UNIVERSITY OF DERBY

COMPARING THE ACUTE EFFECTS OF WARM-UP STRATEGIES USING FREE-WEIGHT AND VARIABLE RESISTANCE ON STRENGTH AND POWER PERFORMANCE

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"It is the mark of an educated mind to be able to entertain a thought without accepting it."

"Educating the mind without educating the heart is no education at all."

"The more you know, the more you know you don't know."

— Aristotle

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Publications and Conference Presentations arising from the research

All research and writing contained within this thesis are my own, unless otherwise identified.

Within the thesis all studies have been published and presented at international conferences. The published research of this thesis has formed strong collaborations with academics at other national and international universities, including the University of Northampton, UK; Edith Cowan University, Australia; and, The University of Thessaly, Greece. All studies have received institutional ethical approval.

PhD Publications

Mina, MA, Blazevich, AJ, Giakas, G, and Kay, AD. Influence of variable resistance loading on subsequent free-weight maximal back squat performance. *Journal of Strength and Conditioning Research* 28: 2988–2996, 2014. [doi: 10.1519/JSC.0000000000000471].

Mina, MA, Blazevich, AJ, Giakas, G, Seitz, LB, and Kay, AD. Influence of chain-loaded variable resistance exercise on subsequent free-weight maximal back squat performance. *European Journal of Sport Science* 16: 932-939, 2016. [doi:10.1080/17461391.2016.1199740].

Mina, MA, Blazevich, AJ, Tsatalas, T, Giakas, G, Seitz, LB, and Kay, AD. Variable, but not free-weight, resistance back squat exercise potentiates jump performance following a comprehensive task specific warm-up. *Scandinavian Journal of Medicine and Science in Sports* 29: 380-392, 2019. [doi: 10.1111/sms.13341].

Conference Presentations

Mina, MA, Blazevich, AJ, Tsatalas, T, Giakas, G, Seitz, LB, and Kay, AD. Optimization of warm-up strategies using free-weight and elastic band back squat exercise on subsequent countermovement vertical jump performance. Presented at: *22nd Annual Congress of the European College of Sport Science (ECSS 2017), Essen, Germany, 5-8 July 2017.* [Oral]

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Mina, MA, Blazevich, AJ, Giakas, G, and Kay, AD. Influence of chain-loaded variable resistance exercise on subsequent free-weight maximal back squat performance. Invited Presented at: *19th Annual Congress of the European College of Sport Science (ECSS 2014), Amsterdam, Netherlands, 02-05 July 2014.* [Oral]

Mina, MA. Practical guidelines for the use of variable resistance in strength & conditioning Presented at: *Buxton Sports Conference, Derby, United Kingdom, 09 Dec 2013.* [Oral]

Mina, MA, Giakas, G, Blazevich, AJ, and Kay, AD. Influence of variable resistance loading on subsequent free-weight maximal back squat performance. Invited Presentation presented to: *18th Annual Congress of the European College of Sport Science (ECSS 2013), Barcelona, Spain, 26-29 June 2013*. [Oral]

Abbreviations

Calcium	Ca^{2+}
Ca^{2+} conductance	g_{Ca}
Chain-loaded resistance	CLR
Jump squat	CJS
Countermovement vertical jump	CMJ
Effect size	ES
Elastic band	EB
Electromyography	EMG
Free-weight resistance	FWR
Gluteus maximum	Glut
Kinetic energy	KE
Rectus femoris	RF
Semitendinosus	ST
Maximum voluntary contraction	MVC
Meters per second	$m \cdot s^{-1}$
Microsecond	µs
Muscle-tendon unit	MTU
Myosin light chain kinase	MLCK
Myosin Regulatory light chain	MRLC
Repetition maximum	RM
Pre-intervention	Pre
Postactivation potentiation	PAP
Postactivation performance enhancement	PAPE
Quadriceps femoris	QF
Range of motion	ROM
Rate of force development	RFD
Rebound jump squat	RJS
Residual force enhancement	RFE
Series of elastic components	SECs
Stretch-shortening cycle	SSC
Transmitter gated sodium	Na^{+}
Potassium	K^{+}
Tropomyosin and troponin	TN
Variable resistance	VR
Vastus lateralis	VL
Vastus medialis	VM

Thesis Abstract

Warm-up routines are typically designed to precondition the neuromuscular system for enhanced performance and reduced injury risk during subsequent high-intensity physical activities, including during strength training. As such, identifying an effective warm-up routine to augment muscular performance is of clear importance to strength (and other) coaches and athletes. Incorporating variable resistance (VR) via the use of chains or elastic bands during strength training alters the loading characteristics during exercises to impose a greater mechanical stimulus, however the impact of VR on subsequent free-weight exercise performance is unknown. Therefore, the aims of this thesis were to examine the acute effects of conditioning VR exercise compared to free-weight resistance (FWR) exercise on subsequent one-repetition maximum (1-RM) back squat and countermovement vertical jump (CMJ) height performance after the performance of a comprehensive, test-specific warm-up, and to examine possible alterations to mechanics and neuromuscular activity underpinning any changes. Techniques including 3D motion analysis, electromyography (EMG) and ground reaction force measurement were used in three studies on recreationally active volunteers experienced in squatting and jumping. In Study 1, significantly greater 1-RM squat-lift load (6.2 ± 5.0%; $p < 0.01$) and mean eccentric-phase knee extensor EMG amplitude (32.2 ± 6.7%; $p < 0.01$) were found after the chain-loaded resistance (CLR) warm-up, where an increasing load is applied as the subject raises their body with the load, compared to the FWR condition. However, no statistical differences ($p > 0.05$) were detected in concentric phase EMG, knee angular velocity or peak knee flexion angle. Thus, performing a CLR warm-up enhanced subsequent free-weight 1-RM performance without kinematic changes; these data were considered to indicate a real 1-RM increase as the mechanics of the lift were not influenced. Study 2 followed an identical methodological design, however elastic bands were used to provide an inexpensive, portable, easily-implemented, and therefore more practical method of altering the load-time characteristics of the squat lift through VR. Significantly greater 1-RM squat load (7.7 ± 6.2%; $p < 0.01$) with lower peak and mean eccentric (16–19%; $p < 0.05$) and concentric (12–21%; $p < 0.05$) knee angular velocities were found after the elastic band (EB) warm-up compared to the FWR condition. As EB resistance evoked greater mean improvements in squat performance than the CLR used in Study 1, the influence of FWR and EB squat exercises following a comprehensive warm-up were compared using a more functional, CMJ, task at different post-exercise time points (i.e. 30 s, 4 min, 8 min, and 12 min) (Study 3). No changes in any variable were found after the FWR warm-up ($p > 0.05$). However, statistical ($p < 0.05$) and practically-meaningful increases were detected in CMJ height (5.3-6.5%), net impulse (2.7-3.3%), take-off velocity (2.7-3.8%), peak power (4.4-5.9%), kinetic (7.1-7.2%) and potential (5.4-6.7%) energy, peak normalised rate of force development (12.9-19.1%), peak concentric knee angular velocities (3.1-4.1%) and mean concentric vastus lateralis (VL) EMG activity (27.5-33.4%) at all time points after the EB warm-up condition. Thus, when a complete CMJ-specific warm-up was provided, FWR squat had no additional effect on CMJ performance however the alteration of the squat lift force-time characteristics using EB led to a substantial CMJ enhancement. The findings from the present series of studies have important implications for research study design as the warm-up imposed and the resistive modality selected appear to influence subsequent movement performances, i.e. 1-RM back squat or CMJ performances. In previous studies, standardised (or no) warm-up protocols imposed before the baseline testing have been associated with subsequent enhancements in squat lift and CMJ performances following conditioning contractions, although it is unclear whether this is a consequence of acute neuromuscular alteration relating to the conditioning contractions or to the warm-up itself. Collectively, the present findings, show that physical performance can be enhanced in at least some conditions by application of conditioning contractions even after completion of a comprehensive, test-specific warm-up, which have important practical implications in the formulation of pre-performance warm-up routines where maximal force production is an important goal.

Key words: warm-up, conditioning contractions, strength training, accommodating resistance, 1-RM, countermovement jump

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Chapter 1

1 Introduction

1.1 Background to the thesis

Strength expression is the result of muscular action initiated by electrical processes in the nervous system and is defined as the ability of muscles to generate forces under specific conditions (Siff, 2003). Strength training practices have largely evolved over the years through a process of, for the most part, trial and error (Bishop, 2003). The methodologies explored that have triggered progression in strength, power, endurance and muscle size were widely accepted. Evidence of weight training originally found in ancient civilisations of Egypt and India while the cult of well-built and symmetrical body sculptures of athletes training with stone weights preparing for events such as the Olympics or the military were found in ancient Greece (Stojiljkovic et al., 2013). In the 20th century, the purpose of strength training or weightlifting gradually transitioned to sports performance with technological developments allowing more in-depth measurements and evaluations of physiological changes (Kraemer & Hakkinen, 2002). Research has progressed to examine how different training protocols influence the acute neuromuscular responses and adaptive strength responses underpinning muscular force production. Such loading strategies included the use of dumbbells, kettlebells and loadable barbells (Morgan, 2003) and questions arose as to how the magnitude of load, similarity of movement patterns, training status and recovery influenced athletic adaptations and sport capabilities, often with the aim of increasing mass and strength (Kraemer & Hakkinen, 2002). In the 1970's, research tied strength development to specific sports goals to enhance performance (Kraemer & Hakkinen, 2002) leading to more contemporary research foci of examining specific modes of training that influence the biomechanical components of force production, power and velocity in relation to specific sports or activities. Different training modalities can include multi-joint movements, plyometrics, and sport-specific techniques (i.e. variation of load) with the specific sport or activity that is targeted often dictating the type of training used for enhancement. As power and rate of force development are often the greatest predictors of sports performance (Cronin & Sleivert, 2005), supplementing or combining heavy resistance strength training with other methods to fulfil all aspects of the force-velocity spectrum may be of importance for the enhancement of sports performance.

Warm-up, otherwise known as a pre-performance routine, performed prior to exercise and sporting participation is a customary practice, executed with the expectation of enhancing subsequent performance compared to that which could be expected where a warm-up is not performed (Bishop, 2003; Fradkin et al., 2010; MacIntosh et al., 2012a). The proposed benefits of warm-up protocols have largely been attributed to increased muscle temperature, with enhancements in vertical jump height, sprint running and squat lift performances being commonly observed (Bergh & Ekblom, 1979; Chatzopoulos et al., 2007; Gourgoulis et al., 2003). In effect, increased muscle temperature may augment subsequent muscle force and power production by decreasing muscle stiffness, increasing rate of force development and potentially increasing cross-bridge cycling rate and thus maximum muscle fibre shortening velocity (Barany, 1967; Binkhorst et al., 1977; Gonzalez-Alonso et al., 2000). In addition to the components of a traditional/standardised warm-up (e.g. cardiovascular warm-up followed by static muscle stretching; i.e. without task-specific warm-up), maximal voluntary contractions (MVC) can be incorporated into warm-up protocols to condition the neuromuscular system to enhance performance and, potentially, reduce the risk of injury during high-intensity physical activity (Bishop, 2003; Woods et al., 2007). Such maximal or near-maximal muscle contractions are thought to induce a phenomenon known as postactivation potentiation (PAP) to further augment performance above previously maximal voluntary levels (Sale, 2002; Tillin & Bishop, 2009; Verhoshansky, 1986). This force enhancement has commonly been attributed to the preceding series of contractions resulting in a greater phosphorylation of myosin light chains, leading to a greater calcium sensitivity with subsequent increases in rate of force development (Maffiuletti et al., 2016; Vandenboom et al., 1993). Unsurprisingly, there is a considerable practical interest from coaches and athletes that the performance of maximal or near-maximal muscle contractions might improve muscular performance in a subsequent contraction.

