has been induced by application of a strength training stimuli such as heavy load squats (Docherty, Robbins, & Hodgson, 2004; Sale, 2002, Gilbert & Lee, 2005). Mathews and colleagues (2004) reported significant improvements in sprint time when preceded by a bout of heavy (5RM) back squats. Their marked improvement of 3.9% was consistent with other studies that induced PAP through heavy load protocols (Ebben & Waits, 1989; Young, McLean, & Ardagna, 1995; Pfaaf, 1997; Young, Jenner, & Griffiths, 1998; Radcliffe & Radcliffe, 1999; McBride, Nimphius, & Erickson, 2005; Burger, Boyer-Kendrick, & Dolny, 2000; Linder et al., 2010). This is not the case for all research, as other studies have shown no improvements in performance following a heavy lifting PAP protocol (Lim, & Kong, 2013; Hrysomallis, & Kidgell, 2001; Hughes, Gossen, & Sale, 2001; Chatzopoulos et al., 2007). However, these types of protocols utilize heavy lifting equipment that requires extra space and resources that might not be available to the athlete, and require a particular

level of skill to perform the movement, therefore may not be a realistic means of inducing PAP in a competitive setting (Lorenz, 2011; Maloney et al., 2014). Another means of inducing PAP is through the use of MVCs and dynamic knee extensions (Vandervoort, Quinlan, & McComas, 1983; Masilius et al., 2008; Hamada et al., 2000; Gossen et al., 2000; Morana & Perrey, 2009; Jubeau et al., 2010; Miyatmoto, Kanehisa, & Kawakami, 2012; Seitz et al., 2015). MVCs have been shown to be a successful means of inducing PAP (Vandervoort et al., 1983). However, previous comparison of various protocols demonstrated that MVCs have no effect on performance (Till & Cooke, 2009). Plyometric protocols have been advocated as a means to improve muscular force and RFD and may serve to be more sport specific since it incorporates multiple muscle groups, resulting in an accumulative potentiated affect (Maloney et al., 2014). The scope of my MSc thesis work involves inducing PAP through practical means, therefore focus will be on plyometric protocols used to improve maximal force and RFD (Lorenz, 2011).

Plyometric protocols have been used to potentiate the muscle and thus improve muscular force and RFD (Lorenz, 2011). According to Sweeney and colleagues (1993) repetitive contractions such as those involved in plyometric protocols can advantageously induce phosphorylation of myosin regulatory light chains and thus enhance muscle performance. Lima and colleagues (2011) found significant improvements of 2.4% and 2.7% at 10 and 15 minutes respectively ($p=<0.05$), when a 50 m sprint was preceded by 2 sets of 5 drop jumps (pg. 326). These results were consistent with other studies that found significant improvements when utilizing plyometric protocols (Young, & Behm, 2003; Burkett, Phillips, & Ziuraitis, 2005; Faigenbaum et al., 2006; Hilfiker et al., 2007). Other studies have found no improvements in performance when using plyometric protocols (McBride et al., 2005; Till & Cooke, 2009). However, differences in results are due to the potentiation protocol used, test design, and

physiological differences such as fiber type (Hamada et al., 2000; Lima et al., 2011). Variations in these factors, as outlined in Figure 1-3, amongst research studies makes interpretation of the effects of PAP very complex (Tillin & Bishop, 2009).

### 1.4.4 Measuring PAP

A common measure of PAP is maximally evoked twitch torque (Lorenz, 2011; Sale et al, 2002; Guillich et al., 1996). Muscle twitch torque can be demonstrated through the use of electrical stimulation. Electrical stimulation is defined as the application of electrical stimulus to produce involuntary muscular contractions (Sánchez, Puche, & González-Badillo, 2005). Electrical stimulation is mostly used in orthopedic rehabilitation and physical therapy, and has been shown to decrease muscle wasting, weakness, and atrophy (Requena et al., 2005; Sánchez et al., 2005). Electrical stimulation can be administered through two methods: muscle electrical stimulation and nerve electrical stimulation. Muscle electrical stimulation requires the stimulation to be administered over the muscle belly through the use of stimulating electrodes. This method is a reliable and consistent method for test-retest purposes (Coso, Hamouti, Estevez, & Mora-Rodriguez, 2011). The second method, nerve electrical stimulation, requires stimulation of the nerve through the use of a ball-shaped cathode or stimulating electrodes that are applied against the skin over the underlying nerve trunk (Coso et al., 2011). However, difficulty in application yields inconsistent results due to nerve location, applying constant pressure to the cathode, and discomfort produced when stimulating the nerve (Coso et al, 2011). Although electrical stimulation is non-invasive and practical in nature, it remains to be an underused application in testing for PAP.

The majority of studies of PAP have not confirmed the presence of PAP by assessing the electrically evoked twitch torque (Docherty & Hodgson, 2007). Several studies to date have used

electrical stimulation, before and after the PAP protocol to measure the magnitude of force characteristics, and to confirm PAP was elicited (O'Leary, Hope, & Sale, 1997; Gossen et al., 2000; Hamada et al., 2000; Hughes et al., 2001; Masiulis et al., 2008; Seitz et al., 2015). Gossen and colleagues (2000) performed a twitch test prior to having their participants perform a control or PAP trial. The participants completed maximal dynamic knee extensions with loads of 15%, 30%, 45% and 60% of maximal isometric knee extension peak torque. A 10 second MVC was used to induce PAP was measured as an increase in twitch torque during the first and second extensions with each load. This test designs made it possible to compare the magnitude of PAP before and after the PAP protocol.

It is not known whether plyometric protocols induce PAP, since no study to date reported such findings, through the use of electrical stimulation. Consequently, the observed changes in performance cannot be attributed to the induced PAP, and the mechanisms responsible for any observed changes remain unknown. The work described in Chapter 2 will determine whether a plyometric protocol and not standard warm-up, will potentiate the quadriceps. The time course and magnitude of the induced PAP will be assessed to determine the best time, prior to performance, to implement drop jumps, to maximize the force generating capacity of the muscle.

## 1.5 Summary

Many athletic events require maximal acceleration and explosive power to optimise performance. Protocols designed to induce PAP have been applied in performance and training environments as a means to improve performance. The ability of such PAP protocols to increase electrically evoked twitch torque and RTD could make it to be superior to activity specific warm-ups. Although PAP protocols have potential benefits on performance, there are multiple factors that need to be controlled and accounted for. These factors include fatigue, fiber type of the

individual, time between PAP protocol and the performance measure, training status of the individual, type of PAP protocol, and performance measures. PAP can be elicited through either heavy load (e.g. back-squat), plyometric (e.g. drop jumps), or MVC protocols, and studies eliciting PAP using either of these methods have shown improvements in performance measures. Plyometric protocols however are favorable in sports requiring explosive movements due to its specificity and practicality. This type of protocol has been advocated as a means to improve muscular force and RFD. Results that failed to see a change in performance could be due to test design, type of PAP protocol, fiber type, and experience of the athletes. Applying electrical stimulation allows the researcher to confirm the presence of PAP, and assess the time course of PAP. Without this measure it is not known whether the observed increase in performance is due to the induced PAP. PAP is time dependant and if used strictly and efficiently between standard warm-up and performance, it could allow for an optimal level of potentiation in the muscle that results in improved performance.

## 1.6 Thesis outline

Previous investigators have tested for the performance enhancement effects of plyometric protocols (Hilfiker et al., 2007; Guggenheimer et al., 2009; Lima et al., 2011; Byrne, Kenny, & O'Rourke, 2014; Maloney, Turner, & Fletcher, 2014; Turner, Bellhouse, Kilduff, & Russell, 2014), but these investigators did not directly measure the magnitude and temporal characteristics of PAP, therefore it is not known whether the observed improved performance is attributable to the induced PAP. This study has 2 main objectives: 1) To determine whether a plyometric protocol and not standard warm-up will induce PAP; 2) To assess the time course and magnitude of the PAP induced by the plyometric protocol. We hypothesized that the plyometric protocol (drop jumps), but not the standard warm-up (Burkett et al., 2005), would induce PAP. We also

hypothesized that this PAP would dissipate over 10-15 minutes. These hypotheses are based on experiments that have shown that plyometric protocols improve performance for 10-15 minutes (Lima et al., 2011). This information about whether drop jumps induce PAP will help determine whether such protocols improve performance by potentiating the force generating capacity of the muscle and, if so, will help delineate when athletes should perform drop jumps to acutely maximise subsequent performance.

## 1.7 References


Aagaard, P (2003) Training induced changes in neural function. *Journal of Exercise and Sport Science Review* 31(2): 61–67

Allen, DG, Lee, JA, Westerblad, H (1989) Intracellular calcium and tension during fatigue in isolated single muscle fibres from Xenopus laevis. *Journal of Physiology* 415: 433–458

Allen, DG, Lännergren, J, Westerblad, H (1995) Muscle cell function during prolonged activity: cellular mechanisms of fatigue. *Journal of Experimental Physiology* 80: 497–527

Altamirano, KM, Coburn JW, Brown LE, Judelson DA (2012) Effects of warm-up on peak torque, rate of torque development, and electromyography and mechanomyography signals. *Journal of Strength & Conditioning Research* 26(5): 1296-1301

Babić, V, Čoh MM, Dizdar DD (2011) Differences in Kinematic Parameters of Athletes of Different Running. *Biology of Sport* 28(2): 115-121

Baudry, S, Duchateau, J (2007) Postactivation potentiation in a human muscle: effect on the rate of torque development of tetanic and voluntary isometric contractions. *Journal of Applied Physiology* 102: 1394–1401

Bazett-Jones, D (2004) Neither stretching nor postactivation potentiation affect maximal force and rate of force production during seven one-minute trials. *Journal of Undergraduate Research* VII: 1-5

Behm, DG, Button, DC, Barbour, G, Butt, JC, Young, WB (2004) Conflicting effects of fatigue and potentiation on voluntary force. *Journal of Strength & Conditioning Research 18*(2): 365-372

Behm, DG, Chaouachi, AA (2011) Review of the acute effects of static and dynamic stretching on performance. *European Journal of Applied Physiology* 111: 2633–2651

Bowers, EJ, Morgan, DL, Proske, U (2004) Damage to the human quadriceps muscle from eccentric exercise and the training effect. *Journal of Sport Sciences* 22: 1005-1014

Burger, T, Boyer-Kendrick, T, Dolny, D (2000) Complex training compared to a combined weight training and plyometric training program. *Journal of Strength and Conditioning Research* 26(6): 52-57

Burkett, LN, Phillips, WT, Ziuraitis, J (2005) The best warm-up for the vertical jump in college-age athletic men. *Journal of Strength and Conditioning Research / National Strength & Conditioning Association* 19: 673–676

Byrne, PJ, Moran, K, Rankin, P, Kinsella, S (2010) A comparison of methods used to identify 'optimal' drop height for early phase adaptations in depth jump training. *Journal of Strength and Conditioning Research / National Strength & Conditioning Association* 24(8): 2050-2055

Byrne, P, Kenny, J, O'Rourke, B (2014) Acute potentiating effect of depth jumps on sprint performance. *Journal of Strength & Conditioning Research* 28(3): 610-615

Chiu, L, Fry, AC, Weiss, LW, Schilling, BK, Brown, LE, Smith, SL (2003) Postactivation potentiation response in athletic and recreationally trained individuals. *Journal of Strength & Conditioning Research* 17(4): 671-677

Chatzopoulos, DE, Michailidis, CJ, Giannakos, AK, Alexiou, KC, Patikas, DA, Antonopoulos, CB (2007) Postactivation potentiation effects after heavy resistance exercise on running speed. *Journal of Strength and Conditioning Research* 21: 1278-1281

Chaubet, V, Cormery, B, Maitre, J, Paillard, T (2013) Stimulated contractions delay and prolong central fatigue compared with voluntary contractions in men. *Journal of Strength and Conditioning Research* 27(5): 1378–1383

Comyns, TM, Harrison, AJ, Hennessy, LK, Jensen, RL (2006) The optimal complex training rest interval for athletes from anaerobic sports. *Journal of Strength & Conditioning Research* 20(3): 471-476

Coh, M, Peharec, S, Bacic, P, Kampmiller, T (2009) Dynamic factors and electromyographic activity in a sprint start. *Biology of Sport* 26(2): 137-147

Coh, M, Tomazin, K (2006) Kinematic analysis of the sprint start and acceleration from the blocks. *New Studies in Athletics* 21(3): 13-33

Coso, JD, Hamouti, N, Estevez, E, Mora-Rodriguez, R (2011) Reproducibility of two electrical stimulation techniques to assess neuromuscular fatigue. *European Journal of Sport Science 11*(2): 95-103

Derse, E, Hansen, J, O'Rourke, T, Stolley, K (1995) *LA84 Foundation Track and Field Coaching Manual.* Los Angeles: LA84 Foundation

Docherty, D, & Hodgson, MJ (2007) The application of postactivation potentiation to elite sport. *International Journal of Sports Physiology & Performance 2*(4): 439-444

Docherty, D, Robbins, D, Hodgson, M (2004) Complex Training Revisited: A Review of its Current Status as a Viable Training Approach. *Strength and Conditioning Journal* 26: 52-57

Ebben, WP, Waits, PB (1998) A review of combined weight training and plyometric training modes: Complex training. *Strength and Conditioning Journal* 20: 18-27

Faigenbaum, AD, McFarland, JE, Schwerdtman, JA, Ratamess, NA, Kang, J, Hoffman, JR (2006) Dynamic warm-up protocols, with and without a weighted vest, and fitness performance in high school female athletes. *Journal of Athletic Training* 41(4): 357-363

Fernandez-Del-Olmo, M, Rodriguez, FA, Marquez, G, Inglesias, X, Marina, M, Benitez, A, Acero, RM (2013) Isometric knee extensor fatigue following a Wingate test: peripheral and central mechanisms. *Scandinavian Journal of Medicine and Science in Sports* 23(1): 57-65

Gardiner, PF (2001) *Neuromuscular aspects of physical activity.* Champaign, IL: Human Kinetics

Gilbert, G, Lees, A (2005) Changes in the force development characteristics of muscle following repeated maximum force and power exercise. *Journal of Ergonomics* 48(11-14): 1576-1584

Gourgoulis, V, Aggeloussis, N, Kasimatis, P, Mavromatis, G, Garas, A (2003) Effect of a submaximal half-squat warmup program on vertical jumping ability. *Journal of Strength and Conditioning Research* 17: 342–344

Gossen, ER, Sale, DG (2000) Effect of postactivation potentiation on dynamic knee extension performance. *Journal of Applied Physiology* 83(6): 524-30

Guellich, A, Schmidtbleicher, D (1995) Short-term potentiation of power performance induced by maximal voluntary contractions. *New Study in Athletics Archive* 11:67–81

Guellich, A, Schmidtbleicher, D (1996) MVC-induced short-term potentiation of explosive force. *New Studies in Athletics* 11(4): 67-81

Guggenheimer, JD, Dickin, DC, Reyes, GF, Dolny, DG (2009) The effects of specific preconditioning activities on acute sprint performance. *Journal of Strength and Conditioning Research / National Strength & Conditioning Association* 23(4): 1135-1139

Hamada, T, Sale, DG, MacDougall, JD, Tarnopolsky, MA (2000) Postactivation potentiation, fiber type, and twitch contraction time in human knee extensor muscles. *Journal of Applied Physiology* 88(6): 2131-2137

Hamada T, Sale, DG, MacDougall, JD, Tarnopolsky, MA (2003) Interaction of fibre type, potentiation and fatigue in human knee extensor muscles. *Acta Physiologica Scandinavica* 178 (2): 165-173

Hamada, T, Sale, DG, MacDougall, JD (2000) Postactivation potentiation in endurance-trained male athletes. *Medicine & Science in Sports & Exercise 32*(2): 403-411

Hedrick, A (1992) Physiological responses to warm-up. *Journal of Strength and Conditioning Research* 14: 25–27

Hilfiker, R, Hubner, K, Lorenz, T, Marti, B (2007) Effects of drop jumps added to the warm-up of elite sport athletes with a high capacity for explosive force development. *Journal of Strength and Conditioning Research* 21(2): 550-555

Houston, ME, Green, HJ, Stull, JT (1985) Myosin light chain phosphorylation and isometric twitch potentiation in intact human muscle. *European Journal of Physiology* 403: 348–352

Hrysomallis, C, Kidgell, D (2001) Effect of heavy dynamic resistive exercise on acute upper-body power. *Journal of Strength and Conditioning Research* 15(4): 426-430

Hughes, SC, Gossen, ER, Sale DG (2001) Effect of postactivation potentiation on dynamic knee extension performance (Abstract). *Canadian Journal of Applied Physiology* 26: 486

Jensen, R. L, Ebben, WP (2003) Kinetic analysis of complex training rest interval effect on vertical jump performance. *Journal of Strength and Conditioning Research* 7(2): 345-349