The back squat exercise is a fundamental exercise for the development of lower-limb strength and power (Chiu et al., 2003; Young, 1998) and has been reported to improve functional performance when used in a warm-up (Hodgson et al., 2005; Tillin & Bishop, 2009). However, new training methods are often sought in an attempt to improve strength and power development (Anderson et al., 2008; Baker & Newton, 2009; Israetel et al., 2010; Stevenson et al., 2010; Wallace et al., 2006). One limitation of using traditional free-weight resistance (FWR) is that it may not adequately challenge the musculature through the full range of motion in both eccentric and concentric phases of the exercise due to forces being higher at the "sticking point" and lower at other points in the lift (Wilson & Kritz, 2014). The sticking point can limit lifting performance in lifts of ≥90% 1-RM during a short period in the early ascending (concentric) phase of exercise tasks such as the bench press or back squat lift (Anderson et al., 2008; Elliott and Wilson, 1989; Newton et al., 1997). This is likely a consequence of a poor mechanical advantage during this phase as the muscles are at longer lengths where they are weaker, with smaller internal but greater external moment arms compromising joint moments (Elliott & Wilson, 1989). However, adopting strategies to modify the load during the lift (e.g. by imposing variable resistance [VR]) can reduce the effective load near the sticking point and then allow for greater loading later in the concentric phase where the joints are more extended, internal moment arms are greater, and optimal muscle lengths are achieved (Anderson et al., 2008; Israetel et al., 2010; McMaster et al., 2009; McMaster et al., 2010; Wilson & Kritz, 2014). This enables individuals to more easily complete the lift compared to FWR alone. Therefore, manipulating the loading experienced during the squat exercise to challenge the musculature over a larger range of motion, while mitigating the impact of the sticking point on the ability of the athlete to complete the exercise, may enhance the training stimulus (Elliott & Wilson, 1989; Wilson & Kritz, 2014). It might also prove to be a useful tool to further enhance the effects of warm-up on force production.

Two common methods of implementing VR include elastic bands and chains (McMaster et al., 2010), where the deformation of elastic bands or cumulative effect of increased chain linkages allow a progressive increase in loading that maximises opportunities to operate at higher muscle forces throughout the entire squat lift (Baker & Newton, 2009; Israetel et al., 2010). VR takes advantage of ascending strength curve exercises such as bench press, deadlift, squat and shoulder press where muscle lengths increase during the eccentric lowering phase. During the ascent phase of an ascending strength curve lift, the musculoskeletal system gains a mechanical advantage and force production decreases thus the added VR has the potential to increase muscle stimulation, motor unit recruitment and firing rates, and consequently prevent a decrease in muscular force production throughout the last ~25% of the lift (McMaster et al., 2009; 2010). Previous attempts have been made to quantify the unique stimulus provided by elastic bands and chains in combination with FWR (Baker & Newton. 2009, Coker et al., 2006; Ebben & Jensen, 2002; McMaster et al., 2009; McMaster et al., 2010). Baker & Newton (2009) reported that the use of chains significantly increased mean and peak lifting velocities during the bench press compared with FWR exercise, while Israetel et al. (2010) found significantly higher power, velocity and electromyogram (EMG) values (i.e. muscle activity) during the first quarter of the eccentric phase and the last quarter of the concentric phase of the squat exercise using elastic bands. However, Ebben & Jensen (2002) found that the use of chain-loaded resistance had no significant effect on lift kinetics or EMG activity when compared to a traditional FWR back squat exercise. Similarly, Coker et al. (2006) found no significant difference in velocity or power output during the snatch exercise, with participants also perceiving the exercise to be more difficult under the chains condition. Although disparate findings are reported in the literature, differences in study design likely explain the equivocal findings. Furthermore, no study has examined the influence of different VR modalities when used as part of a comprehensive warm-up on subsequent free-weight 1-RM back squat exercise. A comprehensive warm-up may improve explosive performance, which is a vital element in many sporting contexts, therefore the use of VR can also be examined in higher speed activities such as jumping, sprint running or cycling to determine the wider effects on performance.

Understanding the effect of VR interventions is vital for the design of warm-up strategies in athletic populations, with important implications for experimental study design. Several studies have examined the effects of maximal isometric contractions (MVCs) on subsequent performance in multi-joint “explosive” movements (French et al., 2003) or heavy strength training exercises such as back squats on subsequent performances in tasks such as vertical jumping and sprint running (Chatzopoulos et al., 2007; Gourgoulis et al., 2003); these high-intensity warm-up contractions are often referred to as 'conditioning contractions'. Whilst maximal or near-maximal conditioning contractions ≥80% of dynamic or isometric MVC improved subsequent physical performance (Rahimi, 2007; Saez Saez de Villarreal et al., 2007), Witmer et al. (2010) reported no effect after conditioning contractions were performed at 70% 1-RM, possibly when loads are lifted using slow and controlled speeds. A determining factor may be the intent to make a high-speed contraction at lower loads for fast force production, which may activate the highest-threshold motor units to allow potentiation in an attempt to improve subsequent performance (Behm & Sale, 1993).

Heavy-resistance exercise has been shown to acutely increase muscle force output, at least when a comprehensive warm-up is not completed prior to the testing (Chiu et al., 2003; Young et al., 1998). However, force production can also be reduced immediately following the contractions as a result of either, or both, fatigue and/or motor pattern interference (i.e. perseveration) processes, which may mask potentiating effects for at least minutes after the conditioning contractions. Nonetheless, performance enhancement has typically been detected between 2.5-12.5 min after conditioning contractions (Comyns et al., 2006; Jo et al., 2010; Kilduff et al., 2007; Lowery et al., 2012; Young et al., 1998), with Baker (2008) also reporting that an increased jump squat performance was elicited only 90 s after the use of elastic band resistance in a squat lift conditioning contractions. However, the potentiating effect has commonly been explored either after standardised warm-ups are completed, including light stretching, cycling, running and sub-maximal repetitions (Duthie et al., 2002; French et al., 2003; Jo et al., 2009), or no warm-up is imposed before baseline testing (Hamada et al., 2000; Miyamoto et al., 2011). As a "comprehensive" warm-up is rarely completed within these studies prior to the specific conditioning contractions, the external (ecological) validity for athletic environments is limited. Further research of examining possible performance enhancements resulting from the completion of conditioning contractions subsequent to the completion of a comprehensive, task-specific warm-up is required.

1.2 Aims and objectives

Given the above, the major aims of the thesis were:

Study 1: To compare the effects of VR imposed by chain-loaded resistance (CLR) to FWR during a warm-up on subsequent free-weight 1-RM back squat performance.

Study 2: To compare the effects of VR imposed by elastic bands (EB) to FWR during a warm-up on subsequent free-weight 1-RM back squat performance.

Study 3: To examine and compare the influence of VR (imposed by EB) and FWR following a comprehensive warm-up on subsequent CMJ performance at different post-conditioning time points (i.e. 30 s, 4 min, 8 min, and 12 min).

The present body of research was conducted on recreationally active men experienced in strength training, including performance of the squat lift exercise, between September 2012 and May 2015 with the data collected in the biomechanics laboratories at The University of Northampton (UK) and The University of Thessaly (Greece). Ethical approval was sought and granted from the School of Health at The University of Northampton, UK, and the Department of Physical Education & Sport Science at the University of Thessaly, Greece, with the research conducted in accordance with the Declaration of Helsinki.

1.3 Hypotheses

In Studies 1 and 2, it was hypothesised that the variation in resistance elicited by CLR or EB during squatting in the warm-up would: a) enhance subsequent free-weight squat lift performance (i.e. maximal load), and b) alter lifting mechanics (i.e. knee angular velocities, peak knee flexion angle) and neuromuscular activity during the 1-RM test, when compared to the use of traditional FWR squat warm-up. In Study 3, it was hypothesised that the variation in resistance imposed by EB during the squat lift would: a) enhance subsequent CMJ performance, b) alter CMJ kinetic and kinematic parameters (i.e. peak power, peak eccentric kinetic energy, impulse- and time-based descent-to-ascent asymmetry indexes, rate of force development, hip, knee and ankle joint kinematics), and c) increase the muscle activity of the lower-limb extensor muscles, when compared to the use of traditional FWR squat warm-up more than FWR.

Chapter 2

2 Literature Review

2.1 Introduction

The ability to maximise muscular power is critical to successful outcomes in a number of athletic events that require dynamic and explosive movements, such as back squat and jumping tasks (Hester et al., 2015; Israetel et al., 2010). The execution of pre-performance, or warm-up, protocols prior to intense physical activity is commonly reported to enhance performance and minimise muscular injuries with the primary objectives being: a) to prepare an athlete for the task's demands, and b) to improve muscle function to reduce the risk of injury (Woods, 2007). The inclusion of VR loading as part of these warm-up protocols likely alters the neuromuscular and musculoskeletal stimuli by adding and removing resistance at specific regions of the movement. Understandably, the addition of elastic bands and chains (both commonly used methods of applying VR) in combination with FWR has gained considerable popularity (McMaster et al., 2009). Although limited research has been conducted to confirm the efficacy of these resistance modes, with the evidence currently being somewhat equivocal (Baker, 2008; Baker & Newton, 2009; Cronin et al., 2003; Ebben et al., 2000; Israetel et al., 2010; Wallace et al, 2006), these methods of enabling VR to alter loading patterns may be useful training tools for enhancing athletic performance. The primary aims of this review were to examine the basic physiology and biomechanics underpinning explosive strength and power performance during high-load squat lift and unloaded vertical jumping tasks, the impact of warm-up on force production, and to evaluate the current literature examining the influence of VR techniques on performance.

2.2 Literature search methodology

Original and review journal articles were retrieved from electronic searches of Pubmed and Medline (EBSCO) databases. Additional searches were performed in Google Scholar with recursive reference checking from relevant articles also performed with no restriction on the year of publication. Search terms included 'variable resistance', ‘warm-up strategies’, ‘chain resistance’, ‘elastic bands’, ‘elastic energy’, ‘accommodated resistance’, ‘augmentation’, ‘postactivation potentiation’, ‘back squat’, ‘vertical jump’, ‘one repetition maximum’, ‘resistance training’, ‘stretch shortening cycle’, ‘force length relationship’, ‘force velocity relationship’, ‘kinetic energy’, potential energy’. The final search was concluded in November 2019.

2.3 Neuromuscular parameters of force production

The production of voluntary force via the activation of muscle fibres is ultimately initiated in the motor cortex, although other excitatory neurones also activate the α-motoneurone pool for the development of skeletal muscle force (Evarts, 1979). The functional unit involved in skeletal muscular contraction is the motor unit, which comprises an α-motoneurone and the muscle fibres that it innervates. Muscle fibres are innervated by motoneurones that transmit impulses, i.e. action potentials (electrochemical signals), from the spinal cord to the muscle, which activate the fibres and cause them to develop force. Muscle fibres are recruited according to the all-or-none principle, where an action potential is transmitted through the motoneurone to all its associated muscle fibres (Henneman et al., 1965, 1979). A basic explanation of this process is that each fibre will simultaneously twitch or enter a state of tetanus (contraction) if impulses are continuously delivered, whereas no muscle fibres within a motor unit will contract if their associated neurone does not deliver an action potential. This motor unit recruitment occurs in a relatively fixed order in accordance with a motor unit threshold hierarchy. These processes dictate the number of muscle fibres recruited as well as their opportunity to achieve high firing rates, and ultimately dictates muscular force development, with greater muscular force being associated with a larger number of fibres activated at higher firing rates (Bawa et al., 2014; Henneman et al., 1979).

Muscular force is produced when α-motoneurones depolarise after excitation from higher centres (i.e. motor cortex, reflex inputs such as muscle spindles) and deliver that stimulus to the muscles. If there is sufficient excitatory input then a threshold will be reached causing the α-motoneurone membrane to depolarise, then muscle fibres to contract at the sarcomere level via the interaction of actin and myosin, and force to be generated. Each neurone within the α-motoneurone pool of a muscle has a distinct threshold that requires a specific stimulus strength from descending centres to become activated in accordance with the all-or-none law, and this dictates the number of muscle fibres recruited and influences the level of force production (Henneman et al., 1979). However, force production is ultimately influenced by the firing rate of motor units, which is dictated by the frequency of impulses traversing the α-motoneurones (Morimoto & Masuda, 1984). As motor unit activation accords with the size principle, which is based on the relationship between motor unit twitch force and recruitment threshold, motor units are also recruited in order according to their recruitment and firing rates resulting in a continuum of voluntary force in the agonist muscle. A greater number of motor units are recruited and their firing rates higher when heavier loads are lifted or forces are developed more rapidly. Therefore, maximal voluntary force production requires not only that the maximum number of motor units are recruited, but that high firing rates are achieved. Since direct assessment of motor unit recruitment and firing frequency are not yet possible (although high-density surface electromyography has advanced significantly) a traditional system of estimating the number and firing rate of active motor units is surface electromyography (EMG; Farina et al., 2014). The amplitude of the EMG is thought to predominately reflect the level of motor unit activity, while the frequency content largely reflects the conduction velocity of the active muscle fibres. In the absence of factors directly influencing muscle fibre function (e.g. fatigue), changes in descending drive (from the motor cortex or reflex loops) influence the activity of the α-motoneurone pool and this ultimately affects force production (Avela et al., 1999). Therefore, examination of EMG activity during contraction allows for a rudimentary assessment of changes in muscle activity that might influence muscle force, and provide insights as to possible neuromuscular mechanisms associated with changes in force such as those potentially arising from warm-up activities to longer-term training interventions.