Jubeau, M, Gondin, J, Martin, A, Van Hoecke, J, Maffiuletti, NA (2010) Differences in twitch potentiation between voluntary and stimulated quadriceps contractions of equal intensity. *Scandinavian Journal of Medicine and Science in Sports* 20(1): 1-7

Lim, JJH, Kong, PW (2013) Effects of isometric and dynamic postactivation potentiation protocols on maximal sprint performance. *Journal of Strength & Conditioning Research* 27(10): 2730-2736

Lima, JCB, Marin, DP, Barquilha, G, Da Silva, LO, Puggina, EF, Pithon-Curi, T (2011) Acute effects of drop jump potentiation protocol on sprint and counter movement vertical jump performance. *Human Movement Science Journal* 12(4): 324-330

Linder, EE, Prins, JH, Murata, NM, Derenne, C, Morgan, CF, Solomon, JR (2010) Effects of preload 4 repetition maximum on 100-m sprint times in collegiate women. *Journal of Strength and Conditioning Research* 24(5): 1184-90

Lorenz, D (2011) Clinical commentary: Postactivation potentiation: An introduction. *International Journal of Sports Physical Therapy* 6(3): 234-240

Maloney, SJ, Turner, AN, Fletcher, IM (2014) Ballistic exercise as a pre-activation stimulus: A review of the literature and practical applications. *Journal of Sports Medicine* 44(10): 1347-1359

Mann, D, Jones, M (1999) Guidelines to the implementation of a dynamic stretching program. *Journal of Strength and Condition Research* 21: 53-55

Masiulis, N, Skurvydas, A, Kamandulis, S, Sniečkus, A, Brazaitis, M, Daniusevičiūtė, L, Ramanauskienė, I (2008) Post-activation potentiation and fatigue in quadriceps femoral muscle after a 5 s maximal voluntary isometric contraction. *Journal for Education, Physical Training and Sport* 68(1): 55-60

Matthews, MJ, Matthews, HP, Snook, B (2004) The acute effects of a resistance training warmup on sprint performance. *Research in Sports Medicine* 12(2): 151-159

McBride, JM, Nimphius, S, Erickson, TM (2005) The acute effects of heavy-load squats countermovement jump on sprint performance. *Journal of Strength and Conditioning Research* 19(4): 893–897

Mero, A (1988) Force-time characteristics and running velocity of male sprinters during the acceleration phase of sprinting. *Research Quarterly for Exercise & Sport 59*(2): 94-98

Merton, PA (1954) Voluntary strength and fatigue *Journal of Physiology* 123: 553-564

Moore, RL, Stull, JT (1984) Myosin light chain phosphorylation in fast and slow skeletal muscles in situ. *American Journal of Physiology- Cell Physiology* 247: C462–C471

Morana, C, Perrey, S (2009) Time course of postactivation potentiation during intermittent submaximal fatiguing contractions in endurance and power0trained athletes. *Journal of Strength and Conditioning Research* 23(5): 1456-1464

Miyamoto, N, Kanehisa, H, Kawakami, Y (2012) Potentiation of Maximal Voluntary Concentric Torque in Human Quadriceps Femoris. *Medical Science Sports Exercise Journal* 44(9): 1738–1746

O'Leary, DD, Hope, K, Sale, DG (1997) Posttetanic potentiation of human dorsiflexors. *Journal of Applied Physiology* 83: 2131–3138

Palmer, BM, Moore, RL, (1989) Myosin light chain phosphorylation and tension potentiation in mouse skeletal muscle. *American Journal of Physiology* 257: C1012–C1019

Place, N, Yamada, T, Bruton, JD, Westerblad, H (2010) Muscle fatigue: from observations in humans to underlying mechanisms studied in intact single muscle fibres. *European Journal of Applied Physiology* 110(1): 1-15

Radcliffe, JC, Radcliffe, JL (1996) Effects of different warm-up protocols on peak power output during a single response jump task. *Medical Science Sports Exercise Journal* 28: S29

Rassier, DE, MacIntosh, BR (2000) Coexistence of potentiation and fatigue in skeletal muscle. *Brazilian Journal of Medical & Biological Research* 33: 499–508

Requena, B, Gapeyeva, H, Garcia, I, Ereline, J, Paasuke, M (2008) Twitch potentiation after voluntary versus electrically induced isometric contractions in human knee extensor muscles. *European Journal of Applied Physiology* 104(3): 463–472

Robins, DW (2005) *Postactivation potentiation and its practical applicability: A brief review*. *Journal of Strength and Conditioning Research* 19(2): 453-458

Ross, A, Leveritt, M, Riek, S (2001) Neural influences on sprint running: Training adaptations and acute responses. *Journal of Sports Medicine* 31(6): 409-425

Sale, DG (2002) Postactivation potentiation: Role in human performance. *Exercise & Sport Sciences Reviews* 30(3): 138-143

Safran, MR, Seaber, AV, Garrett, WE (1989) Warm-up and muscular injury prevention—an update. *Journal of Sports Medicine* 8: 239–249

Sánchez, BR, Puche, PP, González-Badillo, JJ (2005) Percutaneous electrical stimulation in strength training: An update. *Journal of Strength & Conditioning Research* 19(2): 438-448

Schilling, BK, Stone, MH (2000) Stretching: Acute effects on strength and power performance. *Journal of Strength and Conditioning Research* 22: 44–47

Schmidtbleicher, D (1987) Motorized stress forming force - Definitions and Trainability. Assessment of motor function, patient-orientated practice and training concepts. *Muscular Rehabilitation Journal* 62-85

Schluter, JM, Fitts, RH (1994) Shortening velocity and ATPase activity of rat skeletal muscle fibers: effects of endurance exercise training. *American Journal of Physiology* 266: C1699–C1673

Seitz, LB, Trajano, GS, Dal Maso, F, Haff, GG, Blazevich, AJ (2015) Postactivation potentiation during voluntary contractions after continued knee extensor task-specific practice. *Applied Physiology, Nutrition, and Metabolism* 40(3): 230-237

Shellock, FG, Prentice, WE (1985) Warming-up and stretching for improved physical performance and prevention of sports related injuries. *Journal of Sports Medicine* 2(4): 267-278

Smith, CA (2004) The warm-up procedure: To stretch or not to stretch. A brief review. *Journal of Orthopedic Sports and Physical Therapy* 19: 12–17

Sweeney, HL, Bowman, BF, Stull, JT (1993) Myosin light chain phosphorylation in vertebrate striated muscle: Regulation and function. *The American Journal of Physiology-Cell Physiology* 264(33): 1085-1095

Tellez, T, Doolittle, D (1984) Sprinting from start to finish. *Track Technique* 88: 2802-2805

Tesch, PA, Karlsson, J (1985) Muscle fiber types and size in trained and untrained muscles of elite athletes. *Journal of Applied Physiology* 59: 1716 –1720

Till, KA, Cooke, C (2009) The effects of postactivation potentiation on sprint and jump performance of male academy soccer players. *Journal of Strength and Conditioning Research* 23: 1960–1967

Tillin, NA, Bishop, D (2009) Factors modulating post-activation potentiation and its effect on performance of subsequent explosive activities. *Journal of Sports Medicine* 39(2): 147-166

Turner, AP, Bellhouse, S, Kilduff, LP, Russell, M (2014) Post-activation potentiation of sprint acceleration performance using plyometric exercise. *Journal of Strength and Conditioning Research / National Strength & Conditioning Association* 16: 530-538

Vandervoort, AA, Quinlan, J, McComas, AJ (1983) Twitch potentiation after voluntary contraction. *Journal of Experimental Neurology* 81: 141-152

Westerblad, H, Allen, DG (1991) Changes of myoplasmic calcium concentration during fatigue in single mouse muscle fibers. *Journal of General Physiology* 98(3): 615–635

Widrick, JJ, Trappe, SW, Blaster, CA, Costil, DL, Fitts, RH (1996) Isometric force and maximal shortening velocity of single muscle fibers from elite masters runners. *American Journal of Physiology* 271: C666–C675

Wilson, JM, Duncan, NM, Brown, PJ, Loenneke, JP, Wilson, SM, Jo, E, Lowery, RP, Ugrinowitsch, C (2013) Meta-analysis of postactivation potentiation and power: effects of conditioning activity, volume, gender, rest periods, and training status. *Journal of Strength and Conditioning Research* 27(3): 854-859

Young, WB (1993) Training for speed/strength: Heavy versus light loads. *National Strength and Conditioning Journal* 15(5): 34–43

Young, WB, Behm, DG (2003) Effects of static stretching and practice jumps on explosive force production and jumping performance. *The Journal of Sports Medicine and physical fitness* 43: 21–27

Young, WB, Jenner, A, Griffiths, K (1998) Acute enhancement of power performance from heavy load squats. *Journal of Strength & Conditioning Research* 12(2): 82-84

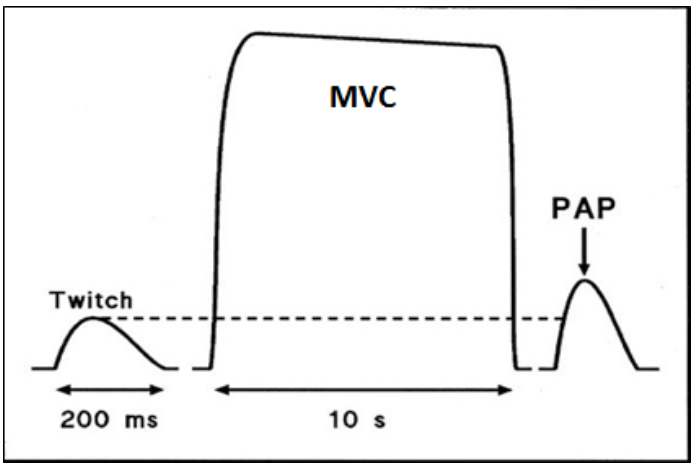



**Figure 1-1** An example of PAP (adapted from Sale, 2002). First, a baseline twitch is evoked in a muscle that has been at rest for a period of time. Secondly, a conditioning contraction, such as a maximal voluntary contraction (MVC) is done. Once potentiated, an evoked isometric twitch is used to demonstrate the increased peak torque and rate or torque development (Sale, 2002)

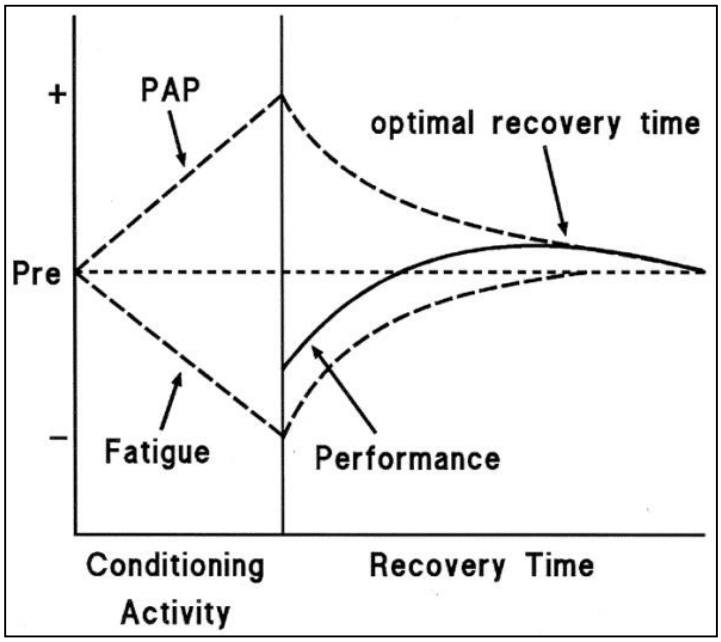



**Figure 1-2** (Sale, 2002). Strategy for exploiting PAP to improve performance. The PAP protocol potentiates the muscle and is monitored as the change in isometric twitch torque. Peripheral fatigue is potentially induced by the PAP. However, if fatigue dissipates faster than PAP

decays, as illustrated, performance will be enhanced (Sale, 2002).

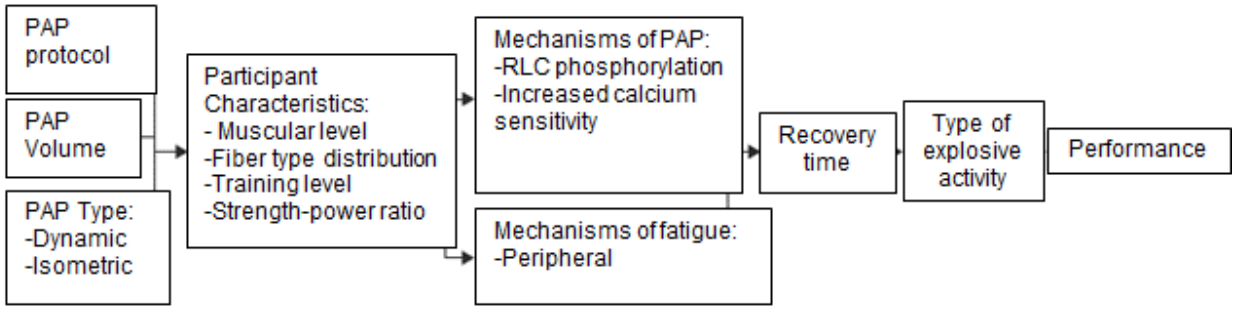



**Figure 1-3** An example of complex factors (adapted from Tillin & Bishop, 2009) influencing performance of a voluntary explosive activity following a PAP protocol. The mode and volume of PAP affect individuals differently, depending on their fiber type and training status. Collectively, these factors will influence the extent to which the mechanisms of PAP and fatigue are affected. The interaction between the mechanisms of PAP and fatigue will determine whether subsequent performance is enhance or diminished (Tillin & Bishop, 2009).

# CHAPTER 2: THE EFFECT OF A PLYOMETRIC PROTOCOL ON MUSCLE POTENTIATION

## 2.1 Introduction

The ability to produce maximal muscle force as quickly as possible are key components of many athletic endeavors. However, contractile history of a muscle can markedly affect these aspects of muscular performance (Robins, 2005). Warm-up procedures that involve dynamic movements have become increasingly popular ways to potentiate the force generating capability of the muscle, elevate body temperatures, and maximize dynamic ranges of motion, ultimately maximizing performance by creating an optimal environment for power production (Mann & Jones, 1999; Faigenbaum et al., 2006). Plyometric protocols have been incorporated into warm-up routines to potentiate the muscle and have resulted in improved performance. Although researchers have claimed that the improved performance was as a result of potentiation in the muscle (Burkett, Phillips, & Ziuraitis, 2005; Hilfiker et al., 2007; Young, & Behm, 2003; Faigenbaum et al., 2006; Lima et al., 2011; Byrne, Kenny, O'Rourke, 2014), known as post activation potentiation (PAP), there is no evidence to support these claims. Thus, the present experiments were designed to determine whether a plyometric protocol induces PAP, and if so, quantify the magnitude and time course of PAP.

The term "PAP" was defined by Robbins (2005) as: "The phenomenon by which acute muscle force output is enhanced as a result of contractile history" (pg. 453). The most widely accepted mechanism of PAP is the phosphorylation of myosin regulatory light chains (Sweeney et al., 1993). Phosphorylation amplifies the sensitivity of myosin to calcium, augmenting the rate by which actin-myosin cross-bridges move to a force producing state (Gardiner, 2001; Sweeny et al.,

1993). The result is an increase in contraction force and rate of force development (RFD; Sweeny et al., 1993). However, muscle contractions can produce both PAP and fatigue, and it is the balance between these two factors that determine whether muscle force is augmented or reduced (Robins, 2005). Therefore, to optimise performance, one must select a protocol that maximizes PAP and minimises fatigue. A particular challenge for the application of such a protocol is the variable time delay between warm-up and performance. This delay makes it difficult to know when to incorporate a protocol to maximise power production when it is most needed, at the time of the performance.

The present study was designed to characterize PAP in the quadriceps muscles induced when a standard warm-up was followed by a plyometric protocol that has been previously suggested to induce PAP. This design allowed us to; 1) quantify the magnitude of PAP and, 2) assess the temporal characteristics of PAP over time intervals that would be relevant for real world competitions. A goal of this work was to identify when the most optimal time is to incorporate a plyometric protocol for maximal enhancement of power production. All participants completed a standard warm-up, followed by either a series of drop jumps (plyometric protocol) or a low pace walk (control protocol), on separate days. Torque and electromyography (EMG) were recorded during nine sets of 3 electrically-evoked maximal twitches throughout both sessions. An increase in twitch torque, with no change in the amplitude of the evoked EMG response (M-wave), was taken as confirmation that PAP was induced (Sweeny et al., 1993; Baudry & Duchateau, 2007). We hypothesized that the plyometric protocol (drop jumps), but not the standard warm-up (Burkett, Phillips, Ziuraitis, 2005), would induce PAP. We also hypothesized that this PAP would dissipate over 10-15 minutes. These hypotheses are based on experiments that have shown that plyometric protocols improve performance for 10-15 minutes (Lima et al., 2011). The results of

these experiments will help determine whether plyometric protocols improve the force generating capacity of the muscle and, if so, will delineate when athletes should perform drop jumps to possibly maximise subsequent performance.