The force that a muscle exerts is dependent upon the total motor unit activity, which changes with the number of motor units recruited and the rates at which the motoneurones discharge action potentials (rate coding; Duchateau et al., 2006). The recruitment and rate coding contributions relative to the force exerted by a muscle vary with the level of muscle force and the muscle performing the contraction (Duchateau et al., 2006). Due to the exponential distribution of recruitment thresholds within a motor unit pool, the majority of the motor units have low recruitment thresholds, therefore low-to-moderate forces are mainly produced by the recruitment of motor units with the upper limit of recruitment occurring at ~85% of maximum force (De Luca et al., 1982; van Cutsem et al., 1997). Any further increase in force is achieved by increased discharge rate of motor units rather than recruiting additional active units in the motoneurone pool (Duchateau et al., 2006). During rapid contractions, motor units are activated earlier at a lower percentage of maximal voluntary contraction (MVC) to produce peak force (Desmedt & Godaux, 1977), and are likely to be recruited with a load ~33% of maximum during a high-speed contraction. Recruitment thresholds can also be lower during a dynamic contraction than an isometric contraction (Tax et al., 1989) with changes in MVC force attributed to the force capacity adaptations of the muscle fibres and the motor unit activation. The neural mechanisms contributing to changes in MVC force depend on the maximal contraction being performed (Duchateau et al., 2006). Del Vecchio et al. (2019) found that an increase in the maximal dorsiflexor force occurred with a decreased relative recruitment threshold and increased discharge rate during submaximal contractions for the same motor units following 4 weeks of isometric strength training. Therefore, it is suggested that gains in muscle strength may be attributable to an increase in the excitatory input, or to adaptations in the properties of motoneurones (Del Vecchio et al., 2019). Based on the synopsis above, acute or chronic interventions that either decrease motor unit recruitment thresholds or increase firing rates should result in a greater muscle force (and rate of force development). This is because the greater number of action potentials reaching the muscles (e.g. as detected using EMG) will result in more fibres being recruited and for those fibres to develop higher forces.

2.4 Excitation-contraction coupling

The motor unit represents the operational unit by which the single joint system modulates muscle force, with the action potential issued by the motoneurone converted by the muscle fibres into force in a two-step process. Firstly, the motoneurone action potential is translated into a muscle action potential in order to transport the signal to the contractile unit. Secondly, a muscle action potential is transformed into muscle force through excitation-contraction coupling, where the excitation results in calcium (Ca^{2+})

release from the sarcoplasmic reticulum and the ultimate interaction of actin and myosin filaments (Enoka, 2015). After arrival of the action potential at the neuromuscular junction, the neurotransmitter acetylcholine (ACh) takes less than 100 μs to diffuse across the synaptic cleft and attach to receptors on the postsynaptic (muscle fibre) membrane. The attachment of Ach to the receptors opens the transmitter-gated (i.e. ligand-gated) sodium (Na^+) to enable the influx of Na^+ into the muscle fibre triggering the generation of a muscle fibre action potential (Enoka, 2015; MacIntosh et al., 2012b).

The conversion of a muscle fibre potential into muscle force is known as the excitation-contraction coupling process (Figure 2.1 below). This process involves the propagation of the action potential along the muscle fibre and down the T tubule, coupling of the action potential to the change in Ca^{2+} conductance of the sarcoplasmic reticulum, release of Ca^{2+} from the sarcoplasmic reticulum, Ca^{2+} binding to tropomyosin and troponin (TN) and the interaction of the contractile proteins (Enoka, 1988; 2015). The majority of these steps allow the interaction of actin and myosin through the removal of inhibition (Ca^{2+} disinhibition) of tropomyosin whereas only the interaction of contractile proteins relate to the crossbridge cycle. Ca^{2+} disinhibition is initiated with propagation of the muscle fibre muscle action potential along the sarcolemma and into the T tubule and within the muscle fibre. The action potential of the T tubule activates the voltage sensitive dihydropyridine receptors that transmit a signal to the ryanodine receptors in the sarcoplasmic reticulum and allows the release of Ca^{2+} from the sarcoplasmic reticulum (MacIntosh et al., 2012b) into the sarcoplasm of the muscle fibre (Enoka, 2015). In the absence of an action potential, Ca^{2+} conductance (g_{Ca}) is low and Ca^{2+} has difficulty crossing the membrane of the sarcoplasmic reticulum, therefore once $g_{Ca^{2+}}$ is increased by membrane depolarisation, Ca^{2+} moves from the sarcoplasmic reticulum through the ryanodine release channels into the sarcoplasm. The quantity of ryanodine is two to threefold greater in faster contracting fibres, which allows greater Ca^{2+} to be released by each action potential. The Ca^{2+} binds to TN causing a structural change in the thin filament to uncover the myosin-binding site on actin. This allows a transient rotation of the regulatory complex (TN tropomyosin-nebulin) that enables the interaction of actin and myosin, and engage in the cross-bridge cycle (Enoka, 2015).

Following Ca^{2+} disinhibition, the interaction between the contractile proteins involves biochemical events that produce transient structural protein changes. These biochemical events involve the globular heads of myosin attaching to actin, known as the cross-bridge cycle. Altered cross-bridge kinetics appears to be a primary mechanism by which Ca^{2+} sensitivity is modulated in skeletal muscle, although another possible mechanism, yet to be evidenced, is the altered binding of Ca^{2+} to troponin (MacIntosh, 2003). Cross-bridge kinetics can be affected by a number of factors including regulatory light chain (RLC) phosphorylation, temperature, pH concentration, sarcomere length, and inorganic phosphate concentration ($P_{i;}$ MacIntosh et al., 2012b). These factors are therefore, able to influence muscle contraction capacity *in vivo* in humans. Actin-myosin interaction allows the three-phase cross-bridge attach-rotate-detach cycle to occur, and thus for muscle force production and shortening (Enoka, 1988). Ca^{2+} is then pumped back into the sarcoplasmic reticulum and returned to the lateral sacs, causing the resumption of inhibition by the regulatory proteins troponin and tropomyosin. During contraction, any stimuli that increase Ca^{2+} release or enhance the effect of a quantum of Ca^{2+}, i.e. anything that increases actin-myosin interaction in response to a given neural signal, would enhance force production by mechanisms unrelated to muscle activation. Not only is altered cross-bridge kinetics the primary mechanism, but changes in cross-bridge formation due to the actin and myosin proximity appears to be the primary mode of action for the modulators of Ca^{2+} sensitivity. The phospohorylation of the myosin regulatory light chain specifically in Type II muscle fibres, for example, influences Ca^{2+} sensitivity of the actin-myosin complex and consequently enhances force development (Grange et al., 1995; Grange et al., 1998). Therefore, interventions that increase myosin light chain phosphorylation will potentially influence muscle force production and human movement performance.

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Figure 2.1. Excitation-contraction coupling (from Enoka, 2015).

2.5 Postactivation potentiation (PAP) and postactivation performance enhancement (PAPE)

Strength and conditioning practitioners often use physical strategies to induce a postactivation potentiation (PAP) response to acutely enhance subsequent performance. Historically, PAP has been defined as an enhancement of the contractile response for a given electrically-induced stimulation of the muscle that is initiated subsequent to the performance of a high-intensity voluntary contraction (Desmedt & Hainaut, 1968; Hamada et al., 2000; MacIntosh et al., 2012a; Sale, 2002). However, the term PAP (and its associated mechanisms) is often misinterpreted in current human literature and is used to describe an enhancement in voluntary muscle function (rather than improvements in electrically-induced twitch force) following a high-intensity contraction as part of a warm-up, with no confirmation that the mechanism lies within the muscle(s) involved (Blazevich & Babault, 2019; Zimmerman et al., 2019). Attempts have been made in the literature to evaluate PAP in relation to the enhancement of high-intensity voluntary performance with no confirmation of the presence of PAP, referred to herein as "classical PAP". PAP has been traditionally measured as an increase in the force of an isometric muscle twitch contraction following a conditioning contraction. The majority of studies have used similar experimental methodologies (Pre-test > conditioning contraction > rest > Post-test). However, whilst the persistence of classical PAP is apparent for only a few minutes (usually <3 min) following the conditioning contraction with a dramatic one-half decrease after 28 s (Vandervoort et al., 1983), peak voluntary performance is often reported to occur 6-10 min following the conditioning contraction (Wilson et al., 2013). Therefore, it appears unlikely that the acute enhancement in voluntary performance is strongly associated with classical PAP (Blazevich & Babault, 2019; Zimmerman et al., 2019). Nonetheless, performance enhancements are often found at some point after conditioning contractions, demonstrating a practical effect. Consequently, Cuenca-Fernandez et al. (2017) proposed using the term PAPE when high-intensity contractions enhance performance of a subsequent voluntary post-test measure. To clarify the terms within the present thesis, PAP refers to an increase in twitch force, whilst PAPE refers to increases in voluntary force. Consequently, whilst a similar outcome of increased force is a product of conditioning contractions regardless of the test method, a closer examination of the likely underlying mechanisms associated with PAP versus PAPE needs to be undertaken.

2.6 Mechanisms associated with the PAP/PAPE response

2.6.1 Overview

Warm-up routines prior to exercise are a widely accepted practice for improving physical function, and extensive research has been conducted to determine the key warm-up elements specific to exercise demands for enhancing performance. A series of intense voluntary muscular contractions performed as part of a warm-up (i.e. pre-exercise) routine can induce short-term increases in force production and physical performance through a number of mechanisms, including increases in myofilament calcium sensitivity (Moore & Stull, 1984; Smith & Fry, 2007), increases in muscle temperature (Racinais & Oksa, 2010), decreases in muscle tendon stiffness (Kay & Blazevich, 2009a), and increases in neural drive leading to higher-frequency motor unit discharge (Tillin & Bishop, 2009).

2.6.2 Myofilament light chain phosphorylation

The effects of PAP are observed immediately as an increase in peak force and rate of force development (RFD) of a twitch contraction (Baudry & Duchataeu, 2007; Hamada et al., 2000). A commonly cited mechanism underpinning this effect is an increase in intramuscular calcium concentration [Ca^{2+}] from the sarcoplasmic reticulum via ryanodine receptors that open in response to membrane depolarisation. This activates myosin light chain kinase (MLCK) and phosphorylates the regulatory myosin light chain (MRLC; Grange et al., 1993; MacIntosh et al., 2012a,b). This tends to distort the myosin head, bringing it closer to the actin binding sites and thus increasing the probability of strong actin-myosin binding for a given concentration of Ca^{2+}, i.e. the sensitivity of the actin-myosin complex is increased. There is a strong relationship between the magnitude of increase in twitch response and the magnitude of MRLC phosphorylation (Moore & Stull 1984, Vandenboom & Gittings, 2013). Whilst this does not affect the maximum tetanic force of a fibre, it increases the rate of cross-bridge formation allowing a faster RFD (MacIntosh et al., 2012b). Sweeney & Stull (1990) reported that the contractile response is increased at a given submaximal Ca^{2+} concentration and more force is produced when the MRLC is phosphorylated. Calmodulin (calcium-binding protein) then binds to and activates myosin regulatory light chain kinase (MLCK), which is associated with an increased Ca^{2+} sensitivity in isolated skinned muscle fibres (Sweeney & Stull, 1990). The process of phosphorylation allows the myosin heads to move closer to actin binding sites (Alamo et al., 2008), increasing the rate of cross-bridge formation (Sweeney & Stull, 1990; Metzger et al., 1989). Therefore, MRLC is commonly the mechanism identified as being largely responsible for PAP in fast-twitch isolated skinned skeletal muscle fibres, however it is less clear whether this mechanism significantly impacts voluntary, whole muscle function *in vivo* in humans (Houston & Grange, 1990; Smith & Fry, 2007).