## 2.2 Methods

### 2.2.1 Participants

Eight female and twelve male athletes participated in this study. Fifteen participants were varsity athletes at the University of Alberta involved in football (n=8), track (n=3), rugby (n=2), or swimming (n=2). The other five participants were power trained, recreational athletes, at the time of the study, and were previously competitive at high school or club level. Mean participant characteristics for age, height, and mass are summarized in Table 1. The experimental protocol was approved by the Human Research Ethics Board at the University of Alberta. Participants signed an informed consent form that explained the nature, purpose, and risks involved in this study.

**Table 1**. Participant physical characteristics (20)
(mean ± SD)

| Age (years) | Height (m) | Mass (kg) |
|---|---|---|
| 22.1±2.7 | 1.7±0.1 | 76.1±16.4 |

Participants were required to have been injury free six months prior to enrollment, and have drop jump experience. All participants completed a familiarization, control, and PAP session on separate days. The order of the control and PAP sessions was randomly assigned for each participant. All three sessions were completed at the same time of day, for a given participant. Participants were instructed to refrain from any heavy lower leg training 24 hours prior to the sessions, as well as any caffeinated beverages 12 hours prior to testing.

### 2.2.2 Electrical Stimulation

One millisecond square wave pulses were delivered to the right quadriceps muscles using a high voltage constant current stimulator (Digitimer Ltd, DS7AH, Hertfordshire, England) to generate maximal twitches. Skin surfaces were shaven, abraded and swabbed with alcohol pads. Stimulating electrodes (ValuTrode 3" by 5" Neurostimulation Electrodes) were placed over the muscle belly, with the cathode placed proximally over vastus lateralis and the anode over the vastus medialis according to recommendations of Strojnik (1995). Figure 2-1A provides an illustration of the location of the stimulation electrodes.

### 2.2.3 Electromyography (EMG)

A Neurolog system (Digitimer Neurolog System NL136, Digitimer Ltd, Hertfordshire, England) was used to record M-waves evoked in the vastus medialis muscle. Skin surfaces were shaven, abraded and swabbed with alcohol pads. As illustrated in Figure 2-1A, the electrodes (NeuroPlus 1" Disposable Solid Gel Electrodes) were placed ~4-8 cm proximal from the apex of right patella (Gossen & Sale, 2000, pg. 526) with an inter-electrode distance of 1 cm. The ground electrode was placed on the patella. A digital multimeter was used to measure the skin impedance six times during each experiment (after T2-T4, and T6- T8). Impedance was monitored to ensure consistent electrical signal conduction and stayed below 5 kohm (Morana & Perrey, 2009; Strojnik & Komi, 1998 ) for all participants in both sessions.

### 2.2.4 Dynamometer

A Biodex System III dynamometer (Biodex Medical Systems, Inc., Shirley, NY, USA) was used to measure isometric knee extension torque. The participant was comfortably seated in the

Biodex chair with their hip and knee positioned at ~90°. A Velcro strap was used to secure the lower limb to the Biodex at the ankle.

### 2.2.5 Experimental procedure

#### *2.2.5.1 Familiarization session*

All participants first attended a familiarization session which lasted ~30 minutes. The purpose of this session was to introduce the participants to the electrical stimulation, standard warm-up and drop jumps. Initially, participants were seated in the Biodex. A test was completed to find the stimulation intensity that produced maximal twitches. Once this intensity was found, participants completed the standard warm-up and then performed three drop jumps. Participants then sat in the Biodex chair and received 3 maximal electrically-evoked twitches. Further details of all procedures are provided below.

#### *2.2.5.2 Control and plyometric sessions*

The plyometric and control sessions each lasted ~1.5 hours. Each of these sessions began with a test to find the stimulation intensity that produced maximal twitch torque. Stimulation intensity was gradually increased at 5 second intervals, until three successive increases did not result in any increases in peak twitch torque. This allowed us to identify the lowest stimulation intensity that produced a maximal twitch torque for each participant. The stimulation intensity used to generate maximal twitches during the experiment was 1.15 times this intensity. This supramaximal intensity was used to ensure maximal twitch torque was achieved at all times. The average number of twitches during this test ranged from 20-25.

Nine sets of three maximal twitches were delivered throughout each session, with a 5 second interval between every twitch in each set. The experimental protocol is outlined in Figure

2-2. After the first set of twitches (T1 in Figure 2-2), participants in both sessions performed the standard warm-up. This warm-up consisted of cycling for 5 minutes on a stationary bicycle (Monark Exercise 828E, Vansbro, Sweden) at 60 rpm with a resistance of 1 kilopond, followed by 14 lower body static stretches, each held for 20 seconds, according to recommendations of Burkett and colleagues (2005).

Within 30 seconds after the standard warm-up, participants in both sessions were seated back in the Biodex chair and received 4 sets of twitches (T2-T5) at 10 minute intervals. After these twitches the protocol for the control and plyometric sessions differed. Participants in the control session performed a 5 minute low pace walk. Participants in the plyometric session performed 2 sets of 5 drop jumps from a height of 0.76 meters (Lima et al., 2011). The interval between each drop jump was 15 seconds, with a 3 minute rest period between each set. To perform the drop jumps participants stepped down, proceeding into a 90 degree squat position, then jumped vertically as explosively as possible, keeping ground reaction times as short as possible, according to recommendations of Marshall and colleagues (2013). Following the drop jumps and control walk, participants were seated back in the Biodex within 30 seconds and received 4 sets of twitches (T6-T9) at 5 minute intervals.

### 2.2.6 Data Collection

EMG signals were pre-amplified 1000x (Neurolog System NL844 Pre-Amplifier, Hertfordshire, England) and high-pass filtered (cut-off frequency = 10 Hz). The signal was then amplified 5x and was band-pass filtered (10 Hz - 1000 Hz). All data were sampled at 5000 Hz using a 12-bit A/D converter (National Instruments, PCI-MIO-16E-4), and stored on a personal computer using custom written software (Labview 8.5, National Instruments, Austin, TX, USA).

### 2.2.7 Data Analyses

Data analyses were conducted using custom-written MATLAB® software (MathWorks Inc., United States). Five outcome measures were quantified from each twitch, four of which are illustrated in Figure 2-1B. Peak twitch torque (PTT) was defined as the point where maximal torque was generated. The amplitude of M-waves was measured as peak-to-peak. Peak rate of torque development (RTD) was calculated as the highest slope for any 50-millisecond epoch over the initial 200 milliseconds of the torque produced by each twitch according to recommendations of Thompson and colleagues (2013). Time to peak torque (TTPT) was calculated as the time to reach peak twitch torque. Impulse was calculated as the area under the torque-time curve from 0-50 milliseconds (Thompson et al., 2013). The 5 outcome measures calculated for the 3 twitches were averaged for every participant for both sessions.

Statistical analyses were performed using StatSoft Statistica (version 6.0) with an alpha level of $p \leq 0.05$. All statistical analyses were conducted on group data. Two-way repeated measures analyses of variance (ANOVA) were used, with 2 levels of condition (plyometric/control protocol) and 9 levels of time. Tukey post-hoc analyses were used (when appropriate) when the ANOVA identified statistically significant effects. When a significant interaction was found, main effects were not reported. Descriptive statistics are reported as means and standard errors.

## 2.3 Results

The only protocol that potentiated muscle twitches significantly was the plyometric protocol. PTT, RTD, and impulse were greater during twitches evoked immediately after the plyometric protocol than during twitches evoked before the plyometric protocol. The induced PAP dissipated within 6 minutes. These changes in PTT occurred despite no change in the amplitudes of the M-waves recorded during the muscle twitches.

### 2.3.1 Individual participant data

Torque and EMG recorded during twitches evoked throughout the plyometric and control sessions are shown for a single participant in Figure 2-3. Each panel shows data recorded during twitches evoked immediately before and after the standard warm-up (T1 and T2). The top panel shows that for this participant the standard warm-up increased the amplitude of muscle twitches slightly (by ~8%) during both the plyometric and control sessions, compared to T1. These data also show that twitches were augmented after the plyometric protocol but not the control protocol (see thick versus thin lines at T6). Compared to twitches recorded immediately prior to the plyometric protocol (T5), twitches were augmented by ~20% after the plyometric protocol (T6) and then returned to baseline amplitude within 6 minutes (T7). M-waves were relatively stable throughout both protocols with the exception of a decline in amplitude following the plyometric protocol.

### 2.3.2 Group data: Peak twitch torque

The plyometric protocol significantly augmented PTT across participants. Panels A and B of Figure 2-4 show the PTT recorded for each participant during the plyometric and control sessions, respectively. Despite the relatively large range of PTT between participants (18Nm-77Nm for T1), the plyometric protocol consistently augmented twitch torque and this effect dissipated within 6 minutes (compare T5, T6, T7; panel A). Neither the standard warm-up nor the control protocol altered PTT in a consistent way across participants.

Panel C of Figure 2-4 shows the mean PTT for both the plyometric and control sessions across the group of 20 participants. There was a significant interaction between Condition and Time [$F_{(8,152)}$=12.76, $p<0.001$]. The asterisks on panel C show that PTT recorded during the

plyometric session were significantly larger than during the control session at T6 (by ~17%, p=<0.001) and were significantly smaller (~9%) during the plyometric session than the control sessions at T8 (p=0.01) and T9 (p=0.01) Across the group, the standard warm-up did not alter twitch torque; there were no significant differences in PTT between T1 and T2 for either the plyometric or control sessions. The only significant difference in PTT between twitches evoked during the control sessions was a decrease of 8% at T3 compared to T1 (p=0.03). In contrast, during the plyometric session, PTT recorded during twitches from T3-T9 were all significantly different from T1. On average PTT from T3-T5 was decreased by 9%, compared to T1. The plyometric protocol increased PTT by ~23%, compared to twitches evoked immediately before the plyometric protocol at T5 (p=<0.001) and by ~15% compared to T1 (p=<0.001). At T7, 5 minutes after T6, the PAP dissipated and peak twitch torque dropped by ~22% (p=<0.001), compared to T6. By 10 to 15 minutes after T6, PTT at T8 and T9 were 13% on average lower than the PTT at T1 (p=<0.001).

### 2.3.3 M-waves

M-wave amplitudes were not significantly different between the PAP and control sessions and did not change significantly over time during either session. Figure 2-5 shows the amplitude of M-waves for individual participants (panels A and B) and averaged across the group (panel C). There was no significant interaction between Condition and Time [$F_{(8,152)}$=0.41, p=0.92] and no main effect of condition [$F_{(8,152)}$=0.05, p=0.83]. There was a significant main effect of Time [$F_{(8,152)}$=2.03, p=0.047], however post-hoc analysis of this main effect did not identify any significant differences.

### 2.3.4 Rate of torque development

There was a significant increase in RTD following the plyometric protocol. Figure 2-6A shows RTD for both the plyometric and control sessions across the group of 20 participants. There was a significant interaction between Condition and Time [$F_{(8,152)}$=10.77, p<0.001]. The asterisk shows that the RTD during the twitches evoked immediately after the plyometric protocol was significantly larger (by ~32%, p=<0.001) than twitches evoked immediately after the control protocol. Across the group, the standard warm-up did not alter RTD; there were no significant differences in RTD between T1 and T2 for either the plyometric or control sessions. There were no significant differences in RTD between any of the twitches evoked throughout the control session. In contrast, during the plyometric session, RTD recorded during twitches T3 (p=0.04), T4 (p=0.04), T6 (p= <0.001), T8 (p= <0 .001), and T9 (p=<0.001) were all significantly different from T1. On average RTD from T3-T4 was decreased by 12%, compared to T1. The plyometric protocol increased RTD by ~39% (p=<0.001), compared to twitches evoked immediately before the plyometric protocol (T5) and by ~23% (p=<0.001) compared to T1. At T7, 5 minutes after T6, the RTD dropped by ~27%, compared to T6 (p=<0.001). By 10 to 15 minutes after T6, RTD at T8 and T9 were significantly lower and RTD were 16 % on average lower than RTD at T1 (p=<0.001).

### 2.3.5 Time to peak torque

There were no significant differences between TTPT between the plyometric and control session. Figure 2-6B shows the TTPT for both the plyometric and control sessions across the group of 20 participants. A significant interaction between Condition and Time [$F_{(8,152)}$=2.19, p=0.03] was found, however no significant differences were found between TTPT at T6 for both groups (p=0.58). Across the group, the standard warm-up did not alter TTPT; there were no significant differences in TTPT between T1 and T2 for either the plyometric or control sessions.

There was variability between TTPT values throughout the control session with significant increases in TTPT between twitches evoked at T4 (p=0.01), T5 (p=0.01), T8 (p=0.01), and T9 (p=0.002), compared to the baseline value at T1. In contrast, the plyometric protocol significantly decreased TTPT by ~7% (p=0.01), compared to twitches evoked immediately before the plyometric protocol (T5). There were no significant differences between TTPT following the plyometric protocol at T7, T8 and T9, respectively, at 5, 10, and 15 minutes after T6, when compared to T1 and T5 prior to the plyometric protocol. In contrast, 10 to 15 minutes following the control protocol, there was a significant increase in TTPT at T8 (~9%, p=0.005) and T9 (~10%, p=0.002) respectively, compared to the baseline at T1. There were no significant differences in points of interest (T6-T9) for TTPT between respective twitches recorded during the plyometric and control sessions.

### 2.3.6 Impulse

There was a significant increase in impulse following the plyometric protocol. There was a significant interaction between Condition and Time [$F_{(8,152)}$ =2.53, p=.013]. The asterisk on panel C shows that impulse for the twitches evoked immediately after the plyometric protocol were significantly larger (by ~31%) than the control protocol at T6. Figure 2-6C shows the mean impulse for both the plyometric and control sessions across the group of 20 participants. Across the group, the standard warm-up did not alter impulse; there were no significant differences in impulse between T1 and T2 for either the plyometric or control sessions. The only significant differences in impulse between twitches evoked during the control session was a decrease of 22% at T4 (p=0.02) and 21% at T9 (p=0.03) compared to T1. The plyometric protocol increased impulse by ~46%, compared to twitches evoked immediately before the plyometric protocol at T5 (p=<0.001) and by ~26% compared to T1 (p=<0.004). At T7, 5 minutes after T6, the impulse

dropped by ~27%, compared to T6 (p=<0.001). Impulse was significantly different 10 to 15 minutes after T6 at T8 and T9 respectively, with an average decrease of 9% compared to T1 (p=<0.001).

## 2.4 Discussion

It has been suggested that drop jumps improve athletic performance by inducing PAP and enhancing the force generating capacity of the muscle (Hilfiker et al., 2007; Guggenheimer et al., 2009; Lima et al., 2011; Byrne, Kenny, & O'Rourke, 2014; Maloney, Turner, & Fletcher, 2014; Turner, Bellhouse, Kilduff, & Russell, 2014). However, whether drop jumps induce PAP has not been previously tested. The present results supports our first hypothesis that drop jumps induce PAP, whereas a standard warm-up does not. PAP dissipated within 6 minutes, which is contrary to our second hypothesis that PAP induced by drop jumps would last for 10-15 minutes. Thus, drop jumps are an effective way to induce PAP and when incorporated immediately prior to sports requiring short bouts of explosive movements, drop jumps may enhance performance, at least in part, by inducing PAP.

### 2.4.1 Drop jumps but not standard warm-up induce PAP

Drop jumps induced PAP in the quadriceps muscles. PAP is associated with an increase in sensitivity of actin-myosin cross-bridges to calcium, thus enhancing the force generating capacity of the muscle. Immediately after the plyometric protocol, peak twitch torque increased by 23% and RTD increased by 39%, compared to immediately before the plyometric protocol. The amplitude of M-waves recorded before and after the plyometric protocol were not significantly different, showing that the electrical activity of the muscle was not influenced by the plyometric protocol. Thus the increase in the peak twitch torque and RTD must have been due to PAP as the mechanism is located distal to the sarcolemma.

The standard warm-up did not induce PAP. There were no significant differences in PTT, RTD, or M-wave amplitudes between twitches evoked immediately before and after the standard warm-up. In fact, the standard warm-up decreased PTT by 8% and 9% for both control and plyometric sessions, respectively. In previous studies, standard warm-ups of similar intensity as that used in the present study did not improve performance (Burkett, Phillips, Ziuraitis, 2005; Byrne, Kenny, O'Rourke, 2014). Altamirano and colleagues (2012) examined the effects of a slightly higher intensity warm-up and found that it did not induce PAP, but did reduce muscle stiffness and intramuscular fluid pressure (Altamirano et al., 2012). Since standard warm-ups of mild to moderate intensity do not induce PAP and may even induce fatigue, implementation of a protocol such as drop jumps after a standard warm-up may be an effective way to enhance athletic performance.