If the muscle fibre is fully activated, the peak isometric force cannot be improved because the greatest possible cross-bridge formation already exists (Metzger et al., 1989). However, at submaximal levels of Ca^{2+}, such as at the onset of contraction or during a submaximal contraction, fibre force can be enhanced. This enhancement is more prominent in individuals with a higher proportion of Type II muscle fibres, which have a lower basal Ca^{2+} sensitivity compared to Type I fibres (Metzger & Moss, 1990) and are more prone to improved sensitivity (Grange et al., 1993). The activated Type II muscle fibres have a higher MLCK activity than Type I muscle fibres, as they derive more benefit from phosphorylation (Hamada et al., 2000) and exhibit a greater PAP response (Seitz et al., 2015). However, Type I muscle fibres already have a higher Ca^{2+} sensitivity, and have a lower MLCK activity (Metzger & Moss, 1990). In Type II muscle fibres, MRLC phosphorylation can be identified as a requirement for optimum muscle function therefore it is vital to trigger MRLC phosphorylation through intense muscular contractions. For this reason, previous research (Hamada et al., 2000) suggests that the potentiated state is more pronounced in individuals with greater Type II skeletal muscle fibre percentages, although according to Vandervoort et al. (1983) this effect only lasts for a few minutes (usually <3 min; half-life ~28 s). Therefore, any enhancement in performance attributable to MRLC phosphorylation following a short bout of muscle activity is short-lived and can only be effective within a short time-frame of e.g. <5 min (MacIntosh et al., 2012a). The majority of recent studies examining the PAPE effect demonstrate that enhancement takes at least several minutes to appear (Bevan et al., 2010; Wilson et al., 2013) and lasts up to 15 min, which indicates that MRLC phosphorylation may not be the main mechanism responsible for voluntary performance enhancements following high intensity muscular activity. That is, the commonly theorised mechanism underpinning the PAP phenomenon may not be the key factor influencing PAPE.

2.6.3 Muscle-tendon stiffness

The stiffness of intramuscular series elastic structures can affect peak twitch torque, submaximal tetanic forces and RFD (Josephson & Edman, 1998; Edman & Josephson, 2007), as muscle forces initially stretch series elastic structures (storing energy) prior to muscle force being transmitted to the bone. Edman & Josephson (2007) reported that around 40% of the time to reach 50% maximum force resulted from the time taken to stretch series elastic structures, while the remaining 60% of time to 50% force is attributed to the time for the excitation contraction-coupling process. However, larger muscles may take a longer time for force to increase, which influences RFD and the peak force achieved in twitch or maximal voluntary contraction. Importantly, as stiffness influences RFD and peak twitch torque, the currently-accepted *in vivo* test of PAP (i.e. muscle twitch torque) may be affected where warm-up activities influence the stiffness of these tissues.

A conditioning contraction can induce significant acute changes in tendon mechanical properties (Kay & Blazevich, 2009a; Kubo et al., 2002) depending on the intensity, duration, and action type of the conditioning task. Increases in tendon or aponeurosis stiffness could theoretically contribute to force enhancement. However, a 6 s maximal isometric plantar flexor twitch contractions tend to reduce tendon stiffness (Kay & Blazevich, 2009a; Kubo et al., 2002), at least until 4 – 6 contractions are performed (Gago et al., 2014; Maganaris & Paul, 1999; Kay et al., 2015), whereas concentric conditioning contractions have been found to have limited (Kay & Blazevich, 2010; Kubo et al., 2002) or no effect (Mademli et al., 2006). Conditioning contractions consisting of repeated dynamic maximal or submaximal isometric muscle contractions have been commonly used to induce PAPE (Tillin & Bishop, 2009), therefore it is possible that such conditioning protocols may have caused an acute reduction in stiffness. However, this should not considerably enhance muscle function, which is more likely to occur with increases in tendon stiffness. Nonetheless, more research is required to more fully understand the effects of acute changes in tendon stiffness on both PAP and PAPE.

2.6.4 Muscle temperature and contraction velocity

Muscle temperature is an important factor influencing performance after warm-up as it enhances muscle metabolism (Bishop, 2003; McGowan et al., 2015), decreases muscle and joint viscocity, decreases stiffness (Buchthal et al., 1944), increases unloading of oxygen from haemoglobin and myoglobin, increases speed of rate-limiting oxidative reactions and anaerobic metabolism (McCutcheon et al., 1999) and increases nerve conduction velocity (Ross & Leveritt, 2001). The temperature-dependence of muscle force production appears to be somewhat proportional to the relative workrate during submaximal exercise (Saltin et al., 1968). Moderate-intensity exercises (80-100% lactate threshold) cause muscle temperature to increase rapidly from resting levels (~35°C) to above rectal temperature by 3-5 min, reaching relative equilibrium following 10-20 min of exercise (Fisher et al., 1999). Furthermore, Gonzalez-Alonso et al. (2000) found that a dynamic voluntary knee extensor activity (3 min) increased muscle temperature by ~0.9%, indicating that temperature increases necessary to augment force output might be achieved with brief intense exercise muscle actions used in many PAPE studies.

Power output and muscle temperature have been strongly associated (depending on the type and velocity of voluntary muscular contractions [i.e. PAPE]) during drop jump (Oksa et al., 1996), vertical jump (Bergh & Ekblom, 1979) and cycle ergometer (Sargeant, 1987) tasks, improving muscle force/power by 2-5% per 1°C increase in muscle temperature. Importantly, Sargeant (1987) examined the effects of muscle temperature on the power-velocity relationship during sprint cycling exercise and found a velocity-dependent effect, with maximum cycling power increasing by ~2% per °C at 50 rev/min but by ~10% per °C at 140 rev/min. Collectively, the data indicate that increases in muscle force (and thus power) are more pronounced at faster movement speeds (Bergh & Ekblom, 1979; Racinais & Oksa, 2010; Sargeant, 1987). Therefore, performance enhancements of 1-5% (Yetter & Moir, 2008) may be largely explained by increases in muscle temperature, although perhaps additional mechanisms may have been important in studies demonstrating 5-10% increase (Iacono et al., 2016; Kummel et al., 2016), especially at lower contraction velocities commonly seen in strength- (e.g. back squat 1-RM) rather than power-based (e.g. vertical jumping) tasks.

Many activities more likely to demonstrate greater temperature-induced force increases use high-velocity muscle contractions such as jumping, running, hopping, throwing, and kicking utilising the stretch-shortening cycle (SSC), where the muscle-tendon units (MTUs) are stretched (eccentric phase) before shortening rapidly (concentric phase) without a significant delay between the eccentric and concentric phases. However, even without temperature-induced enhancement, the SSC can improve performance compared to concentric only muscle actions, i.e. vertical jump height is improved by 8% (Markovic et al., 2004) and running economy by ~50% (Cavagna et al., 1964). Cavagna et al (1964) examined different submaximal speeds (~3-6 m/s) and found that the total mechanical work increased linearly with speed and the mechanical efficiency in running ranged from 40-50%. Debate exists as to the mechanisms underpinning the enhancement of performance using the SSC, but can include greater elastic energy storage and subsequent recoil (Finni et al., 2003), an increased time for muscle activation (Bobbert et al., 1996; Finni et al., 2003), force potentiation/residual force enhancement (Joumaa et al., 2018; Rassier & Herzog, 2004), reflex contribution (Ishikawa & Komi (2007), and changes in relative contributions of muscle and tendon allowing the muscle to operate at lower shortening speeds and over shorter distances (Hof et al., 1983). Whilst SSC actions may be optimised by improving movement speed and power, further research is required to better understand the relative importance of these mechanisms.

The increase in muscle force production likely resulting from increased time for muscle activation, force potentiation/residual force enhancement, and stretch reflexes, will ultimately increase energy storage in the series elastic components (SECs). Thus, more elastic potential energy can be stored, since the stored energy is dependent upon the tissue's stiffness and the elongation of the tissue ($E = \frac{1}{2}kx^2$, where k is tissue stiffness and x is tissue deformation; Blazevich, 2011). Of perhaps more importance, since the acceleration of a person, limb or object is directly proportional to the applied force (Newton's second law, F = ma), the recoil force of the SEC will also be proportional to its stiffness and elongation according to Hooke's Law, -F = kx (again, k = stiffness and x = elongation/deformation), so a greater elongation resulting from higher muscle force production will also result in a greater recoil force, and thus power. Therefore, force enhancements potentially resulting from PAPE temperature- and stiffness-dependent effects might be expected to strongly influence performances in SSC activities such as the countermovement jump.

2.6.5 Increased neural drive

Another possible factor affecting PAPE is the neural facilitation associated with acute force enhancements and maximum voluntary RFD following high-intensity exercise (Heckman & Enoka, 2012). In voluntary contractions (i.e. PAPE) these changes may result from increases in spinal excitability (i.e. increased activation of the α-motoneurone pool) and associated increases in muscle activity following repetitive muscle contractions (Nuzzo et al., 2016). Increases in H-reflex amplitude in several studies following a voluntary conditioning contraction (Güllich & Schmidtbleicher, 1996; Trimble & Harp, 1998) can be assumed to reflect the transmission of Ia afferent terminals and postsynaptic membranes of the α-motoneurones via an increased excitability or decreased presynaptic inhibition. This can increase the action potential propagation from Ia terminals across synaptic junctions at the spinal cord. Nuzzo et al. (2016) found that acute strength training exercise leads to increased efficacy of corticospinal-motoneuronal synapses or increased motoneurone excitability following repetitive maximal conditioning contractions, which were strongly associated with enhanced voluntary force and muscle activity (EMG). Thus, the possibility exists that an improved muscle activation results from the performance of conditioning contractions, which could cause a PAPE although not PAP. However, increased H-reflex amplitudes observed following high intensity voluntary muscular contractions have been observed in some studies (Enoka, 1980; Folland et al., 2008; Trimble & Harp, 1998) but not others (Wallace et al., 2019). Furthermore, these measurements were taken in resting muscle, and it is possible that these data do not reflect the status of the neural system during muscular contractions (Tucker et al., 2005). Additionally, the

H-reflex potentiation has been reported at >12 min (Folland et al., 2008), >15 min (Güllich & Schmidtbleicher, 1996) or longer (Trimble & Harp, 1998) after a set of muscle conditioning contractions. These are typically longer than the observed PAPE effect. Of final note is that Folland et al (2008) found that increases in H-reflex amplitude occurred without increases in subsequent voluntary knee extensor function. Therefore, the potential increases in neural drive to the muscle and the prolonged timecourse for H-reflex potentiation compared to changes in voluntary muscle functions suggests that other possible mechanisms may contribute to such changes.

Although an increase in EMG activity might be expected following high-intensity contractions (i.e. neural drive enhancement; Güllich & Schmidtbleicher, 1996; Trimble & Harp, 1998), several studies have not observed increases in EMG activity even when improvements in performance were clearly detected (Hough et al., 2009; Seitz et al., 2014). However, Sotiropoulos et al. (2010) detected an increase in EMG (VL) at 3 min after 2 sets of 5 loaded squats for both the low intensity (25% and 35% 1-RM) and moderate intensity (45% and 65% 1-RM) groups. Nonetheless, it is unclear whether the effect was a function of the warm-up or a potentiating effect from the additional conditioning contractions as a control condition was not included. These results suggest that an increase in voluntary muscular performance following intense muscle activity, adopted in most PAPE studies, is unlikely to be underpinned by increases in neural drive. This suggestion is consistent with a study by Behm et al. (2004) that found decreased voluntary activation (twitch interpolation technique), an increased twitch response (i.e. PAP), but muscular voluntary performance (i.e. PAPE) to be unchanged following 1-3 (10 s) maximal voluntary isometric knee extensor contractions. However, the lack of increase in EMG in the majority of the studies may suggest that such increase occurs under specific conditions for example when the conditioning contraction and the subsequent activity are identical although this was not the case in Seitz et al (2015) or the EMG does not have sufficient resolution to detect minor increases in activation of highly activated muscles particularly when processes such as, fatigue and potentiation are present (Enoka, 2012). Collectively, these findings indicate that alterations in spinal circuitry may occur after the performance of maximal muscular contractions, however changes in voluntary muscle activity or activation are not clearly observed and PAPE effects do not appear to coincide with improvements in the ability to activate the muscles. Nonetheless, additional research is required in order to more explicitly test the effects of conditioning contractions on muscle activity and performance.

2.6.6 Muscle blood flow/water inflow

One possible mechanism that has not yet been examined in PAPE-related studies is the increase in muscle blood flow or, ultimately muscle water, following high-intensity exercise, which can possibly increase muscle fibre force and shortening velocity (Edman & Anderson, 1968). This influences ionic strength (i.e. hypotonicity) within the muscle fibres due to water movement into intracellular space (Sjøgaard et al., 1985), which may be beneficial to muscle force production and is greater in mammalian Type II fibres (Fink et al., 1986); these findings are consistent with both PAP and PAPE effects being greater in individuals with greater Type II fibre proportions. As the reduction of ionic strength increases force production and can enhance muscle function *in vivo* (for review, see Blazevich & Babault, 2019), this mechanism can possibly explain (at least part of) the PAPE effect, however its delayed temporal profile suggests it is too slow to influence peak PAP.

2.7 **Methodological factors influencing PAP/PAPE research**

2.7.1 Influence of the level of strength and training experience

Stronger individuals often exhibit a greater performance enhancement than weaker individuals as measured using both twitch (i.e. PAP; Hamada et al., 2000) and voluntary test contractions (i.e. PAPE; Ruben et al., 2010; Seitz et al., 2014). The greater PAP effect is suggested to relate to a higher percentage of Type II muscle fibres in stronger individuals and hence a greater MRLC phosphorylation (Aagaard & Andersen, 1998; Wilson et al., 2013) in response to conditioning contractions. Previous research also supports the view that stronger individuals may express higher levels of PAPE (Chiu et al., 2003; Ruben et al., 2010; Seitz et al., 2014). Ruben et al. (2010) found that stronger individuals expressed greater voluntary potentiation effects between the control and potentiation trials for peak power and peak velocity compared to weaker individuals. Some have speculated that athletes or stronger individuals who are highly trained and have a greater percentage of Type II fibres (Aagaard and Andersen, 1998) may be able to recover faster from a potentiation-inducing activity and show a greater degree of potentiation (Chiu et al., 2003; Gourgoulis et al, 2003; Seitz & Haff, 2016), although there is no direct evidence to support this contention with greater Type II profiles more likely to exhibit greater fatigue. Gourgoulis et al. (2003) observed that participants with greater maximal strength improved vertical jump height (4%), more than participants with lower maximal strength. A stronger participant can often be characterised by a greater muscle cross-sectional area (Maughan et al, 1983) or volume (Fukunaga et al., 2001), which may explain an increase in tissue-specific force that will be amplified following a conditioning contraction. However, muscle size can possibly be a factor influencing PAPE depending on the fibre (motor unit) type. Seitz et al. (2016a) found that PAPE was strongly correlated with maximal voluntary knee extensor torque, quadriceps cross-sectional area and volume, and a significant correlation between maximal voluntary knee extensor torque production (strength) and Type II myosin heavy chain isoform percentage was observed, which indicates a link between muscular strength and fibre type (Aagaard & Andersen, 1998). Therefore, the likelihood and magnitude of performance enhancements in PAP/PAPE studies may be particularly reliant upon subject-specific characteristics.

Inter-individual variability in factors such as strength level and training experience may also affect recovery durations. Golas et al. (2016) confirmed the effectiveness of PAPE in well-trained athletes from three different disciplines (basketball, luge and athletic throws) and included an individualised recovery time between the conditioning and explosive activity (jumping, throwing and pushing). The individualised recovery times differed in relation to an athlete's muscular strength, training status and muscle fibre type distribution (Golas et al., 2016). Thus, a generalisation of recovery durations (Golas et al., 2016) cannot accurately reflect the known inter-individual variability, which has speculatively been considered to result from the balance between potentiation and fatigue. Although fatigue may influence twitch force output (i.e. PAP) in the early stages following a conditioning contraction (Rassier & MacIntosh, 2000) this is not evident in PAPE studies. However, only seconds or a few minutes of recovery (>1 min) is required following a short-bout of maximal-effort exercises (i.e. maximal squat or bench press; Hitchcock, 1989, Weir et al., 1994). Thus, as a prolonged fatigue response (up to 8 min) in low-volume activities used in most PAPE studies is unlikely to influence performance, it does not preclude fatigue where the muscle work involved is much higher (Hamada et al., 2003; Xenofondos et al., 2018); nonetheless, more study is warranted in this area to more fully examine the relationship between potentiation and fatigue.

2.7.2 Free-weight conditioning contractions: type, duration, intensity and volume

Maximum voluntary contractions (MVCs), both dynamic and isometric, have been used as conditioning contractions to elicit a PAPE effect. However, most studies have utilised dynamic exercises such as squat lift and bench press exercises (McBride et al., 2005; Young et al., 1998), with varying repetition numbers, exercise intensity and rest periods. Other studies have imposed plyometric exercises such as drop jumps (Hilfiker et al., 2007) and double-legged tuck jumps (Masamoto et al., 2003) as well as isometric MVC leg extensions (French et al., 2003; Gossen & Sale, 2000) to elicit a PAPE response. Rixon et al. (2007) compared two types of conditioning contractions (isometric vs. dynamic) and found a significant increase in countermovement jump height and peak power 3 min after 3 isometric MVC back squats, although no change in countermovement jump height but a significant increase peak power was reported 3 min after a 3-RM dynamic back squat. While these data are suggestive that isometric contractions induced a greater potentiation response compared to dynamic contractions, the two conditions were not identical in terms of volume to allow a direct comparison of their PAPE effect. Similarly, Gourgoulis et al. (2003) found that a warm-up protocol including half-squats with submaximal loads and explosive execution significantly increased vertical jump performance, whereas Hanson et al. (2007) examined light- (40%) and heavy-load (80%) squats and found no significant changes in vertical jump performance in either condition. The wide variety of methods, intensities and durations used highlights both the difficulty in comparing findings across studies and determining the most effective protocol to elicit PAPE, with the equivocal findings in the literature likely a consequence of substantial methodological differences across studies.

Previous research suggests that the volume and intensity of the conditioning contraction as well as the rest period between the conditioning contraction and subsequent activity can influence PAPE magnitude (Wilson et al., 2013). Generally, a lower conditioning volume may induce less fatigue and an earlier PAPE could be observed, whereas the opposite may be true of a higher volume (Figure 2.2). However, greater levels of PAPE are reported when multiple sets of a conditioning contraction are completed at moderate intensities and the test is repeated after ~7-10 min of recovery (Wilson et al., 2013). Such findings are also likely influenced by training status. For example, individuals with less training experience (recreationally trained) were found to decrease power, whereas trained individuals (>1 year of resistance training experience) or experienced athletes (>3 years resistance training experience) increased power when performing multiple versus single sets of a heavy (95% 1-RM) conditioning contraction (Wilson et al., 2013). Collectively, these finding indicate that training status, volume and intensity of the conditioning contractions, and rest periods are likely factors influencing the magnitude of PAPE, although the possible influence of fatigue remains unclear.

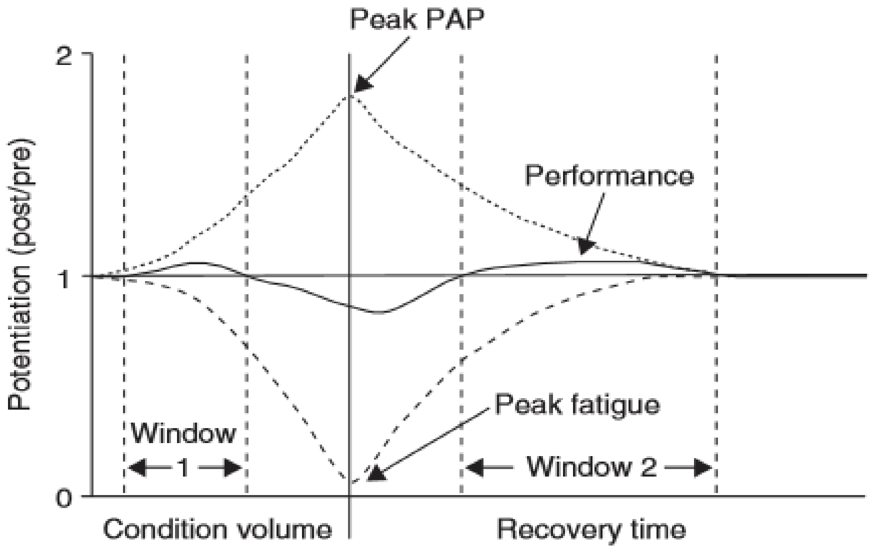

Figure 2.2. A hypothetical timeline model of the relationship of the loading volume of the conditioning contraction, fatigue and PAPE (Tillin & Bishop, 2009). In theory, PAPE is more dominant where the condition volume is low (Window 1) or following a high-volume conditioning contraction (Window 2).

Rather than fatigue, the lack of PAPE effect in the first minutes after a conditioning contraction might also speculatively result from motor pattern perseveration, a motor pattern interference effect. The motor pattern of one task can "persevere" as a subsequent task commences (termed the "motor pattern interference effect"), so there can be a loss of coordination following sequentially performed tasks (Classen et al., 1998). In motor tasks, perseveration has been observed in simulation of lower-limb locomotor movement patterns (Classen et al., 1998) but interference has been observed when a motor pattern is performed prior to another (Gottschall and Palmer, 2002). Therefore, the perseveration effect, rather than fatigue, may explain the delay in performance enhancement following a high intensity muscular activity. If true, such effects may be reduced through a specific task practice following a conditioning contraction, although limited research exists describing these possible effects with further research required in this area to better understand the implications of specific prior exercises on subsequent task-specific and alternate task performance.

Because improvements in calcium sensitivity of the acto-myosin complex only enhance force production at submaximal levels of calcium (i.e. submaximal levels of activation), high-intensity muscle contractions (i.e. maximal exercise or heavy lifts) in which maximal or near-maximal levels of muscle activation are attained cannot be enhanced by the generation of PAP (Sweeney & Stull, 1990). PAP affects the force-calcium relation augmenting force at lower levels of activation during short-duration contractions or early in an MVC where maximal force cannot be achieved. This can influence performance during short duration activities (e.g. vertical jumping, kicking; Comyns et al., 2006; Duthie et al., 2002; Esformes et al., 2013). However, MRLC phosphorylation may enhance muscular RFD and performances in high-intensity short-duration concentric tasks (Grange et al., 1998; MacIntosh & Bryan, 2002); thus, in theory the PAPE effect may be partly explained by mechanisms associated with the PAP effect. However, limited research has examined both PAPE and PAP simultaneously in order to assess similarity of their temporal responses (Mitchell & Sale, 2011; Prieske et al., 2018) by measuring changes in twitch force as well as voluntary force outcome. Previous research has not shown that changes in twitch force are related to changes in voluntary muscle function either because a) PAP was distinct from PAPE (Seitz et al., 2014), b) PAP was clearly elicited despite a PAPE response not being observed (isometric knee extensor [Behm et al., 2004], vertical jump [Prieske et al., 2018]), c) a small increase in twitch force occurred (~10%) at a time point (4 min) when a small increase in performance (countermovement jump; 2.8%) was observed (Mitchell & Sale, 2011). Therefore, PAP appears to be distinct from PAPE and the reported PAPE responses do not appear to be attributable to PAP. Seitz et al. (2015) found that dynamic conditioning contractions, regardless of the movement velocity and total work done, could improve subsequent voluntary (7 min; up to ~6% - PAPE) compared to twitch (4 min; up to 13.5% - PAP) torque even after the completion of an extensive task-specific warm-up. This further suggests that these are two partly different phenomena, indicating that PAP would be higher at time points <1 min (>80% according to Hamada et al., 2000). However, Prieske et al. (2018) found significant increases in twitch force (peak torque [21%] and rate of torque [43%]) after a strength-training-based conditioning contraction without any change in jump height (voluntary performance), while a combination of balance and strength-training exercises evoked significant increases in jump height (3%) without improved twitch force. Thus, the PAPE response could not be attributed to a PAP effect, so such PAPE effects are likely to be explained by mechanisms other than PAP. Therefore, as PAPE and PAP effects are rarely observed concurrently, it is likely that these two phenomena are largely distinct and that the physiological changes underpinning PAP contribute little to the total PAPE effect.