### 2.4.2 PAP dissipated quickly

The PAP induced by the drop jumps dissipated rapidly. Within 6 minutes of the plyometric protocol (T7), PTT and RTD declined by 23% and 27% respectively, compared to twitches recorded immediately after the plyometric protocol (T6), and were not significantly different from baseline (T1). A similar decline in PTT and RTD within 6 minutes has also been shown following MVCs (Gossen et al., 2000; Hamada et al., 2000; Baudry et al., 2007; Requena et al., 2008; Morana and Perrey, 2009). In the present, study evoked twitches were administered in 5 minute intervals, therefore if shorter time intervals were used, we may have found the PAP dissipated even sooner. Our hypothesis that PAP would last for 10-15 minutes was based on the previous finding that the same drop jump protocol as used in the present study improved sprint and jump performance for up to 15 minutes (Lima et al., 2011). Participants in the Lima study performed jumps and sprints 3 times in 5 minute intervals, which may have prolonged the PAP induced by the drop jumps.

The magnitude and time course of PAP are dependent on the balance between PAP and fatigue and both are known to be influenced by fiber type (Sale, 2002). A 10-second MVC induced PAP in the tibialis anterior muscle and plantar flexor muscles that lasted 6 minutes and 8-10 minutes, respectively (Vandervoort, et al., 1984). The tibialis anterior is comprised of predominantly type I fibers (Henriksson-Larsen, Lexell, & Sjostrom, 1983), whereas the plantar flexors are comprised of predominantly type II fibers (Ochala et al., 2015). This could explain why the PAP induced in the tibilais anterior dissipated at a slower rate, since muscles that typically express a higher proportion of type I muscle fiber composition are more fatigue resistant (Tesch & Karlsson, 1985; Schluter & Fitts, 1994; Widrick et al., 1996; Hamada, Sale, & MacDougall, 2003). Morana and Perrey (2009) assessed the PAP induced by a 10 minute intermittent knee extension exercise (5 second contraction, 5 second rest) at 50% of MVC in two groups of athletes. The power trained group (i.e. rugby players and power lifters) who typically have a higher proportion of type II muscle fibers, demonstrated more PAP than the endurance group (i.e. distance runners and triathletes), who typically have a higher proportion of type I muscle fibers. The PAP dissipated within 5 minutes for the power group, but was still evident in the endurance group by the end of the 10 minute MVC protocol. The present study utilized power trained athletes involved in sports that require a high expression of type II muscle fibers. Given the results of previous findings, in conjunction with the time course of PAP following the drop jumps in our study, it is clear that fatigue was most likely a factor and affected the magnitude and time course of PAP. Thus the rapid decay in peak twitch torque and RTD in the present study likely reflects both a decline in PAP and underlying fatigue, and this time course may have been slower if endurance athletes were tested.

By 11 - 16 minutes after the plyometric protocol PTT fell significantly below baseline (T1). Fatigue has been defined as: "The depression of contractile response, which can be attributed to prior activity" (Rassier et al., 2000, pg.500). As PTT declined, there were no changes in M-wave amplitudes, which indicates that the mechanisms responsible for the decline in the force generating capacity of the muscle were distal to the sarcolemma (Merton, 1954; Westerblad & Allen, 1991). Such mechanisms include structural and metabolic perturbations that affect excitation-contraction coupling, metabolite accumulation, muscle structural integrity, and glycogen depletion (Allen, Lee, & Westerblad, 1989; Allen, Lannergren, & Westerblad, 1995; Proske & Morgan, 2001; Bowers, Morgan, & Proske, 2004; Place et al., 2010; Chaubet et al., 2013; Fernandez-del-Olmo et al., 2013). Morana and Perrey (2009) reported ~30% reduction in PTT of their group of power trained athletes below baseline level between 5-10 minutes of performing the 10 minute PAP, whereas the group of endurance athletes still had increases in twitch torque by ~30% at this time (Morana & Perrey, 2009). Thus, within the last 5 minutes of the 10 minute plyometric protocol, intermittent knee extensions failed to keep the knee flexors potentiated within the power group, indicating that effects of fatigue were more prominent than the effects of PAP. The present study utilized a plyometric protocol consisting of drop jumps, lasting ~6 minutes and it is likely fatigue induced by the drop jumps was more prominent than the PAP at 11-16 minutes following the drop jumps. However, this present study did not utilize measures to determine the onset of the metabolic and structural mechanisms responsible for fatigue. Although the resultant fatigue was due to something in the muscle, the exact mechanisms responsible for the decline in the force generating capacity of the quadriceps remains unknown. Although power athletes have a faster decay in PAP than endurance athletes, given the time course of PAP, drop jumps would not be suitable for endurance events since these events last longer and don't usually require explosive movements.

Instead, protocols that induce PAP would be most beneficial for sports that require explosive movements lasting no longer than ~6 minutes. Protocols that maximize PAP with minimal fatigue would be ideal, but whether PAP can exist without fatigue is not known, and is very unlikely. In order to minimize fatigue following drop jumps future studies could assess how many drop jumps it takes to induce PAP, which may decrease the amount of activity needed to produce the same potentiated result with less fatigue.

### 2.4.3 Does PAP induced by drop jumps improve performance?

The changes in PTT, RTD, impulse and TTPT reported in the present study reflect an augmented force generating capacity of the muscle and have important functional implications. Increases in maximal force and the rate at which the force is developed directly affect acceleration of the limb, which is a crucial component in explosive performance (Coh & Tomazin, 2006). Previous researchers have suggested that plyometric protocols improve sprint and vertical jump performance due to PAP (Young, & Behm, 2003; Burkett, Phillips, & Ziuraitis, 2005; Faigenbaum et al., 2006; Hilfiker et al., 2007; Guggenheimer et al., 2009; Lima et al., 2011; Byrne, Kenny, & O'Rourke, 2014; Maloney, Turner, & Fletcher, 2014; Turner et al., 2014). However, no measure was used to assess whether PAP was induced. Given the results of the present study, it is likely that the PAP was induced by the drop jumps and did contribute to enhanced performance. However more research needs to be done to confirm the ecological validity of our findings and its direct implication on sprint or jump performance. Due to the unreliable study designs in previous investigations of PAP and performance, future studies could apply the present study's protocol in a field setting, using a single performance measure to assess the effects of drop jumps on performance at different time intervals, on separate days. This type of study design prevents the performance test from possibly prolonging the time course of PAP.

### 2.4.4 How to incorporate drop jumps to improve performance

Athletes involved in sports that require explosive movements could benefit from drop jumps since the primary benefits of inducing PAP are increases in the peak force and rate of force development. Sports that involve short periods of performance such as track, swimming, powerlifting, gymnastics, and baseball would be most suitable for incorporation of such a protocol. However, PAP in our study dissipated within 6 minutes, therefore the time course of implementation prior to performance is a key element for optimal performance benefits. Coaches who incorporate drop jumps in warm-up protocols should be aware of the rate of dissipation of PAP and the trade-off between PAP and fatigue. The present study shows that in order to maximally benefit from PAP induced by drop jumps, athletes should perform drop jumps immediately before competition.

### 2.4.5 What is the best PAP protocol?

PAP can be induced through heavy lifting, plyometrics, and MVCs (Sale, 2002). Heavy lifting protocols have shown to improve sprint and jump performance (Ebben & Waits, 1989; Young, McLean, & Ardagna, 1995; Pfaff, 1997; Young, Jenner, & Griffiths, 1998; Radcliffe & Radcliffe, 1999; McBride, Nimphius, & Erickson, 2005; Burger, Boyer-Kendrick, & Dolny, 2000; Linder et al., 2010). Significant improvements of 3.9% were reported for sprint performance following a bout of heavy 5 repetition maximum back squats (Mathews et al., 2004). However, heavy lifting protocols require heavy equipment, specific skill set and technique, and are not practical for a competitive setting (Lorenz, 2011; Maloney et al., 2014). Protocols such as MVCs or drop jumps, however, would be more suitable for performance environments. MVCs induce PAP, increasing peak twitch torque by 53 (4) % (SE) and 43 (3) % at ~15 and 40 seconds, respectively (Gossen et al., 2000). Thus, the MVC generated more than a 2-fold increase in peak

twitch torque, compared to our findings. However, subsequent leg extensions themselves, performed during the experimental protocol, may have potentiated the muscle and contributed to the reported increase in peak twitch torque (Gossen et al., 2000). Whether MVCs improve performance is not clear. Improvements in vertical jump of up to ~6% have been reported (French et al., 2003). Which is consistent with improvements in jump heights following drop jumps (Lima et al., 2011). However not all studies reported improvements in sprint and jump performance (Till & Cook, 2009; Lim & Kong, 2013).

Both MVCs and drop jumps improve performance and both are practical and effective in a performance environment. However drop jumps may be more suitable for performance since drop jumps require activation of multiple muscle groups (Maloney et al., 2014). Therefore drop jumps could simultaneously potentiate more muscle groups than a MVC, resulting in a summation of multiple potentiated muscles that could, in unison, generate more force. This would be more beneficial for performance since majority of explosive movements require maximal activation of multiple muscle groups (e.g. sprint start; Coh & Tomazin, 2006). We suggested that drop jumps would be more applicable in sports that utilize multiple muscle groups, however one must consider the specificity of the protocol to the performance to maximize the force generating capacity of the muscles.

### 2.4.6 Conclusion

Drop jumps increased peak twitch torque, RTD and impulse, and decreased TTPT. M-wave amplitudes did not change when peak twitch torque was augmented, confirming that PAP was responsible for the augmented twitch force. This PAP dissipated within 6 minutes, and 11-16 minutes following the drop jumps PTT were below baseline (T1). These results provide evidence that drop jumps enhance the force generating capacity of muscle and would be beneficial to

improve performance of explosive activities of short duration, that require maximal force and maximal rate of force development. It is recommended that drop jumps be implemented directly prior to athletic performances that require explosive movements, lasting no longer than ~6 minutes, to acutely enhance the force generating capacity of the muscles.

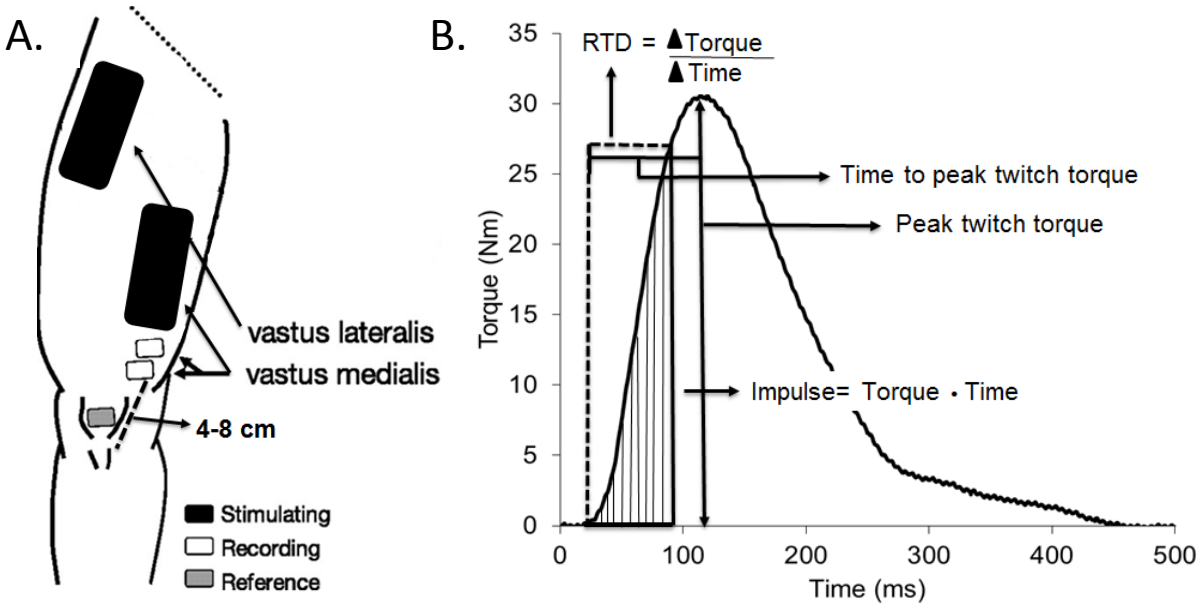



**Figure 2-1 A.** Illustration of stimulating, recording and ground electrodes. Stimulation electrodes were applied on the muscle belly of the vastus lateralis and vastus medialis of the right quadriceps muscle. The recording electrodes were applied ~4-8 cm from the apex of the right patella on the vastus medialis, with an interelectrode distance of 1cm (adapted from Bergquist et al., 2012). **B.** An illustration of a torque-time curve of a single electrically evoked isometric twitch. PTT was identified as the highest point on the torque-time curve. TTPT was calculated as the time to PTT. RTD was calculated as the slope of the torque-time curve. Impulse was calculated as the area under the torque-time curve.

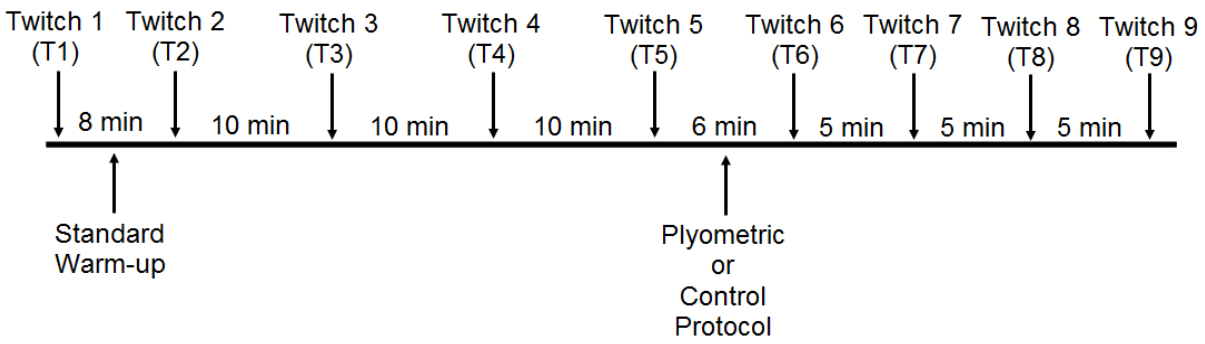



**Figure 2-2** Overview of the experimental protocol. Each participant completed both the plyometric and control protocol, in separate sessions and on different days. Nine sets of three maximal twitches were delivered throughout each experimental session.