2.7.2.1 Methodological limitations in free-weight resistance research

Most studies that have reported a PAPE effect have used methods that allowed the testing of whether PAP might have contributed to the effect. Comparisons of muscle twitch and voluntary force measurements allow the assessment of the magnitude and time courses of PAP in relation to PAPE (Piersche et al., 2018; Seitz et al., 2015). There are several important methodological considerations including a) comparison of two or more conditions b) inclusion of a familiarisation session, c) a randomised, double-blinded (researcher and participant) study design between conditions on separate days, and d) other controls prior to testing (muscle temperature, physical activity, time of day, diet and hydration). Cuenca-Fernandez et al. (2017) examined the impact of the training level, physical activity, diet, dietary supplements and reported an increase in jump height following a non-exercising control condition inducing PAP/PAPE, indicating that the warm-up (temperature and task practice) effect from the completion of the baseline tests may have contributed to the increase in jump height. Alternatively, twitch/voluntary torque produced during maximal or near-maximal voluntary contractions (i.e. control condition) may also be influenced by the increased temperature

(Bergh & Ekblom, 1979). Another important consideration is that a complete task-specific warm-up should be executed prior to a conditioning contraction, in order to assess the practical impact of conditioning contractions in an applied setting. Previous research imposed limited (i.e. short-duration, low-intensity) or no warm-up exercises (Batista et al. 2007; Hamada et al., 2000; Miyamoto et al., 2011), and studies that imposed a warm-up (see Table 2.1) included typically light aerobic exercise followed by stretching, body-weight exercise or athletic drills (Seitz et al., 2016a; Till & Cooke, 2009). Such warm-ups do not reflect real-life athletic practices and are not sufficient to enhance muscle performance; therefore, high-intensity test-specific warm-ups should be examined in future studies to determine whether a conditioning contraction can enhance performance compared to a traditional/standardised warm-up alone.

Table 2.1. Warm-up studies that refer to voluntary potentiation			
Study	**Conditioning contraction**	**Performance enhancement**	**Warm-up**
Batista et al., 2007	Unilateral knee extensions	Yes	5 min cycle (70–80 rpm) and light stretching
Chiu et al., 2003	Rebound jump squats Concentric only jump squats	No	Control: 2 sets of 5 reps of unloaded parallel squats, 2 sets of 3 repetitions of vertical jumps Heavy: Control warm-up and 5 sets of 1 rep at 90% 1-RM in the parallel back squat. Two series of maximal effort RJS or CJS were performed with 30%, 50%, and 70% 1-RM at 1 min intervals
French et al., 2003	Drop jump, Knee extension CMJ, 5-s cycle sprint	Yes	5 min cycle (60 W at 0.5-kg load) followed by light stretching and submaximal familiarisation trials of the assessment exercises
Gossen & Sale, 2000	Maximal dynamic knee extension with loads	No	No warm-up
Gourgoulis et al., 2003	Submaximal half-squats	No	5 sets of 2 reps half-squats each with 20, 40, 60, 80, and 90% of the 1-RM load
Güllich & Schmidtbleicher, 1996	Bench Press	Yes	10 min jog followed by 10 min stretching
Hanson et al., 2007	Vertical Jump CMJ	No	5 min cycle at a self-selected pace followed by light stretching
Jensen & Ebben, 2003	CMJ	No	3 min cycle (low intensity) and static stretching of 1 exercise for each major muscle group (held 12-15 s), 5 reps of back squat at 50% 5-RM and 3 reps at 80% 5-RM and 2 sets of 5 vertical jumps
Kilduff et al., 2007	CMJ	Yes	5 min cycle (light-intensity) followed by dynamic stretching
Saez Saez de Villarreal et al., 2007	CMJ CMJ with load Drop jump height	Yes	10 min submaximal running at 9 km followed by light stretching, half-squats with low loads (two sets of ten reps at 50% of body mass) and submaximal familiarisation trials with the assessment exercises
Scott & Docherty, 2004	Countermovement vertical jump Countermovement horizontal jump	No No	5 min cycle followed by 5 min stretching
Young et al., 1998	Vertical loaded CMJ	Yes	3 min jog followed by stretching, half squats 10 reps at 50% of 5-RM and 2 sets of 5 reps at 75% 5-RM

CMJ = countermovement jump height, RJS = rebound jump squat, CJS = concentric-only jump squat

2.7.3 Variable-resistance conditioning contractions: concept, percentage load, type

The back squat exercise is one of the most widely performed exercises in strength and conditioning routines with previous research reporting that the lift can elicit a PAPE effect (Kilduff et al., 2007; Young et al., 1998) – a primary aspect of the present thesis. When heavy loads are lifted during exercises such as the free-weight back squat (or bench press, or other) exercise, the ability to lift the load after completing the descent (eccentric) phase is limited by the difficulty in producing sufficient force just after the start of the upward (concentric) phase, i.e. at the "sticking point". The sticking point refers to the point in the range of motion (ROM) during an exercise where the resistance load exceeds the amount of internal muscular force produced (Tillar & Ettema, 2009). This difficulty in lifting the load results partly from the muscles being at long lengths (where they are weaker, according to the force-length relationship) and partly because of the smaller internal moment arms (i.e. of the muscles across the joints) but larger external moment arms (i.e. the distance between joint centres and the ground reaction force vector) at this point (Elliott & Wilson, 1989).

To resolve this issue, the resistance can be varied throughout the lift to reduce the loading at the end of descent and increase it as the load is raised. This 'variable resistance' (VR) technique can easily be implemented with the use of chain-loaded resistance (CLR) or elastic bands (EB). VR has previously been used as a means of achieving training adaptation beyond that of traditional free-weight resistance training (FWR; Anderson et al., 2008; Rhea et al., 2009; Wallace et al., 2006; Wallace et al., 2019). VR is a feasible alternative to FWR and is designed to alter the resistance placed on the musculoskeletal system throughout the range of motion in an attempt to better match the various exercise strength curves. The force-length relationship changes allowing greater loads to be lifted at the point in the lift where mechanical advantage is greatest. The progressive load imposed through the range of motion mitigates the mechanical disadvantage of the sticking point encountered in traditional FWR (Anderson et al., 2008; Baker & Newton, 2005; Baker & Newton 2009). VR allows a greater external load to be used since the mechanical disadvantage is reduced by reducing the external load, and thus force required, when working in less efficient movement ranges (Anderson et al., 2008; Elliott & 1989). Wallace et al. (2006) found that the use of an elastic band of sufficient resistance set at 35% of the total load in an upright position reported significant increases in force and power during a squat exercise compared to FWR. In contrast, Stevenson et al. (2010) found that the use of elastic bands set at 15% or 30% did not significantly increase power compared to FWR alone. Furthermore, Ebben & Jensen (2002) found that the use of chain-loaded and elastic band resistance set at 10% had no significant effect on lift kinetics or EMG activity when compared to a traditional free-weight back squat exercise. Collectively, these findings indicate that future studies need to ensure an appropriate amount of loading originates from elastic band and chain resistances in dynamic and high-intensity exercises to improve the likelihood of successful conditioning regimes for different exercise and sport activities.

The resistive properties of EB and CLR are similar in that resistance increases via deformation or displacement, with EB adding resistance in a curvilinear manner (Wallace et al., 2006) but CLR adding in a linear manner (Berning et al., 2008); both types add resistance toward the end of the range of motion (McMaster et al., 2009). The curvilinear deformation-tension properties of EB allows for increased acceleration in the early concentric phase of the lift, where the resistance is less and as a result the movement velocity can be increased. During the ascending phase, the musculoskeletal system gains a mechanical advantage and the required muscular force production decreases (when compared with free-weight resistance). Therefore, the added band tension increases resistance in the eccentric and concentric phases of the lift where the individual is further from the sticking point and has the potential to increase muscle activation (i.e. motor unit recruitment and firing rates; Ebben &Jensen, 2002; McMaster et al., 2009; McMaster et al., 2010; Wilson & Kritz, 2014). EB resistance is determined by its viscoelastic properties (stiffness; stress-strain relationship) whereas CLR is gravity dependent and is determined by the type or density of the steel and length or diameter of the chains (McMaster et al., 2009); factors that could affect the mechanics of the lift and in turn, subsequent changes in performance.

Previous research examining Olympic clean (Berning et al., 2008) and snatch (Coker et al., 2006) lifts at 80% and 85% 1-RM of which 5% was from chains found no significant differences in vertical bar displacement, RFD and vertical ground reaction forces. However, there was an individual perception that the addition of chains made them work harder throughout the lift and that oscillation of the chains required the shoulders, abdominals and back to work harder to stabilise the bar (Berning et al., 2008; Coker et al., 2006; McCurdy et al., 2009). Previous studies using EB have demonstrated an improvement in peak power during explosive movements using elastic bands tension at 30% and 65-80% 1-RM for EB and FWR, respectively (Joy et al., 2016; McMaster et al., 2009; Wallace et al., 2006). A training study by Anderson et al. (2008) compared a 7-week training programme with and without the use of elastic bands and found that training with elastic bands in combinations with free-weight resistance increased muscle strength and power. Collectively, these findings indicate that addition of a VR method to traditional free-weight resistance exercises can increase force and power production compared to FWR alone. Therefore, the use of VR methods in combination with free-weights may speculatively be used to enhance any PAPE effects on subsequent lifting performance, however to date no studies have examined the acute effects of VR methods performed during a warm-up on subsequent FWR squat performance, i.e. one of the most common exercises performed in strength and conditioning programmes.

2.7.3.1 Methodological limitations in variable resistance research

Although a potentiating effect may exist, and notwithstanding the limited number of studies examining the acute effects of VR on lifting mechanics and neuromuscular activity, there are various methodological issues that may limit the external validity of previous research findings. Findings in the literature suggest the acute effects of VR, i.e. EB or CLR in combination with free-weight resistance, may be more effective at enhancing force and power production than traditional FWR alone. However, these improvements are limited to high intensities (≥75% 1-RM; Baker & Newton, 2009; Rhea et al., 2009; Wallace et al., 2006), with no difference reported when intensity of the external load falls below 60% 1-RM (Stevenson et al., 2010; Wallace et al., 2006). Further, VR loads as low as 15% of the total load failed to increase force production and muscle activity (Ebben & Jensen, 2002; Stevenson et al., 2010), VR loads >30% resulted in significant increase in force, power and rate of force development (Wallace et al., 2006). Different exercise tasks including bench press, clean, back squat (Anderson et al., 2008; Baker & Newton, 2009; McMaster et al., 2010; Wallace et al., 2006), the selected magnitude of VR (10%, Ebben & Jensen, 2002; 15% and 30%, Stevenson et al. (2010); 35%, Wallace et al., 2006), performance measures such as 1-RM, peak forces, EMG and joint angle/velocity (Ebben et al., 2000; Israetel et al, 2010; Stevenson et al., 2008; Wallace et al., 2006) and participant characteristics, i.e. experienced versus novice lifters (Chiu et al., 2003; Young et al., 1998) may explain the disparate findings. Thus, careful consideration of the type of conditioning contractions affecting the performance task and delay between the conditioning contractions and testing are required to ensure that valid conclusions are drawn about the PAPE effects of VR, which to date has not yet been examined.

2.8 Summary of the literature review

High-intensity muscle contractions such as those used in maximal lifting may evoke PAP and PAPE. It has been reported that PAP, i.e. an increase in twitch force following muscle activity, is a distinct physiological phenomenon to PAPE, i.e. an increase in voluntary force production evoked by prior muscle activity. PAPE has been shown to have a longer window of action compared to PAP that lasts for a few seconds to several minutes (Blazevich & Babault, 2019), indicative of distinct underlying mechanisms. Importantly, enhancements in voluntary muscular force production (PAPE) can be particularly useful in athletic environments, thus identifying effective warm-up strategies is of great importance to strength and conditioning practitioners. One possibility is that the forces produced during a traditional strength training exercise such as the back squat might be improved with the use of VR. This is because VR may reduce the effective load near the sticking point experienced early in the concentric phase where the joints are more extended, internal moment arms are greater, and optimal muscle lengths are achieved, enabling individuals to more easily complete the lift compared to FWR alone (McMaster et al., 2009; McMaster et al., 2010; Wilson & Kritz, 2014). A common limitation in the literature is that brief, or no warm-up, protocols were often implemented prior to a conditioning activity that subsequently resulted in an enhancement in performance (Duthie et al., 2002; Hamada et al., 2000), although it is yet to be determined whether a benefit, additional to a comprehensive warm-up, can be achieved. To date no research has examined the effects of VR as part of a warm-up on subsequent dynamic activities. Therefore, the major aims of the present thesis were to compare the influence of two forms of VR (i.e. chains [CLR] and elastic bands [EB]) with free-weight resistance (FWR) during a warm-up on subsequent free-weight 1-RM back squat performance and examine the impact of a comprehensive warm-up on any performance improvements using EB and FWR on countermovement jump performance. It was hypothesised that the variation in resistance elicited by CLR or EB during squatting would: a) enhance subsequent free-weight squat lift performance (maximal load) and b) alter lifting mechanics (i.e. knee angular velocities, peak knee flexion angle) and neuromuscular activity during the 1-RM test, when compared to the use of traditional free-weight squat warm-up. It was also hypothesised that the variation in resistance imposed by EB during the squat lift would: a) enhance subsequent CMJ performance, b) alter CMJ kinetic and kinematic parameters (i.e. peak power, peak eccentric kinetic energy, impulse- and time-based descent-to-ascent asymmetry indexes, rate of force development, knee joint kinematics), and c) increase the muscle activity of the lower-limb extensor muscles more than squatting with traditional free-weight resistance.

Chapter 3

3 Study 1

Influence of chain-loaded variable resistance exercise on subsequent free-weight maximal back squat performance

3.1 Abstract

The acute influence of resistance exercise on subsequent free-weight one-repetition maximum (1-RM) back squat performance was examined in 16 recreationally active men. Participants performed either a free-weight resistance (FWR) or chain-loaded resistance (CLR) back squat warm-up at 85% 1-RM on two separate occasions. After a 5 min rest, the participants attempted a free-weight 1-RM back squat; if successful, subsequent 5% load additions were made until participants failed to complete the lift. During the 1-RM trials, 3D knee joint kinematics and knee extensor and flexor EMG were recorded simultaneously. Significantly greater 1-RM (6.2 ± 5.0%; $p < 0.01$) and mean eccentric knee extensor EMG (32.2 ± 6.7%; $p < 0.01$) were found after the CLR warm-up compared to the FWR condition. However, no difference ($p > 0.05$) was found in concentric EMG, eccentric or concentric knee angular velocity, or peak knee flexion angle. Performing a CLR warm-up enhanced subsequent free-weight 1-RM performance when compared to FWR, without changes in knee flexion angle or eccentric and concentric knee angular velocities. Thus, a real 1-RM increase was achieved as the mechanics of the lift were not altered. These results are indicative of a potentiating effect of CLR in a warm-up, which may benefit athletes in tasks where high-level strength is required.

Keywords: PAP, accommodating resistance, 1-RM, preconditioning, strength training.

3.2 Introduction

Variable resistance (VR) strength training using chains or elastic bands attached to a loaded barbell has been widely used in competitive powerlifting and more recently, in strength and conditioning programs for the development of strength and power (Baker & Newton, 2009; Swinton et al., 2009; Wallace et al., 2006). The use of variable resistance (e.g. chain resistance) in combination with free-weight resistance has become popular as an alternative training method to improve upper and lower body strength and power capacity in exercises such as the back squat, bench press and deadlift (Anderson et al., 2008; Baker & Newton, 2009; McMaster et al., 2010; Wallace et al., 2006). Chains attached to, and thus hanging from, a bar can be used to manipulate the load experienced in an exercise by providing a VR that reduces the load at the bottom of the lift, where fewer chain links add to the total load, while progressively increasing resistance toward the top of the lift as more chain links add to the load (Baker & Newton, 2009; Neelly et al., 2010). In successful one-repetition maximum (1-RM) attempts, the barbell decelerates early in the lifting (concentric) phase for a short period, often referred to as the ‘sticking point’. Newton et al. (1997) reported that this deceleration briefly occurs in lifts of ≥90% 1-RM in the early concentric phase of the lift as a likely consequence of a poor mechanical advantage, where smaller internal and greater external moment arms are developed at the hip and knee. In addition to mechanical disadvantage, the force-length characteristics of lower limb muscles limit maximal force production during the early concentric phase (Anderson et al., 2008; Elliott and Wilson, 1989). Therefore, reducing the loading characteristics of the lift using VR techniques within this range of motion (ROM), while maintaining average loading throughout the lift, may limit the impact of the sticking point and enable the athlete to operate at near maximal levels for a greater proportion of the exercise, which likely provides a greater stimulus and thus may be a more effective training tool.

Imposing a high-intensity conditioning contraction on muscles during a warm-up can induce a potentiating effect (PAPE) to acutely increase force production capacity and is often observed to improve lifting performances (Baker & Newton, 2009; Hodgson et al., 2005; Rassier & MacIntosh, 2000; Sale, 2002; Tillin & Bishop, 2009). The performance of maximal muscular contractions is thought to potentiate the neuromuscular system for several minutes via a) improved phosphorylation of myosin regulatory light chains increasing Ca^{2+} sensitivity of actomyosin complex (Esformes et al., 2010; Hanson et al., 2007; Hodgson et al., 2005) or b) increased recruitment of higher-order motor units through enhanced spinal excitability (Esformes et al., 2010; Güllich & Schmidtbleicher, 1996; Rassier & MacIntosh, 2000) although increases in temperature, motivation and acute improvements in motor control strategies cannot be discounted. Regardless of the mechanism, maximal or near maximal contractions performed during a warm-up routine have commonly been reported to induce a potentiation response, enhancing mechanical power above previous capacity (Chatzopoulos et al., 2007; Chiu et al., 2003; Gourgoulis et al., 2003; Güllich & Schmidtbleicher, 1996; Miyamoto et al., 2010). The achievement of peak performance is dependent on the balance between fatigue and potentiation, i.e., high-intensity (heavy load) exercise can potentiate the muscle groups involved but can also reduce maximum force generating capacity immediately after the contractions (Young et al., 1998), which may reduce the effect of mechanisms that elicit potentiation (Jo et al., 2010). Performance enhancement is typically observed 4–12 min after the performance of maximal or near-maximal contractions (i.e. a conditioning stimulus) on subsequent explosive muscular activity to induce an increase in force production possibly when fatigue and potentiation processes predominate (Güllich & Schmidtbleicher, 1996; Jo et al., 2010; Kilduff et al., 2008; Lowery et al., 2012; Young et al., 1998).

It has been suggested that the use of chains can alter the mechanics of traditional resistance exercises, allowing the lifter to move more explosively and maintain a high force production when elevating the barbell to its final position (Baker & Newton, 2009; Wallace et al., 2006). While improvements in peak force production (Wallace et al., 2006) and peak lifting velocities during the eccentric phase (Stevenson et al., 2010) have been reported following the performance of contractions using elastic bands during a back squat exercise, only a limited number of studies have examined the use of chains to provide variable resistance, with equivocal findings reported. Ebben and Jensen (2002) found that the inclusion of chains set at 10% of the total load during a back squat exercise had no significant effect on force production or muscle electromyogram (EMG) activity when compared to a traditional free-weight resistance (FWR). Similarly, Coker et al. (2006) found no significant difference in movement velocity or the rate and magnitude of ground reaction force application during the snatch or clean exercises (Berning et al., 2008) with only 5% resistance imposed via chains. In contrast, Baker and Newton (2009) reported significantly greater mean and peak lifting velocities during a bench press exercise with chain-loaded resistance (CLR) set at 12–16% 1-RM compared to FWR alone. These disparate findings are likely due to different study methodologies and exercise tasks (e.g. bench press, clean, back squat), the selected magnitude of variable resistance, performance measures (1-RM, peak forces, EMG and joint angle/velocity) and participant characteristics (e.g. experienced/novice lifters). However, no studies have examined the influence of chain-loaded resistance during conditioning contractions on subsequent free-weight maximal lifting performance.

The back squat exercise is commonly used as a fundamental training exercise across many sports for the development of lower limb strength and power (Stevenson et al., 2010; Young, 2006). Therefore, the purpose of the present study was to examine the influence of another form of variable resistance (i.e. CLR) during a warm-up on subsequent free-weight 1-RM back squat performance compared to FWR alone. It was hypothesised that the variation in resistance elicited by chains during squatting in the warm-up would: (1) enhance subsequent free-weight squat lift performance (maximal load); and (2) alter lifting mechanics (i.e. knee angular velocities, peak knee flexion angle) and neuromuscular activity during the 1-RM test, when compared to the use of traditional free-weight squat warm-up.

3.3 Methods

3.3.1 Participants

Sixteen active men (age = 26.0 ± 7.8 y, height = 1.7 ± 0.2 m, mass = 82.6 ± 12.7 kg) experienced in weight training (>3 years) volunteered to participate in the study. Prior to testing, the participants completed a written informed consent (Appendix 4) and pre-test medical questionnaire (Appendix 5), had no recent illness or lower limb injury and avoided strenuous exercise or stimulant use for 48 h prior to testing. Ethical approval was granted by the ethics committee at the University of Northampton in accordance with the Declaration of Helsinki. To ensure an adequate population to reach statistical power (set at 0.8) was recruited, effect sizes (ES; Cohen's d) were initially calculated from related research; (Anderson et al., 2008; Caterisano et al., 2002; Swinton et al., 2012) for 1-RM back squat load (ES = 1.9), EMG (1.9) and peak knee flexion angle (ES = 2.1). To ensure an adequate sample, the measure with the smallest ES (i.e. 1-RM back squat load [ES = 1.89]) was used to calculate sample size. The analysis revealed that the initial sample size required for statistical power was 12, therefore considering the possibility of participant withdrawal and data loss, 16 participants were recruited with 16 participants completing the study.

3.3.2 Study design

A randomised, cross-over design was implemented to compare 1-RM free-weight back squat performance after two warm-up conditions: CLR (experimental) and FWR (control). Following a 5 min cycling warm-up, participants performed either a CLR or FWR task-specific warm-up and then attempted a free-weight back squat exercise at their previously determined (i.e. during familiarisation) 1-RM load. After each successful lift, a further 5% load was added with a 5 min rest between attempts. The final successful attempt was considered their 1-RM. The study design timeline is presented in Figure 3.1.

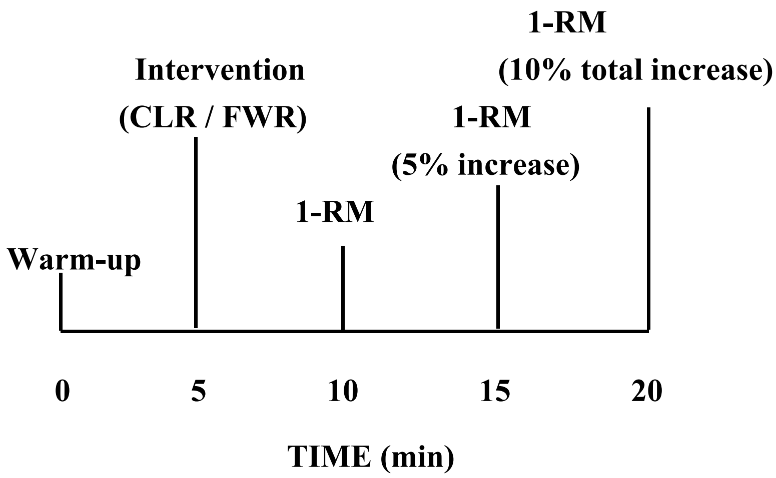

Figure 3.1. Study design timeline of the back squat warm-up and 1-RM (one-repetition maximum) protocol.

3.3.3 Procedures and overview

Participants visited the laboratory on three occasions each separated by at least 72 h initially under familiarisation and then either (i.e. counterbalanced) control (FWR) or experimental (CLR) conditions. In the first session, the participants were familiarised with all testing protocols and their back squat 1-RM load was determined. During subsequent sessions, the participants were dressed in dark Lycra shorts, t-shirt and athletic shoes to improve motion analysis marker placement. Participants performed a 5 min warm-up on a cycle ergometer (Monark 874E, Varberg, Sweden) at 65 rpm with a 1-kg resistance load producing a power output of 65 W followed by 2 sets of 10 back squat repetitions with an unloaded bar (i.e. 20 kg). After 5 min, the participants performed 2 sets of 3 repetitions of either FWR or CLR at 85% of their previously determined 1-RM as a task-specific conditioning warm-up with 3 min rest between sets to prepare for the 1-RM trial. Following a further 5 min rest participants attempted to lift their previously determined 1-RM. Successful attempts were followed 5 min later by a 5% increase in load (to the nearest kg) until failure, data from the initial 1-RM and final (best) 1-RM were used for analysis. No participants were able to lift more than 10% of their initial 1-RM.