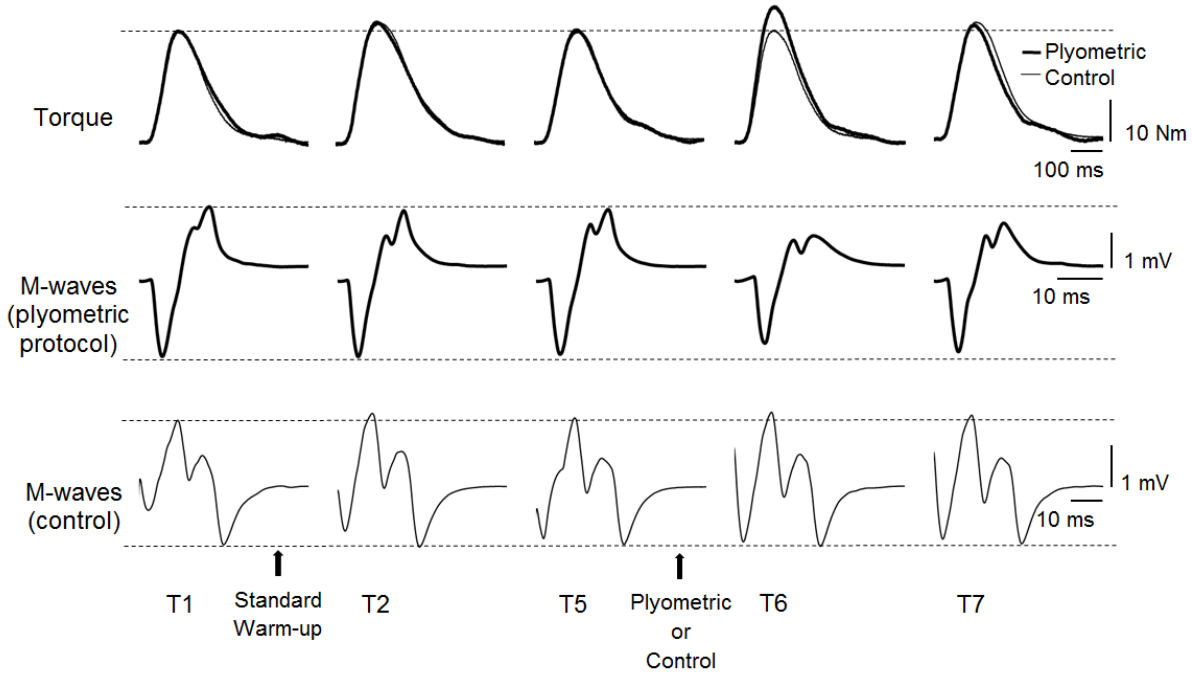
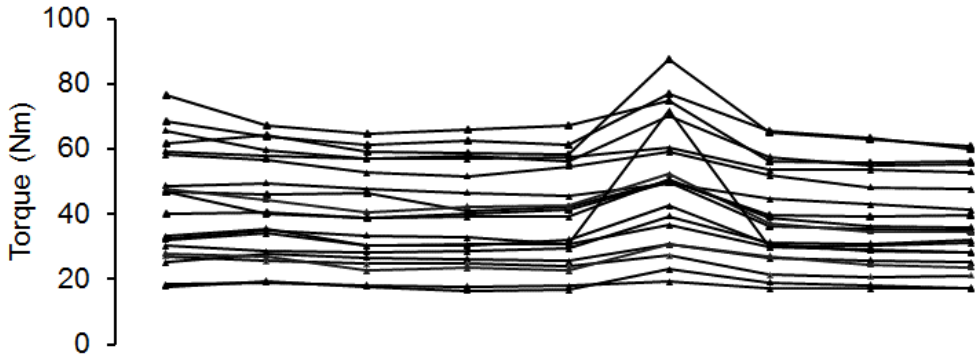
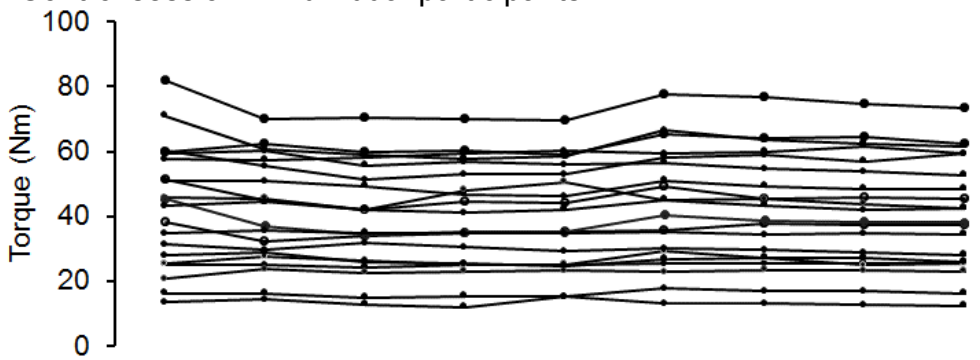



**Figure 2-3** Torque and EMG recorded from a single participant. The top panel shows torque recorded during twitches evoked during the plyometric and control sessions. Corresponding M-waves recorded during the plyometric and control sessions are shown in the middle and lower panels, respectively. Twitches 1 and 2 were recorded immediately before and after the standard warm-up, respectively. Twitches 5 and 6 were recorded before and after the plyometric or control protocols, respectively. Twitch 7 was recorded 5 minutes after twitch 6. Each twitch was calculated as the average of 3 twitches.

A. Plyometric session – Individual participants




B. Control session – Individual participants




C. Group data

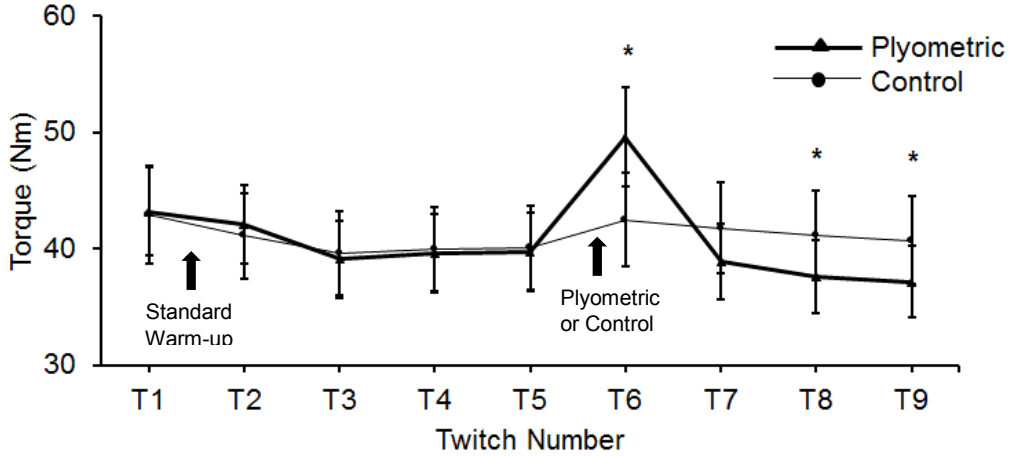
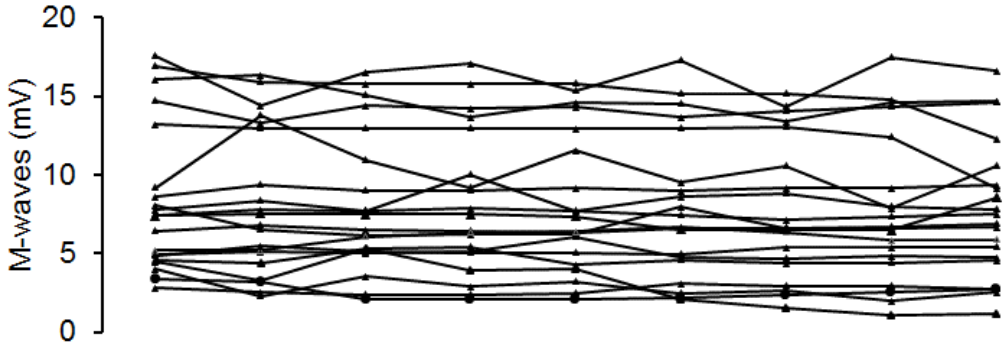
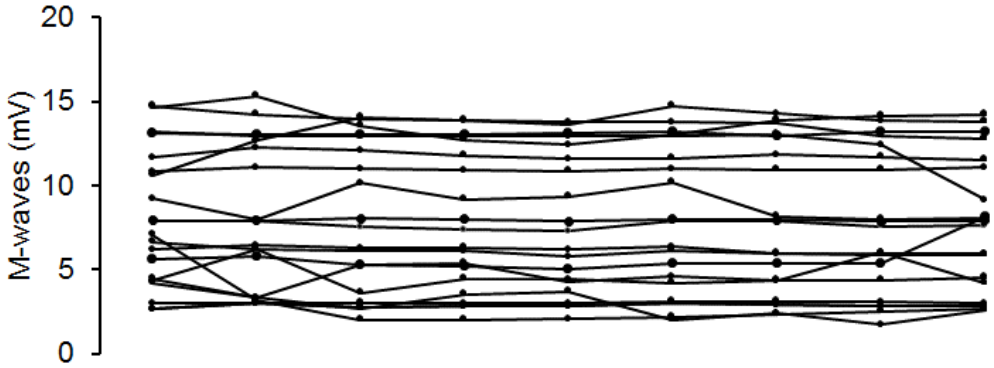



**Figure 2-4** PTT recorded during twitches for individual participants (panels A and B) and averaged across the group (panel C). Each line in panels A and B show data from an individual participants and data points represent the PTT averaged across 3 twitches. Panel C shows group data from the plyometric and control sessions. Each data point represents the average across the 20 participants. Error bars represent 1 standard error. Asterisks denote significant differences between the plyometric and control sessions.

A. Plyometric session– Individual participants




B. Control session – Individual participants




C. Group data

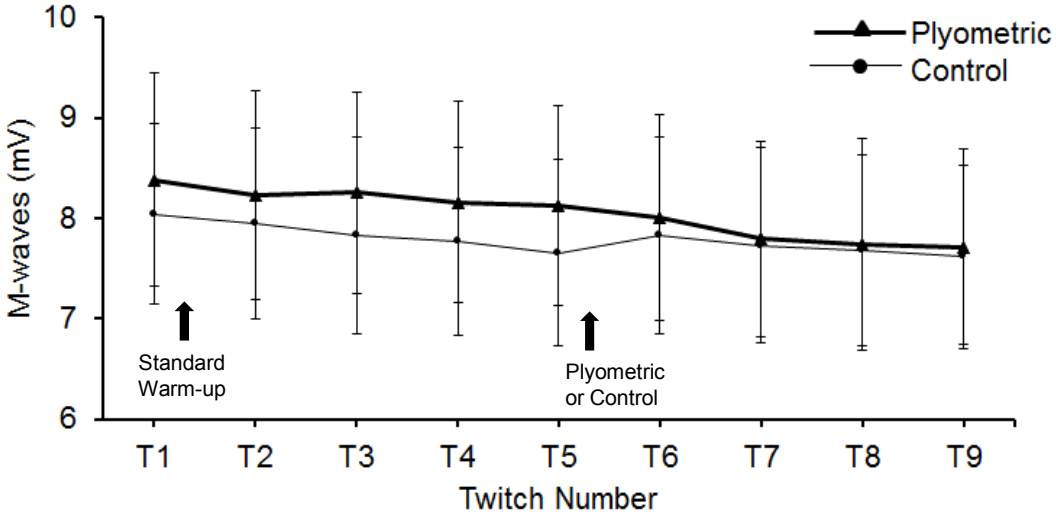
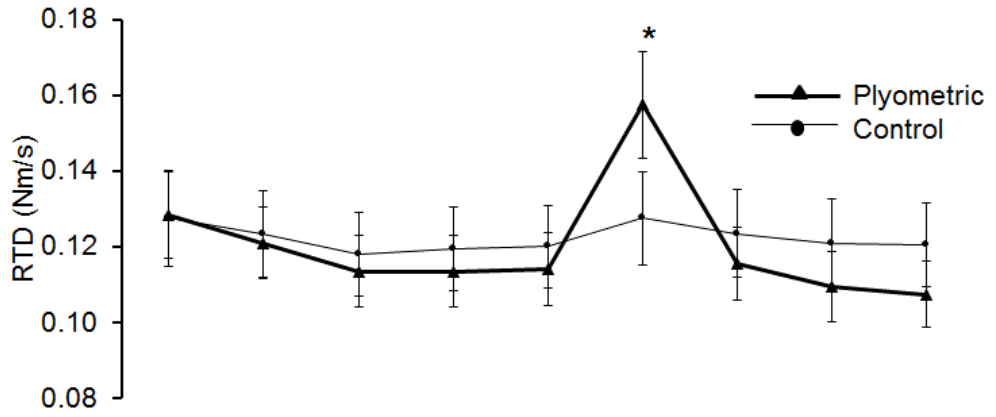
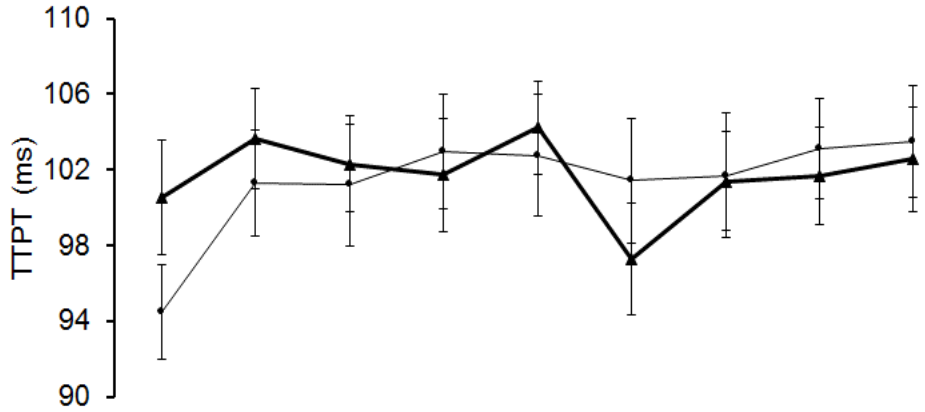



**Figure 2-5** Amplitude of M-waves recorded during twitches for individual participants (panels A and B) and averaged across the group (panel C). Each line in panels A and B show data from an individual participants and data points represent the mean amplitude of three M-waves. Panel C shows group data for the plyometric and control sessions. Each data point represents the average across the 20 participants. Error bars represent 1 standard error.

A. Rate of torque development - Group data




B. Time to peak torque - Group data




C. Impulse - Group data

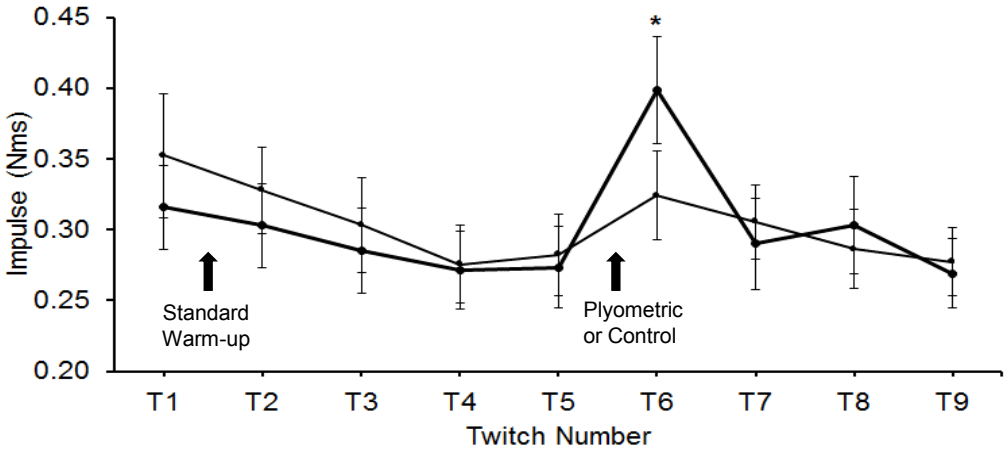



**Figure 2-6** Peak rate of torque development (panel A), time to peak torque (panel B) and impulse (panel C), averaged across the group of 20 participants for the plyometric and control sessions. Error bars represent 1 standard error. Asterisks denote significant differences between the plyometric and control sessions.

## 2.5 References


Aagaard, P (2003) Training induced changes in neural function. *Journal of Exercise and Sport Science Review* 31(2):61–67

Allen, DG, Lännergren, J, Westerblad, H (1995) Muscle cell function during prolonged activity: cellular mechanisms of fatigue. *Journal of Experimental Physiology* 80: 497–527

Allen, DG, Lee, JA, Westerblad, H (1989) Intracellular calcium and tension during fatigue in isolated single muscle fibres from Xenopus laevis. *Journal of Physiology* 415: 433–458

Altamirano, KM, Coburn JW, Brown LE, Judelson DA (2012) Effects of warm-up on peak torque, rate of torque development, and electromyography and mechanomyography signals. *Journal of Strength & Conditioning Research* 26(5): 1296-1301

Baudry, S, Duchateau, J (2007) Postactivation potentiation in a human muscle: effect on the rate of torque development of tetanic and voluntary isometric contractions. *Journal of Applied Physiology* 102: 1394–1401

Bowers, EJ, Morgan, DL, Proske, U (2004) Damage to the human quadriceps muscle from eccentric exercise and the training effect. *Journal of Sport Sciences* 22: 1005-1014

Burkett, LN, Phillips, WT, Ziuraitis, J (2005) The best warm-up for the vertical jump in college-age athletic men. *Journal of Strength and Conditioning Research / National Strength & Conditioning Association* 19: 673–676

Burger, T, Boyer-Kendrick, T, Dolny, D (2000) Complex training compared to a combined weight training and plyometric training program. *Journal of Strength and Conditioning Research* 26(6): 52-57

Burgquist, AJ, Wiest, MJ, Collins, DF (2012) Motor unit recruitment when neuromuscular electrical stimulation is applied over a nerve trunk compared with a muscle belly: quadriceps femoris. *Journal of Applied Physiology* 113(1): 78-89

Byrne, P, Kenny, J, O'Rourke, B (2014) Acute potentiating effect of depth jumps on sprint performance. *Journal of Strength & Conditioning Research* 28(3): 610-615

Chaubet, V, Cormery, B, Maitre, J, Paillard, T (2013) Stimulated contractions delay and prolong central fatigue compared with voluntary contractions in men. *Journal of Strength and Conditioning Research* 27(5): 1378–1383

Coh, M, Tomazin, K (2006) Kinematic analysis of the sprint start and acceleration from the blocks. *New Studies in Athletics 21*(3): 13-33

Docherty, D, & Hodgson, MJ (2007) The application of postactivation potentiation to elite sport. *International Journal of Sports Physiology & Performance 2*(4): 439-444

Faigenbaum, AD, McFarland, JE, Schwerdtman, JA, Ratamess, NA, Kang, J, Hoffman, JR (2006) Dynamic warm-up protocols, with and without a weighted vest, and fitness performance in high school female athletes. *Journal of Athletic Training* 41(4): 357-363

Fernandez-Del-Olmo, M, Rodriguez, FA, Marquez, G, Inglesias, X, Marina, M, Benitez, A, Acero, RM (2013) Isometric knee extensor fatigue following a Wingate test: peripheral and central mechanisms. *Scandinavian Journal of Medicine and Science in Sports* 23(1): 57-65

French, DN, Kraemer, WJ, Cooke, CB (2000) Changes in dynamic exercise performance following a sequence of preconditioning of preconditioning isometric muscle actions. *Journal of Applied Physiology* 88 (1): 35-40

Gardiner, PF (2001) *Neuromuscular aspects of physical activity.* Champaign, IL: Human Kinetics

Gossen, ER, Sale, DG (2000) Effect of postactivation potentiation on dynamic knee extension performance. *Journal of Applied Physiology* 83(6): 524-30

Guellich, A, Schmidtbleicher, D (1996) MVC-induced short-term potentiation of explosive force. *New Studies in Athletics* 11(4): 67-81

Guggenheimer, JD, Dickin, DC, Reyes, GF, Dolny, DG (2009) The effects of specific preconditioning activities on acute sprint performance. *Journal of Strength and Conditioning Research / National Strength & Conditioning Association* 23(4): 1135-1139

Hamada, T, Sale, DG, MacDougall, JD, Tarnopolsky, MA (2000) Postactivation potentiation, fiber type, and twitch contraction time in human knee extensor muscles. *Journal of Applied Physiology* 88(6): 2131-2137

Hamada T, Sale, DG, MacDougall, JD, Tarnopolsky, MA (2003) Interaction of fibre type, potentiation and fatigue in human knee extensor muscles. *Acta Physiologica Scandinavica* 178 (2): 165-173

Henriksson-Larsen, KB, Lexell, J, Sjoestrom, M (1983) Distribution of different fiber types in human skeletal muscles. Method for the preparation and analysis of cross-sections of whole tibialis anterior. *The Histochemical Journal* 15(2): 167-178

Hilfiker, R, Hubner, K, Lorenz, T, Marti, B (2007) Effects of drop jumps added to the warm-up of elite sport athletes with a high capacity for explosive force development. *Journal of Strength and Conditioning Research* 21(2): 550-555

Houston, ME, Green, HJ, Stull, JT (1985) Myosin light chain phosphorylation and isometric twitch potentiation in intact human muscle. *European Journal of Physiology* 403: 348–352

Hultman, E, Del Canale, S, Sjoholm, H (1985). Effect of induced metabolic acidosis on intracellular pH, buffer capacity and contraction force of human muscle. *Journal of Clinical Science* 69(5): 505-510

Jenkins, NDM, Palmer, TB, Cramer, JT (2013) Comparisons of voluntary and evoked rate of torque development and rate of velocity development during isokinetic muscle actions. *Journal of Isokinetics and Exercise* 21: 253-261

Jubeau, M, Gondin, J, Martin, A, Van Hoecke, J, Maffiuletti, NA (2010) Differences in twitch potentiation between voluntary and stimulated quadriceps contractions of equal intensity. *Scandinavian Journal of Medicine and Science in Sports* 20(1): 1-7

Lima, JCB, Marin, DP, Barquilha, G, Da Silva, LO, Puggina, EF, Pithon-Curi, T (2011) Acute effects of drop jump potentiation protocol on sprint and counter movement vertical jump performance. *Human Movement Journal* 12(4): 324-330

Linder, EE, Prins, JH, Murata, NM, Derenne, C, Morgan, CF, Solomon, JR (2010) Effects of preload 4 repetition maximum on 100-m sprint times in collegiate women. *Journal of Strength and Conditioning Research* 24(5): 1184-90

Lorenz, D (2011) Clinical commentary: Postactivation potentiation: An introduction. *International Journal of Sports Physical Therapy* 6(3): 234-240

Maloney, SJ, Turner, AN, Fletcher, IM (2014) Ballistic exercise as a pre-activation stimulus: A review of the literature and practical applications. *Journal of Sports Medicine* 44(10): 1347-1359

Mann, D, Jones, M (1999) Guidelines to the implementation of a dynamic stretching program. *Journal of Strength and Condition Journal* 21: 53-55

Marshall, BM, Moran, KA (2013) Which drop jump technique is most effective at enhancing countermovement jump ability, "countermovement" drop jump or "bounce" drop jump? *Journal of Sport Sciences* 31(12): 1368-1374

Masiulis, N, Skurvydas, A, Kamandulis, S, Sniečkus, A, Brazaitis, M, Daniusevičiūtė, L, Ramanauskienė, I (2008) Post-activation potentiation and fatigue in quadriceps femoral muscle after a 5 s maximal voluntary isometric contraction. *Journal for Education, Physical Training and Sport* 68(1): 55-60

McBride, JM, Nimphius, S, Erickson, TM (2005) The acute effects of heavy-load squats countermovement jump on sprint performance. *Journal of Strength and Cond Research* 19(4): 893–897

Merton, PA (1954) Voluntary strength and fatigue, *Journal of Physiology* 123: 553-564

Moore, RL**,** Stull, JT (1984) Myosin light chain phosphorylation in fast and slow skeletal muscles in situ. *American Journal of Physiology- Cell Physiology* 247: C462–C471

Morana, C, Perrey, S (2009) Time course of postactivation potentiation during intermittent submaximal fatiguing contractions in endurance and power0trained athletes. *Journal of Strength and Conditioning Research* 23(5): 1456-1464

Miyamoto, N, Kanehisa, H, Kawakami, Y (2012) Potentiation of Maximal Voluntary Concentric Torque in Human Quadriceps Femoris. *Medical Science Sports Exercise Journal* 44(9): 1738–1746

Ochala, J, Lambertz, D, Pousson, M, Goubel, F, Hoecke, J (2015). Changes in mechanical properties of human plantar flexor muscles in ageing. *Journal of Experimental Gerontology* 39: 349-358

Pfaff, D (1997) Training methods for elite sprinters. In: Appalachian High Preformance Conference, Boone, NC

Place, N, Yamada, T, Bruton, JD, Westerblad, H (2010) Muscle fatigue: from observations in humans to underlying mechanisms studied in intact single muscle fibres. *European Journal of Applied Physiology* 110(1): 1-15

Proske, U, Morgan, DL (2001) Muscle damage from eccentric exercise: mechanism, mechanical signs, adaptation and clinical applications. *Journal of Physiology* 537(2): 333-345

Radcliffe, JC, Radcliffe, JL (1996) Effects of different warm-up protocols on peak power output during a single response jump task. *Medical Science Sports Exercise Journal,* 28: S29

Rassier, DE, MacIntosh, BR (2000) Coexistence of potentiation and fatigue in skeletal muscle. *Brazilian Journal of Medical & Biological Research* 33: 499–508

Requena, B, Gapeyeva, H, Garcia, I, Ereline, J, Paasuke, M (2008) Twitch potentiation after voluntary versus electrically induced isometric contractions in human knee extensor muscles. *European Journal of Applied Physiology* 104(3): 463–472

Robins, DW (2005) *Postactivation potentiation and its practical applicability: A brief review*. *Journal of Strength and Conditioning Research* 19(2): 453-458

Sale, DG (2002) Postactivation potentiation: Role in human performance. *Exercise & Sport Sciences Reviews* 30(3): 138-143

Schluter, JM, Fitts, RH (1994) Shortening velocity and ATPase activity of rat skeletal muscle fibers: effects of endurance exercise training. *American Journal of Physiology* 266: C1699–C1673

Seitz, LB, Trajano, GS, Dal Maso, F, Haff, GG, Blazevich, AJ (2015) Postactivation potentiation during voluntary contractions after continued knee extensor task-specific practice. *Applied Physiology, Nutrition, and Metabolism* 40(3): 230-237

Shellock, FG, Prentice, WE (1985) Warming-up and stretching for improved physical performance and prevention of sports related injuries. *Journal of Sports Medicine* 2(4): 267-278

Strojnik, V (1995) Muscle activation level during maximal voluntary effort. *Journal of Applied Physiology and Occupational Physiology* 72(1/2): 144-149

Strojnik, V, Komi, PV (1998) Neuromuscular fatigue after maximal stretch-shortening cycle exercise. *Journal of Applied Physiology* 84(1): 344-350

Sweeney, HL, Bowman, BF, Stull, JT (1993) Myosin light chain phosphorylation in vertebrate striated muscle: Regulation and function. *The American Journal of Physiology-Cell Physiology* 264(33): 1085-1095

Tesch, PA, Karlsson, J (1985) Muscle fiber types and size in trained and untrained muscles of elite athletes. *Journal of Applied Physiology* 59(6): 1716-1720

Till, KA, Cooke, C (2009) The effects of postactivation potentiation on sprint and jump performance of male academy soccer players. *Journal of Strength and Conditioning Research* 23(7): 1960-1967

Turner, AP, Bellhouse, S, Kilduff, LP, Russell, M (2014) Post-activation potentiation of sprint acceleration performance using plyometric exercise. *Journal of Strength and Conditioning Research / National Strength & Conditioning Association* 16: 530-8

Vandervoort, AA, Quinlan, J, McComas, AJ (1983) Twitch potentiation after voluntary contraction. *Journal of Experimental Neurology* 81: 141-152

Westerblad, H, Allen, DG (1991) Changes in myoplasmic calcium concentration during fatigue. *Journal of General Physiology* 98: 615-635

Widrick, JJ, Trappe, SW, Blaster, CA, Costil, DL, Fitts, RH (1996) Isometric force and maximal shortening velocity of single muscle fibers from elite masters runners. *American Journal of Physiology* 271: C666–C675

Young, WB. 1995. Laboratory strength assessment of athletes. New Studies in Athletics 10(1): 86-96

Young, WB, Jenner, A, Griffiths, K (1998) Acute enhancement of power performance from heavy load squats. *Journal of Strength & Conditioning Research* 12(2): 82-84

Young, WB, Behm, DG (2003) Effects of static stretching and practice jumps on explosive force production and jumping performance. *The Journal of Sports Medicine and Physical Fitness* 43: 21–27

# CHAPTER 3: GENERAL DISCUSSION

The experiments described in this thesis were designed to assess post activation potentiation (PAP) induced in the quadriceps muscles when a standard warm-up was followed by a plyometric protocol that has been previously suggested to induce PAP (Lima et al., 2011). PAP is defined as a phenomenon by which muscle force is augmented as a result of its contractile history (Robbins, 2005). This design allowed us to; 1) quantify the magnitude of PAP and, 2) assess the temporal characteristics of PAP over time intervals that would be relevant for real world competitions. A goal of this work was to identify when the most optimal time is to incorporate a plyometric protocol for maximal enhancement of power production. In this General Discussion I briefly discuss the structural and metabolic perturbations within the muscle that may have resulted in the decline in the force generating capacity of the muscle following the plyometric protocol. Next I discuss methods that would allow researchers to identify the approximate number and height of drop jumps that would maximize PAP while minimizing fatigue. Finally, I discuss studies that have incorporated MVC protocols to improve performance, and propose future studies to assess both MVCs and drop jumps to determine which is the most beneficial for athletic performance.

## 3.1 Mechanisms of peripheral fatigue

The work described in Chapter two provides evidence that drop jumps induce PAP (Figure 2-4C, pg. 55). However, by 11-16 minutes following the drop jumps, peak twitch torque (PTT) fell below baseline level, indicating that fatigue was present. M-wave amplitudes and PTT were assessed to determine the presence of contractile fatigue. The consistency of M-wave amplitudes and the depression in peak twitch torque and RTD was indicative that fatigue was induced, and

was due to a mechanism located distal to the sarcolemma (Figure 2-5C; Merton, 1954; Westerblad et al., 1991). Such fatigue is responsible for decreased force production, shortening velocity and increased relaxation time of the muscle, resulting in decreased muscle performance (Allen et al., 1995). PAP can be affected by both structural and metabolic mechanisms that affect excitation-contraction coupling, metabolite accumulation, muscle structural integrity, and glycogen depletion, together these result in a decrease in force generating capacity of the muscle (Allen et al., 1989; Allen et al., 1995; Proske & Morgan, 2001; Bowers, Morgan, & Proske, 2004; Place et al., 2010; Chaubet et al., 2013; Fernandez-del-Olmo et al., 2013).

Structural alteration in the muscle fiber can affect the force generating capacity of the muscle. When performing a drop jump, the athlete is required to drastically change direction once they contact the ground to jump vertically as explosively as possible. This is done to keep ground reactions times as short as possible (see 2.2.5.2, pg. 37; Marshall et al., 2013). An eccentric contraction occurs during this phase of the drop jump. An eccentric contraction involves the lengthening of a muscle while generating active tension (Bowers et al., 2004). It has previously been reported that eccentric movements are associated with micro damage in the muscle fiber (Proske & Morgan, 2001; Bowers et al., 2004). According to Proske & Morgan (2001) the two prominent signs of eccentric muscle damage are disrupted sarcomeres in the myofibril and damage to the excitation-contraction system. Firstly, the overextension of sarcomeres lead to contractile disruptions that results in a shift in optimum length for tension to longer muscle lengths (Proske & Morgan, 2001). Further disruption of the sarcomeres leads to possible tearing of t-tubules, which result in uncontrolled $Ca^{+}$ release, triggering contractures within the muscle that augment passive tension (Proske & Morgan, 2001). Damage to t-tubules causes a dissociation between excitation and contraction function and further damage would result in an inflammatory response that is

associated with pronounced muscle soreness (Proske & Morgan, 2001). An eccentric-type exercise consisting of maximal eccentric contractions of the knee flexors (6 sets of 10 repetitions, with a 1 minute rest between sets) has shown to decrease peak force within the quadriceps by ~10% after the first set (Chen et al., 2015). Eccentric-damage markers such as plasma creatine kinase and myoglobin were monitored and increased significantly following the maximal eccentric activity (Chen et al., 2015). This study demonstrates the early onset of decreased muscle force due to eccentric contractions of maximal intensity. The present study described in Chapter 2 utilized drop jumps of maximal effort, and required the participant to drop down from a 0.76 meter height and react up vertically as explosively as possible. Given the effects of eccentric damage on the integrity of the muscle fiber, it is likely that the decrease in PTT could partly be due to micro damage in the muscle. Dropping from a lower height during a drop jump would most likely reduce the eccentric forces on the muscle and reduce the possible micro damage to the muscle fiber, however whether it is possible to reduce structural perturbations and still maximize the force generating capacity of the muscle is not known. Any protocol requiring eccentric contractions to induce PAP should be short in duration, since eccentric contractions can affect the force generating capacity of the muscle. The study described in Chapter 2 did not measure whether there were any structural perturbations due to the eccentric nature of the drop jumps. Future studies that investigate the effects of a plyometric protocol on muscle potentiation would benefit by measuring eccentric-damage markers, associated with eccentric muscle damage, to assess the extent of decreased muscle force due to eccentric muscle damage (Place et al., 2010; Chen et al., 2015).

Metabolic changes within the muscle fiber also affect the force generating capacity of the muscle and are largely due to the effects of hydrogen ions ($H^+$) and inorganic phosphates (Allen et al., 2005). Quadriceps muscle oxidative capacity has been shown to decrease by ~42 %

following an intermittent leg extension protocol (1 second contraction, 1 second rest) at 35 – 45 % MVC, for 3-6 minutes (Layec et al., 2013). The decrease in oxidative capacity is associated with an increase in pH and metabolic acidosis (Layec, et al., 2013). Therefore given the time course of metabolite accumulation, it is very likely that a drop jump protocol lasting ~6 minutes changed the oxidative capacity of the quadriceps muscle to some extent. An increase in relaxation time as well as a slowing of actin-myosin cross-bridge detachment are associated with a rise in $H^+$ (Allen et al., 2005). Hultman and colleagues (1985) reported a significant decrease in contraction force and buffering capacity (removal of $H^+$) during an isometric contraction, following the administration of $NH^4Cl$ (0.3 g/kg of body weight) to induce moderate acidosis. Muscle pH and contraction force was significantly lower following the $NH^4Cl$ administration than the control group (no $NH^4Cl$ administration; Hultman et al., 1985) although metabolic acidosis is not solely responsible for metabolic fatigue, in conjunction with changes in other metabolites (ATP, ADP and inorganic phosphates), they accelerate the rate of decline in force generating capacity of the muscle. In order to determine the presence of metabolites associated with metabolic acidosis, muscle fibers can be loaded with fluorescent indicators and measured under a light spectrum (Place et al., 2010). The present study did not incorporate such measures to monitor fatigue, therefore the exact mechanisms responsible for the decrease in muscle force generating capacity is not known.

In summary, both structural and metabolic changes in the muscle can result in decreased force characteristics that interrupt the functional integrity of the sarcomere. Fatigue is multifaceted and often times the decrease in force is due to multiple mechanisms that act together and as a result, accelerate the effects of fatigue within the muscle, therefore both structural and metabolic mechanisms could simultaneously contribute to the decreases the force generating capacity of the muscle.

## 3.2 Future Research

### 3.2.1 What is the optimal volume of drop jumps to maximize PAP?

Participants in the study described in Chapter 2 completed a plyometric protocol consisting of 2 sets of 5 drop jumps (see 2.2.5.2, pg.37). The drop jumps induced PAP, which dissipated within 6 minutes and by 11-16 minutes fatigue was present (see Figure 2-4C, pg. 55). Methods that manipulate drop jump height and number can be incorporated by researchers to determine what is optimal to maximally enhance the force generating capacity of the muscle while minimizing fatigue. To date no study has manipulated drop jump height to determine what height is sufficient to induce PAP and minimize fatigue. Reducing drop jump height could possibly decrease the eccentric forces associated plyometric movements, however drop jump height still needs to be sufficient to induce PAP. Byrne and colleagues (2010) incorporated a maximum jump height method to determine the 'optimal' jump height that would improve counter movement jump performance. Participants performed drop jumps from heights of 0.2-0.6 m. Heights of 0.3-0.6 m resulted in the highest vertical for the counter movement jump (Byrne, et al., 2010). However, only a 2 minute rest was given between each jump. The present study shows that PAP was present for 6 minutes, therefore it is likely that the counter movement jumps induced PAP and affected the results of consecutive counter movement jumps. Researchers can assess the force characteristics of the muscle (i.e. PTT and RTD) following the different jump heights, to determine the height that maximizes the power generating capacity of the muscle with minimal fatigue.

By manipulating the number of drop jumps it would be possible to find the minimal number needed to maximize the force generating capacity of the muscle with minimal fatigue. Stieg and colleagues (2011) assessed the acute effects of depth jumps (drop jumps) on vertical jump performance. Participants performed 0, 3, 6, 9, and 12 depth jumps (knee height) in random order,

with 10 minutes between the depth jumps and performance measure (i.e. vertical jump; Stieg et al., 2011). It was reported that the depth jumps failed to induce PAP, since there was no change in vertical jump performance. However, given that our research provides evidence that the induced PAP dissipated within 6 minutes, it is likely that 10 minutes was too long of a recovery period, therefore the effects of PAP on performance would have diminished. However, researchers can incorporate this method to assess PAP induced after performing 0, 3, 6, 9, and 12 drop jumps at a set height to determine the amount of drop jumps needed to maximize PAP, with minimal fatigue.

In summary, both drop jump height and number can be manipulated to find the minimal volume of drop jumps needed to maximize the force generating capability of the muscle with minimal fatigue. Decreasing the amount of activity while inducing the same amount of PAP will reduce the rapid dissipation of PAP associated with fatigue. However, whether PAP can exist without fatigue is unlikely, therefore a protocol that results in a magnitude of PAP that dissipates at a slower rate than fatigue would be ideal.

### 3.2.2 MVCs versus drop jumps

This section will briefly discuss findings of previous studies that incorporated MVCs prior to performance and explore whether MVCs or drop jumps are more appropriate and effective for performance. No study to date has assessed and compared the magnitude and time course of PAP induced following both an MVC and drop jump protocol. MVCs are known to induce PAP and have been reported to augment PTT up to a 2 fold increase compared to the PTT within the study described in Chapter 2 (Vandervoort et al., 1983; Gossen et al., 2000; Hamada et al., 2000). MVC have been incorporated following a standard warm-up to enhance sprinting and jumping performance (Gullich & Schmidtbleicher, 1996; French, Kraemer, & Cooke, 2003; Stafilidis & Tilp, 2005; Till & Cook, 2009; Lim & Kong, 2013). However, the results have been contradictory,

with sprint and jump performance being augmented, decreased, or unchanged. For example, an isometric protocol consisting of 3 MVCs (3 second contraction, 2 minutes rest) improved jump performance by 3 %, with no effect of a squatting protocol on jump performance (Rixon et al., 2007). However, lack of randomization between experimental groups made results questionable. Other studies have found no improvement in sprint and jump performance when preceded by MVCs (Lim & Kong, 2013; Till & Cooke, 2009). MVCs are usually performed around a single joint and therefore limit the ability to induce PAP in multiple muscle groups (Lim & Kong, 2013). Explosive sports require the generation of force from multiple muscle groups and therefore MVCs might not be appropriate for a practical setting. Drop jumps, however, have been incorporated following a standard warm-up, to enhance sprint and jump performance (Hilfiker et al., 2007; Guggenheimer et al., 2009; Lima et al., 2011; Byrne, Kenny, & O'Rourke, 2014; Maloney, Turner, & Fletcher, 2014; Turner, Bellhouse, Kilduff, & Russell, 2014). Performance improvements of 2.4% and 2.7% in 50 meter sprint, and 6 % in vertical jump, at 10 and 15 minutes respectively, have been reported when preceded by the same plyometric protocol as the present study described in Chapter 2 (Lima et al., 2011). Given the results of the present study, PAP could to some extent, be responsible for the improved sprint and jump performance.

Both MVCs and drop jumps have been shown to induce PAP, however drop jumps incorporate multiple muscle groups necessary for maximal force production (Maloney et al., 2013) and therefore are more specific to explosive sports. MVCs have proven to augment PTT and RTD to a greater extent than drop jumps (Vandervoort et al., 1983; Gossen et al., 2000; Hamada et al., 2000), however this does not seem to translate to improved sprint and jump performance. Given the specificity of drop jumps to athletic performance, performing drop jumps would be more ideal for maximizing the force generating capacity of the muscle and would most likely translate to

improved performance as previously shown (Hilfiker et al., 2007; Guggenheimer et al., 2009; Lima et al., 2011; Byrne, Kenny, & O'Rourke, 2014; Maloney, Turner, & Fletcher, 2014; Turner, Bellhouse, Kilduff, & Russell, 2014). To determine whether one protocol is more beneficial than the other, researchers can assess the magnitude and time course of PAP induced by both a MVC and plyometric protocol on separate occasions. Using electrically evoked twitches and performance measures (i.e. sprint and vertical jump test) researchers can determine which protocol is more effective and practical in nature.

## 3.3 Conclusion

The study described in Chapter 2 provides evidence that drop jumps induce PAP. The induce PAP dissipated within 6 minutes, back to baseline (T1). By 11-16 minutes following the drop jumps, fatigue was present, resulting in PTT below baseline (T1). Fatigue effects the magnitude and time course of PAP and the decreases in PTT were possibly as a result of structural and metabolic perturbations that effected the force generating capacity of the muscle. The force generating capacity of the muscle is dependent on the balance between PAP and fatigue. Whether PAP can exist without fatigue is unlikely. However future research can determine the optimal height and volume of drop jumps to maximize the force generating capacity of the muscle, while minimizing fatigue. Drop jumps are an effective way to induce PAP and coaches can incorporate drop jumps following an athletes' standard warm-up, to enhance performance. Drop jumps could be beneficial for sports requiring explosive movements, lasting no longer than 6 minutes and coaches or athletes should be aware of the trade-off between PAP and fatigue. To maximize the force generating capacity of the muscle athletes should perform the explosive activity as soon after completing the drop jumps as possible.

## 3.4 References


Allen, DG, Lännergren, J, Westerblad, H (1995) Muscle cell function during prolonged activity: cellular mechanisms of fatigue. *Journal of Experimental Physiology* 80: 497–527

Allen, DG, Lee, JA, Westerblad, H (1989) Intracellular calcium and tension during fatigue in isolated single muscle fibres from Xenopus laevis. *Journal of Physiology* 415: 433–458

Bowers, EJ, Morgan, DL, Proske, U (2004) Damage to the human quadriceps muscle from eccentric exercise and the training effect. *Journal of Sport Sciences* 22: 1005-1014

Byrne, P, Kenny, J, O'Rourke, B (2014) Acute potentiating effect of depth jumps on sprint performance. *Journal of Strength & Conditioning Research* 28(3): 610-615

Chaubet, V, Cormery, B, Maitre, J, Paillard, T (2013) Stimulated contractions delay and prolong central fatigue compared with voluntary contractions in men. *Journal of Strength and Conditioning Research* 27(5): 1378–1383

Chen, C, Chen, TC, Jan, M, Lin, J (2015) Acute effects of static active or dynamic active stretching on eccentric-exercise-induced hamstring muscle damage. *International Journal of Sports Physiology and Performance* 10: 346-352

Fernandez-Del-Olmo, M, Rodriguez, FA, Marquez, G, Inglesias, X, Marina, M, Benitez, A, Acero, RM (2013) Isometric knee extensor fatigue following a Wingate test: peripheral and central mechanisms. *Scandinavian Journal of Medicine and Science in Sports* 23(1): 57-65

French, DN, Kraemer, WJ, Cooke, CB (2003) Changes in dynamic exercise performance following a sequence of preconditioning isometric muscle actions. *Journal of Strength and Conditioning Research* 17(4): 648-685

Gossen, ER, Sale, DG (2000) Effect of postactivation potentiation on dynamic knee extension performance. *Journal of Applied Physiology* 83(6): 524-30

Guggenheimer, JD, Dickin, DC, Reyes, GF, Dolny, DG (2009) The effects of specific preconditioning activities on acute sprint performance. *Journal of Strength and Conditioning Research / National Strength & Conditioning Association* 23(4): 1135-1139

Hamada, T, Sale, DG, MacDougall, JD (2000) Postactivation potentiation in endurance-trained male athletes. *Medicine & Science in Sports & Exercise 32*(2): 403-411

Hilfiker, R, Hubner, K, Lorenz, T, Marti, B (2007) Effects of drop jumps added to the warm-up of elite sport athletes with a high capacity for explosive force development. *Journal of Strength and Conditioning Research* 21(2): 550-555

Hultman, E, Del Canale, S, Sjoholm, H (1985). Effect of induced metabolic acidosis on intracellular pH, buffer capacity and contraction force of human muscle. *Journal of Clinical Science* 69(5): 505-510

Layec, G, Malucelli, E, Le Fur, Y, Manners, D, Yashiro, K, Testa, Cozzone, PJ, Lotti, S, Bendahan, D (2013) Effects of exercise-induced intracellular acidosis on phosphocreatine recovery kinetics. *Radiology Nuclear Medicine & Medical Imaging in Biomedicine* 26(11): 1403-1411

Lim, K, Kong, P (2013) Effects of isometric and dynamic postactivation potentiation protocols on maximal sprint performance. *Journal of Strength and Conditioning Research* 10: 2730-2736

Lima, JCB, Marin, DP, Barquilha, G, Da Silva, LO, Puggina, EF, Pithon-Curi, T (2011) Acute effects of drop jump potentiation protocol on sprint and counter movement vertical jump performance. *Human Movement Journal 12*(4): 324-330

Maloney, SJ, Turner, AN, Fletcher, IM (2014) Ballistic exercise as a pre-activation stimulus: A review of the literature and practical applications. *Journal of Sports Medicine* 44(10): 1347-1359

Marshall, BM, Moran, KA (2013) Which drop jump technique is most effective at enhancing countermovement jump ability, "countermovement" drop jump or "bounce" drop jump? *Journal of Sport Sciences* 31(12): 1368-1374

Merton, PA (1954) Voluntary strength and fatigue. *Journal of Physiology* 123: 553-564

Place, N, Yamada, T, Bruton, JD, Westerblad, H (2010) Muscle fatigue: from observations in humans to underlying mechanisms studied in intact single muscle fibres. *European Journal of Applied Physiology* 110(1): 1-15

Proske, U, Morgan, DL (2001) Muscle damage from eccentric exercise: mechanism, mechanical signs, adaptation and clinical applications. *Journal of Physiology* 537(2): 333-345

Rixon, K, Lamont, H, Bemben, M (2007) Influence of muscle contraction gender and lifting experience on postactivation potentiation performance. *Journal of Strength and Conditioning Research* 21(2): 500-505

Robins, DW (2005) Postactivation potentiation and its practical applicability: A brief review. *Journal of Strength and Conditioning Research* 19(2): 453-458

Stafilidis, S, Tilp, M (2015) Effects of short duration static stretching on jump performance, maximum voluntary contraction, and various mechanical and morphological parameters of the muscle-tendon unit of the lower extremities. *Journal of Applied Physiology* 115(3): 607-617

Stieg, JL, Faulkinbury, KJ, Tran, TT, Brown, LE, Coburn, JW, Judelson, JA (2011) Acute effects of depth jump volume on vertical jump performance in collegiate women soccer players. *Journal of Kinesiology* 1: 25-30

Till, K, Cooke, C (2009) The effects of postactivation potentiation on sprint and jump performance of male academy soccer players. *Journal of Strength and Conditioning Research* 7: 1960-1967

Turner, AP, Bellhouse, S, Kilduff, LP, Russell, M (2014) Post-activation potentiation of sprint acceleration performance using plyometric exercise. *Journal of Strength and Conditioning Research / National Strength & Conditioning Association* 16: 530-538

Vandervoort, AA, Quinlan, J, McComas, AJ (1983) Twitch potentiation after voluntary contraction. *Journal of Experimental Neurology* 81: 141-152

Westerblad, H, Allen, DG (1991) Changes in myoplasmic calcium concentration during fatigue. *Journal of General Physiology* 98: 615-635

## Bibliography

Aagaard, P (2003) Training induced changes in neural function. *Journal of Exercise and Sport Science Review* 31(2): 61–67

Allen, DG, Lee, JA, Westerblad, H (1989) Intracellular calcium and tension during fatigue in isolated single muscle fibres from Xenopus laevis. *Journal of Physiology* 415: 433–458

Allen, DG, Lännergren, J, Westerblad, H (1995) Muscle cell function during prolonged activity: cellular mechanisms of fatigue. *Journal of Experimental Physiology* 80: 497–527

Altamirano, KM, Coburn JW, Brown LE, Judelson DA (2012) Effects of warm-up on peak torque, rate of torque development, and electromyography and mechanomyography signals. *Journal of Strength & Conditioning Research* 26(5): 1296-1301

Babić, V, Čoh MM, Dizdar DD (2011) Differences in Kinematic Parameters of Athletes of Different Running. *Biology of Sport* 28(2): 115-121

Baudry, S, Duchateau, J (2007) Postactivation potentiation in a human muscle: effect on the rate of torque development of tetanic and voluntary isometric contractions. *Journal of Applied Physiology* 102: 1394–1401

Bazett-Jones, D (2004) Neither stretching nor postactivation potentiation affect maximal force and rate of force production during seven one-minute trials. *Journal of Undergraduate Research* VII: 1-5

Behm, DG, Button, DC, Barbour, G, Butt, JC, Young, WB (2004) Conflicting effects of fatigue and potentiation on voluntary force. *Journal of Strength & Conditioning Research 18*(2): 365-372

Behm, DG, Chaouachi, AA (2011) Review of the acute effects of static and dynamic stretching on performance. *European Journal of Applied Physiology* 111: 2633–2651

Bowers, EJ, Morgan, DL, Proske, U (2004) Damage to the human quadriceps muscle from eccentric exercise and the training effect. *Journal of Sport Sciences* 22: 1005-1014

Burger, T, Boyer-Kendrick, T, Dolny, D (2000) Complex training compared to a combined weight training and plyometric training program. *Journal of Strength and Conditioning Research* 26(6): 52-57

Burkett, LN, Phillips, WT, Ziuraitis, J (2005) The best warm-up for the vertical jump in college-age athletic men. *Journal of Strength and Conditioning Research / National Strength & Conditioning Association* 19: 673–676

Burgquist, AJ, Wiest, MJ, Collins, DF (2012) Motor unit recruitment when neuromuscular electrical stimulation is applied over a nerve trunk compared with a muscle belly: quadriceps femoris. *Journal of Applied Physiology* 113(1): 78-89

Byrne, PJ, Moran, K, Rankin, P, Kinsella, S (2010) A comparison of methods used to identify 'optimal' drop height for early phase adaptations in depth jump training. *Journal of Strength and Conditioning Research / National Strength & Conditioning Association* 24(8): 2050-2055

Byrne, P, Kenny, J, O'Rourke, B (2014) Acute potentiating effect of depth jumps on sprint performance. *Journal of Strength & Conditioning Research* 28(3): 610-615

Chatzopoulos, DE, Michailidis, CJ, Giannakos, AK, Alexiou, KC, Patikas, DA, Antonopoulos, CB (2007) Postactivation potentiation effects after heavy resistance exercise on running speed. *Journal of Strength and Conditioning Research* 21: 1278-1281

Chaubet, V, Cormery, B, Maitre, J, Paillard, T (2013) Stimulated contractions delay and prolong central fatigue compared with voluntary contractions in men. *Journal of Strength and Conditioning Research* 27(5): 1378–1383

Chen, C, Chen, TC, Jan, M, Lin, J (2015) Acute effects of static active or dynamic active stretching on eccentric-exercise-induced hamstring muscle damage. *International Journal of Sports Physiology and Performance* 10: 346-352

Comyns, TM, Harrison, AJ, Hennessy, LK, Jensen, RL (2006) The optimal complex training rest interval for athletes from anaerobic sports. *Journal of Strength & Conditioning Research* 20(3): 471-476

Coh, M, Tomazin, K (2006) Kinematic analysis of the sprint start and acceleration from the blocks. *New Studies in Athletics* 21(3): 13-33

Coh, M, Peharec, S, Bacic, P, Kampmiller, T (2009) Dynamic factors and electromyographic activity in a sprint start. *Biology of Sport* 26(2): 137-147

Coso, JD, Hamouti, N, Estevez, E, Mora-Rodriguez, R (2011) Reproducibility of two electrical stimulation techniques to assess neuromuscular fatigue. *European Journal of Sport Science 11*(2): 95-103

Derse, E, Hansen, J, O'Rourke, T, Stolley, K (1995) *LA84 Foundation Track and Field Coaching Manual.* Los Angeles: LA84 Foundation

Docherty, D, Robbins, D, Hodgson, M (2004) Complex Training Revisited: A Review of its Current Status as a Viable Training Approach. *Strength and Conditioning Journal* 26: 52-57

Docherty, D, & Hodgson, MJ (2007) The application of postactivation potentiation to elite sport. *International Journal of Sports Physiology & Performance 2*(4): 439-444

Ebben, WP, Waits, PB (1998) A review of combined weight training and plyometric training modes: Complex training. *Strength and Conditioning Journal* 20: 18-27

Faigenbaum, AD, McFarland, JE, Schwerdtman, JA, Ratamess, NA, Kang, J, Hoffman, JR (2006) Dynamic warm-up protocols, with and without a weighted vest, and fitness performance in high school female athletes. *Journal of Athletic Training* 41(4): 357-363

Fernandez-Del-Olmo, M, Rodriguez, FA, Marquez, G, Inglesias, X, Marina, M, Benitez, A, Acero, RM (2013) Isometric knee extensor fatigue following a Wingate test: peripheral and central mechanisms. *Scandinavian Journal of Medicine and Science in Sports* 23(1): 57-65

French, DN, Kraemer, WJ, Cooke, CB (2000) Changes in dynamic exercise performance following a sequence of preconditioning of preconditioning isometric muscle actions. *Journal of Applied Physiology* 88 (1): 35-40

French, DN, Kraemer, WJ, Cooke, CB (2003) Changes in dynamic exercise performance following a sequence of preconditioning isometric muscle actions. *Journal of Strength and Conditioning Research* 17(4): 648-685

Gardiner, PF (2001) *Neuromuscular aspects of physical activity.* Champaign, IL: Human Kinetics

Gilbert, G, Lees, A (2005) Changes in the force development characteristics of muscle following repeated maximum force and power exercise. *Journal of Ergonomics* 48(11-14): 1576-1584

Gourgoulis, V, Aggeloussis, N, Kasimatis, P, Mavromatis, G, Garas, A (2003) Effect of a submaximal half-squat warmup program on vertical jumping ability. *Journal of Strength and Conditioning Research* 17: 342–344

Gossen, ER, Sale, DG (2000) Effect of postactivation potentiation on dynamic knee extension performance. *Journal of Applied Physiology* 83(6): 524-30

Guellich, A, Schmidtbleicher, D (1995) Short-term potentiation of power performance induced by maximal voluntary contractions. *New Study in Athletics Archive* 11:67–81

Guellich, A, Schmidtbleicher, D (1996) MVC-induced short-term potentiation of explosive force. *New Studies in Athletics* 11(4): 67-81

Guggenheimer, JD, Dickin, DC, Reyes, GF, Dolny, DG (2009) The effects of specific preconditioning activities on acute sprint performance. *Journal of Strength and Conditioning Research / National Strength & Conditioning Association* 23(4): 1135-1139

Hamada, T, Sale, DG, MacDougall, JD, Tarnopolsky, MA (2000) Postactivation potentiation, fiber type, and twitch contraction time in human knee extensor muscles. *Journal of Applied Physiology* 88(6): 2131-2137

Hamada T, Sale, DG, MacDougall, JD, Tarnopolsky, MA (2003) Interaction of fibre type, potentiation and fatigue in human knee extensor muscles. *Acta Physiologica Scandinavica* 178 (2): 165-173

Hamada, T, Sale, DG, MacDougall, JD (2000) Postactivation potentiation in endurance-trained male athletes. *Medicine & Science in Sports & Exercise 32*(2): 403-411

Hedrick, A (1992) Physiological responses to warm-up. *Journal of Strength and Conditioning Research* 14: 25–27

Henriksson-Larsen, KB, Lexell, J, Sjoestrom, M (1983) Distribution of different fiber types in human skeletal muscles. Method for the preparation and analysis of cross-sections of whole tibialis anterior. *The Histochemical Journal* 15(2): 167-178

Hilfiker, R, Hubner, K, Lorenz, T, Marti, B (2007) Effects of drop jumps added to the warm-up of elite sport athletes with a high capacity for explosive force development. *Journal of Strength and Conditioning Research* 21(2): 550-555

Houston, ME, Green, HJ, Stull, JT (1985) Myosin light chain phosphorylation and isometric twitch potentiation in intact human muscle. *European Journal of Physiology* 403: 348–352

Hrysomallis, C, Kidgell, D (2001) Effect of heavy dynamic resistive exercise on acute upper-body power. *Journal of Strength and Conditioning Research* 15(4): 426-430

Hughes, SC, Gossen, ER, Sale DG (2001) Effect of postactivation potentiation on dynamic knee extension performance (Abstract). *Canadian Journal of Applied Physiology* 26: 486

Hultman, E, Del Canale, S, Sjoholm, H (1985). Effect of induced metabolic acidosis on intracellular pH, buffer capacity and contraction force of human muscle. *Journal of Clinical Science* 69(5): 505-510

Jenkins, NDM, Palmer, TB, Cramer, JT (2013) Comparisons of voluntary and evoked rate of torque development and rate of velocity development during isokinetic muscle actions. *Journal of Isokinetics and Exercise* 21: 253-261

Jensen, R. L, Ebben, WP (2003) Kinetic analysis of complex training rest interval effect on vertical jump performance. *Journal of Strength and Conditioning Research* 7(2): 345-349

Jubeau, M, Gondin, J, Martin, A, Van Hoecke, J, Maffiuletti, NA (2010) Differences in twitch potentiation between voluntary and stimulated quadriceps contractions of equal intensity. *Scandinavian Journal of Medicine and Science in Sports* 20(1): 1-7

Layec, G, Malucelli, E, Le Fur, Y, Manners, D, Yashiro, K, Testa, Cozzone, PJ, Lotti, S, Bendahan, D (2013) Effects of exercise-induced intracellular acidosis on phosphocreatine recovery kinetics. *Radiology Nuclear Medicine & Medical Imaging in Biomedicine* 26(11): 1403-1411

Lim, JJH, Kong, PW (2013) Effects of isometric and dynamic postactivation potentiation protocols on maximal sprint performance. *Journal of Strength & Conditioning Research* 27(10): 2730-2736

Lima, JCB, Marin, DP, Barquilha, G, Da Silva, LO, Puggina, EF, Pithon-Curi, T (2011) Acute effects of drop jump potentiation protocol on sprint and counter movement vertical jump performance. *Human Movement Science Journal* 12(4): 324-330

Linder, EE, Prins, JH, Murata, NM, Derenne, C, Morgan, CF, Solomon, JR (2010) Effects of preload 4 repetition maximum on 100-m sprint times in collegiate women. *Journal of Strength and Conditioning Research* 24(5): 1184-90

Lorenz, D (2011) Clinical commentary: Postactivation potentiation: An introduction. *International Journal of Sports Physical Therapy* 6(3): 234-240

Maloney, SJ, Turner, AN, Fletcher, IM (2014) Ballistic exercise as a pre-activation stimulus: A review of the literature and practical applications. *Journal of Sports Medicine* 44(10): 1347-1359

Mann, D, Jones, M (1999) Guidelines to the implementation of a dynamic stretching program. *Journal of Strength and Condition Research* 21: 53-55

Marshall, BM, Moran, KA (2013) Which drop jump technique is most effective at enhancing countermovement jump ability, "countermovement" drop jump or "bounce" drop jump? *Journal of Sport Sciences* 31(12): 1368-1374

Masiulis, N, Skurvydas, A, Kamandulis, S, Sniečkus, A, Brazaitis, M, Daniusevičiūtė, L, Ramanauskienė, I (2008) Post-activation potentiation and fatigue in quadriceps femoral muscle after a 5 s maximal voluntary isometric contraction. *Journal for Education, Physical Training and Sport* 68(1): 55-60

Matthews, MJ, Matthews, HP, Snook, B (2004) The acute effects of a resistance training warmup on sprint performance. *Research in Sports Medicine* 12(2): 151-159

McBride, JM, Nimphius, S, Erickson, TM (2005) The acute effects of heavy-load squats countermovement jump on sprint performance. *Journal of Strength and Conditioning Research* 19(4): 893–897

Mero, A (1988) Force-time characteristics and running velocity of male sprinters during the acceleration phase of sprinting. *Research Quarterly for Exercise & Sport 59*(2): 94-98

Merton, PA (1954) Voluntary strength and fatigue *Journal of Physiology* 123: 553-564

Moore, RL, Stull, JT (1984) Myosin light chain phosphorylation in fast and slow skeletal muscles in situ. *American Journal of Physiology- Cell Physiology* 247: C462–C471

Morana, C, Perrey, S (2009) Time course of postactivation potentiation during intermittent submaximal fatiguing contractions in endurance and power0trained athletes. *Journal of Strength and Conditioning Research* 23(5): 1456-1464

Miyamoto, N, Kanehisa, H, Kawakami, Y (2012) Potentiation of Maximal Voluntary Concentric Torque in Human Quadriceps Femoris. *Medical Science Sports Exercise Journal* 44(9): 1738–1746

Ochala, J, Lambertz, D, Pousson, M, Goubel, F, Hoecke, J (2015). Changes in mechanical properties of human plantar flexor muscles in ageing. *Journal of Experimental Gerontology* 39: 349-358

O'Leary, DD, Hope, K, Sale, DG (1997) Posttetanic potentiation of human dorsiflexors. *Journal of Applied Physiology* 83: 2131–3138

Palmer, BM, Moore, RL, (1989) Myosin light chain phosphorylation and tension potentiation in mouse skeletal muscle. *American Journal of Physiology* 257: C1012–C1019

Pfaff, D (1997) Training methods for elite sprinters. In: Appalachian High Preformance Conference, Boone, NC

Place, N, Yamada, T, Bruton, JD, Westerblad, H (2010) Muscle fatigue: from observations in humans to underlying mechanisms studied in intact single muscle fibres. *European Journal of Applied Physiology* 110(1): 1-15

Proske, U, Morgan, DL (2001) Muscle damage from eccentric exercise: mechanism, mechanical signs, adaptation and clinical applications. *Journal of Physiology* 537(2): 333-345

Radcliffe, JC, Radcliffe, JL (1996) Effects of different warm-up protocols on peak power output during a single response jump task. *Medical Science Sports Exercise Journal* 28: S29

Rassier, DE, MacIntosh, BR (2000) Coexistence of potentiation and fatigue in skeletal muscle. *Brazilian Journal of Medical & Biological Research* 33: 499–508

Requena, B, Gapeyeva, H, Garcia, I, Ereline, J, Paasuke, M (2008) Twitch potentiation after voluntary versus electrically induced isometric contractions in human knee extensor muscles. *European Journal of Applied Physiology* 104(3): 463–472

Rixon, K, Lamont, H, Bemben, M (2007) Influence of muscle contraction gender and lifting experience on postactivation potentiation performance. *Journal of Strength and Conditioning Research* 21(2): 500-505

Robins, DW (2005) *Postactivation potentiation and its practical applicability: A brief review*. *Journal of Strength and Conditioning Research* 19(2): 453-458

Ross, A, Leveritt, M, Riek, S (2001) Neural influences on sprint running: Training adaptations and acute responses. *Journal of Sports Medicine* 31(6): 409-425

Sale, DG (2002) Postactivation potentiation: Role in human performance. *Exercise & Sport Sciences Reviews* 30(3): 138-143

Safran, MR, Seaber, AV, Garrett, WE (1989) Warm-up and muscular injury prevention—an update. *Journal of Sports Medicine* 8: 239–249

Sánchez, BR, Puche, PP, González-Badillo, JJ (2005) Percutaneous electrical stimulation in strength training: An update. *Journal of Strength & Conditioning Research* 19(2): 438-448

Schilling, BK, Stone, MH (2000) Stretching: Acute effects on strength and power performance. *Journal of Strength and Conditioning Research* 22: 44–47

Schmidtbleicher, D (1987) Motorized stress forming force - Definitions and Trainability. Assessment of motor function, patient-orientated practice and training concepts. *Muscular Rehabilitation Journal* 62-85

Schluter, JM, Fitts, RH (1994) Shortening velocity and ATPase activity of rat skeletal muscle fibers: effects of endurance exercise training. *American Journal of Physiology* 266: C1699–C1673

Seitz, LB, Trajano, GS, Dal Maso, F, Haff, GG, Blazevich, AJ (2015) Postactivation potentiation during voluntary contractions after continued knee extensor task-specific practice. *Applied Physiology, Nutrition, and Metabolism* 40(3): 230-237

Shellock, FG, Prentice, WE (1985) Warming-up and stretching for improved physical performance and prevention of sports related injuries. *Journal of Sports Medicine* 2(4): 267-278

Smith, CA (2004) The warm-up procedure: To stretch or not to stretch. A brief review. *Journal of Orthopedic Sports and Physical Therapy* 19: 12–17

Stafilidis, S, Tilp, M (2015) Effects of short duration static stretching on jump performance, maximum voluntary contraction, and various mechanical and morphological parameters of the muscle-tendon unit of the lower extremities. *Journal of Applied Physiology* 115(3): 607-617

Stieg, JL, Faulkinbury, KJ, Tran, TT, Brown, LE, Coburn, JW, Judelson, JA (2011) Acute effects of depth jump volume on vertical jump performance in collegiate women soccer players. *Journal of Kinesiology* 1: 25-30

Strojnik, V (1995) Muscle activation level during maximal voluntary effort. *Journal of Applied Physiology and Occupational Physiology* 72(1/2): 144-149

Strojnik, V, Komi, PV (1998) Neuromuscular fatigue after maximal stretch-shortening cycle exercise. *Journal of Applied Physiology* 84(1): 344-350

Sweeney, HL, Bowman, BF, Stull, JT (1993) Myosin light chain phosphorylation in vertebrate striated muscle: Regulation and function. *The American Journal of Physiology-Cell Physiology* 264(33): 1085-1095

Tellez, T, Doolittle, D (1984) Sprinting from start to finish. *Track Technique* 88: 2802-2805

Tesch, PA, Karlsson, J (1985) Muscle fiber types and size in trained and untrained muscles of elite athletes. *Journal of Applied Physiology* 59: 1716 –1720

Till, KA, Cooke, C (2009) The effects of postactivation potentiation on sprint and jump performance of male academy soccer players. *Journal of Strength and Conditioning Research* 23: 1960–1967

Tillin, NA, Bishop, D (2009) Factors modulating post-activation potentiation and its effect on performance of subsequent explosive activities. *Journal of Sports Medicine* 39(2): 147-166

Turner, AP, Bellhouse, S, Kilduff, LP, Russell, M (2014) Post-activation potentiation of sprint acceleration performance using plyometric exercise. *Journal of Strength and Conditioning Research / National Strength & Conditioning Association* 16: 530-538

Vandervoort, AA, Quinlan, J, McComas, AJ (1983) Twitch potentiation after voluntary contraction. *Journal of Experimental Neurology* 81: 141-152

Westerblad, H, Allen, DG (1991) Changes of myoplasmic calcium concentration during fatigue in single mouse muscle fibers. *Journal of General Physiology* 98(3): 615–635

Widrick, JJ, Trappe, SW, Blaster, CA, Costil, DL, Fitts, RH (1996) Isometric force and maximal shortening velocity of single muscle fibers from elite masters runners. *American Journal of Physiology* 271: C666–C675

Wilson, JM, Duncan, NM, Brown, PJ, Loenneke, JP, Wilson, SM, Jo, E, Lowery, RP, Ugrinowitsch, C (2013) Meta-analysis of postactivation potentiation and power: effects of conditioning activity, volume, gender, rest periods, and training status. *Journal of Strength and Conditioning Research* 27(3): 854-859

Young, WB (1993) Training for speed/strength: Heavy versus light loads. *National Strength and Conditioning Journal* 15(5): 34–43

Young, WB. 1995. Laboratory strength assessment of athletes. New Studies in Athletics 10(1): 86-96

Young, WB, Jenner, A, Griffiths, K (1998) Acute enhancement of power performance from heavy load squats. *Journal of Strength & Conditioning Research* 12(2): 82-84

Young, WB, Behm, DG (2003) Effects of static stretching and practice jumps on explosive force production and jumping performance. *The Journal of Sports Medicine and physical fitness* 43: 21–27