3.3.4 One-repetition maximum (1-RM) back squat assessment

During the familiarisation session each participants' 1-RM was determined using previously validated methods (Baechle and Earle, 2000). Following the standardised 5 min warm-up, participants performed 10 back squat repetitions with an unloaded bar (i.e. 20 kg), then 8-10 repetitions with the load set at 50% of their estimated 1-RM. Gradual adjustments were made where the load was increased by 10-20% and the participants then performed 3-5 repetitions, after a 2 min rest period the load was increased further by 10-20% and 2-3 repetitions were performed. After 2-4 min, the load was increased by 10% and participants then added loads of ~5% every 2-4 min until failing to complete a lift; the previous successful lift was recorded as their 1-RM. To ensure that correct technique was utilised, participants were instructed to place the bar above the posterior deltoids at the base of the neck and position the feet shoulder width apart with the toes pointed slightly outward and attempt to squat to a position where the knee joint was flexed to ~90º (Baechle and Earle, 2000) before returning to a standing position; this was visually assessed by an experienced spotter throughout all testing procedures to ensure correct technique, safety during the lifts with subjects receiving strong verbal encouragement to promote maximal effort. However, the back squat depth was not specifically prescribed or restricted as an aim of the study was to determine whether CLR influenced movement kinematics. No supportive equipment was used during the back squat exercise (e.g. knee wraps, squats suits, weight lifting belts, etc.) and Olympic standard calibrated weight lifting bar, plates, collars and rack (Eleiko, Halmstad, Sweden) were used throughout.

3.3.5 Intervention

In the experimental trials, the standardised warm-up was replicated before the participants performed 2 preconditioning sets of 3 repetitions of back squat exercise in either the FWR or CLR condition at 85% of the previously determined 1-RM with 3 min rest between sets to prepare for the 1-RM trial. After 5 min rest, the participants attempted to lift their previously recorded 1- RM and, where successful, the participants increased the load by 5% until they failed to complete a lift with 5 min rest between each attempt. Any further successes resulted in an attempt with an additional 5% (i.e. 10% total) to the nearest 1 kg. Similar to previous studies, the CLR was set at 35% of the total load (Wallace et al., 2006). To ensure a similar total load across conditions, half of the 35% load was removed from the bar during the preconditioning set. The mechanical properties of the chains (i.e. load-length relationship) were determined to allow 35% of the load to be generated from the chains (Figure 3.2). The participants stood on a force platform (FP4, HUR, Tampere, Finland) with 85% 1-RM load to determine the combined load of the chains and free-weights; data were then directed to a computer running Research Line software (v.2.4, HUR, Tampere, Finland). The Olympic bar was placed on the squat rack and then unloaded. The chains were then adjusted using modified collars and were attached equidistant to the sides of the bar with a portion of chains in contact with the floor to ensure stability. The bar was then lifted from the squat rack and the load from the chains was adjusted to increase the measured load by 35% of the 85% load when the participants were standing upright on the force platform. As an illustrative example, a 100 kg load in the FWR condition would require 35 kg (35%) to be generated from the chains in the CLR condition. Half of the 35 kg load (i.e. 17.5 kg) would be removed from the bar, leaving 82.5 kg combined with the 35 kg from the chains, giving a total load of 117.5 kg in the standing position. Therefore, a range of 35 kg (35%) is achieved through CLR while maintaining an average loading of 100 kg throughout the lift, identical to the FWR condition.

Figure 3.2. Participant performing the back squat exercise during the chain-loaded resistance (CLR) warm-up. Infrared reflective motion analysis markers were placed over the lateral malleolus, femoral epicondyle and greater trochanter of the right lower limb to record knee kinematics. Muscle activity was recorded using electromyography (EMG) electrodes placed over the rectus femoris, vastus lateralis, vastus medialis, and semitendinosus muscle bellies. Chains were attached to the loaded barbell, with a total average of 35% supplied by chains during the back squat exercise.

3.3.6 Muscle Activity (Electromyogram [EMG])

EMG data were collected from vastus medialis (VM), vastus lateralis (VL), rectus femoris (RF) and semitendinosus (ST) during the eccentric and concentric phases of the 1-RM free-weight back squat exercise following the FWR or CLR conditioning. The skin was shaved, abraded and cleansed with alcohol before placing skin-mounted bipolar double-differential active electrodes (model MP-2A, Linton, Norfolk, UK) over the muscle belly and parallel to the predicted muscle fibre orientation. EMG signals were amplified (gain = 300, input impedance = 10 GΩ, common mode rejection ratio ≥100 dB at 65 Hz) and directed to a high-level output transducer (model HLT100C, Biopac, Goleta, CA) before being converted from an analog to digital signal at a 2,000-Hz sampling rate (model MP150 Data Acquisition, Biopac, Goleta, CA). The data were imported into AcqKnowledge software (version 4.1) on a personal computer, filtered using a 20-500 Hz band-pass filter and converted to root-mean-squared (RMS) EMG with a 250-ms symmetrical sampling window. The RMS EMG data were then normalised as a percentage of the peak amplitude recorded during a maximal countermovement vertical jump and VL, VM, and RF data were averaged in order to obtain a representative quadriceps femoris (QF) EMG measurement. The normalised VL, VM, RF and QF EMG amplitudes (% MVC) were used as a measure of neuromuscular activity during the back squat exercises with peak and mean EMG activity recorded during the concentric and eccentric phases.

3.3.7 Motion analysis

A 3D motion capture system with four ProReflex cameras (Qualisys, Gothenburg, Sweden) operating Track Manager 3D (v.2.0) software was used by placing three spherical infrared reflective markers (20 mm) over the greater trochanter (hip), lateral femoral epicondyle (knee) and lateral malleolus (ankle) with all participants performing the back squats wearing Lycra shorts to minimise marker movement. Peak knee flexion angle and both mean and peak eccentric and concentric knee angular velocities were measured during the 1-RM trials with angular velocity (ω) was calculated as average and peak rates of change in the angular position during concentric and eccentric phases, where $\Delta\theta$ is change in angular displacement, Δt is change in time, expressed as:

$$\omega = \Delta\theta / \Delta t$$

Raw coordinate data were sampled at 100 Hz and smoothed using a 100-ms moving average before joint angle and velocities were calculated using Track Manager 3D (v.2.0) software (Kay & Blazevich, 2009b). Initial recordings were obtained with the participant in the anatomical position to enable knee angle data to be corrected (i.e. knee angle recorded in the standing position equated to 180° or full extension) before knee flexion ROM and both peak and mean eccentric and concentric knee velocity data were calculated.

3.3.8 Statistical Analyses

All data were analysed using the SPSS statistical software (v.19.0); all data are presented as mean ± SE. Normal distribution was assessed using the Shapiro-Wilk test; no significant difference ($p > 0.05$) was detected in any variable, indicating that all data sets were normally distributed. Separate repeated measures MANOVAs were used to determine the influence between conditions on peak and average eccentric and concentric velocities and EMG activity during initial 1-RM trials of the same load (136.1 ± 5.6 kg). Where MANOVAs revealed a significant difference, post-hoc analyses with Bonferroni correction were used to determine the location of the differences. A paired t-test was used to examine peak knee flexion angle between conditions. Further analyses were conducted on the greatest 1-RM performance between the conditions using the previously described analyses as above. A paired t-test was used to compare 1-RM load between conditions. Significance was accepted at $p < 0.05$ for all tests.

3.3.9 Reliability

The reliability of eccentric and concentric peak and mean knee angular velocity, peak and mean EMG activity and peak knee flexion angle data were determined during the 2nd repetition of both sets during the free-weight resistance warm-up condition. No significant difference ($p > 0.05$) was detected in any measure with high intraclass correlation coefficients (ICC) calculated for EMG data ranged for RF (0.93-0.98), for VL (0.91-0.95), for VM (0.61-0.97), for ST (0.97-0.99), and QF (0.94-0.96), respectively. High ICCs were also calculated for knee angular velocities (0.88-0.96) and knee flexion angle (0.97). Low coefficients of variation (CoV) for EMG data (expressed as a percentage of the mean) were also calculated for RF (9.0-13.7%), for VL (6.7-12.0%), for (VM 5.2-7.7%), for ST (11.4-20.2%), and for QF (5.4-10.0%), respectively.

Low CoV were also calculated for knee angular velocities (6.1-8.2%) and knee flexion angle (1.8%).

3.4 **Results**

Initial 1-RM attempt

During the initial 1-RM attempt, all participants successfully lifted their previously determined (136.1 ± 5.6 kg) 1-RM after both conditions, indicating that neither FWR nor CLR induced fatigue. No significant difference ($p > 0.05$) was found in peak or mean EMG amplitudes or knee angular velocities during the eccentric and concentric phases of the lift (Table 3.1) between conditions. However, peak knee flexion angle was significantly greater (3.8 ± 1.8° more flexion; $p < 0.05$) following the CLR condition compared to the FWR condition (Figure 3.3).

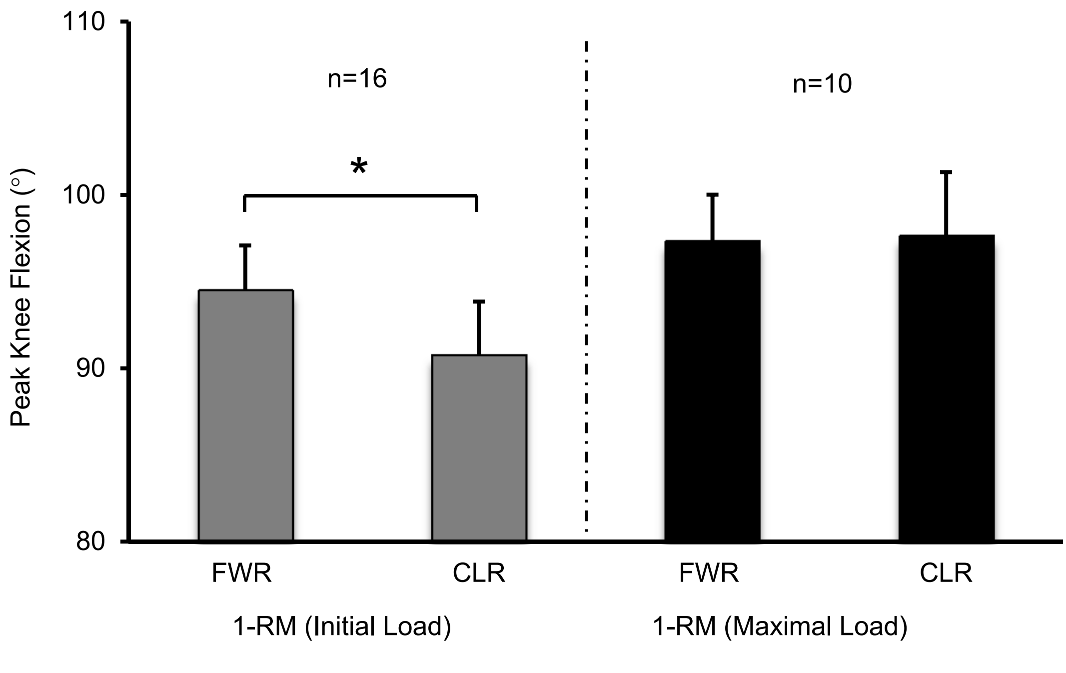

Figure 3.3. Peak knee flexion angle during the initial and maximal 1-RM back squat exercise. Following the free-weight resistance (FWR) and chain-loaded resistance (CLR) warm-up conditions, knee flexion angle was determined to establish squat depth.

*Significantly greater mean knee flexion angle (3.7° more flexion; $p < 0.05$) was observed during 1-RM free-weight back squat following CLR compared to FWR condition when tested set under the same 1-RM conditioning load (136.1 ± 5.6 kg). No significant difference was found in knee flexion angle (0.3°; $p > 0.05$) during the increased 1-RM free-weight back squat exercise following CLR compared to the FWR condition.

Table 3.1. Mean and peak quadriceps femoris (QF), vastus lateralis (VL), vastus medialis (VM), rectus femoris (RF) and semitendinosus (ST) electromyogram (EMG) amplitude maximum voluntary contraction (%MVC) and knee angular velocities ($°\cdot s^{-1}$) during the eccentric and concentric phases of the initial one repetition maximum (1-RM) free-weight back squat attempt. No significant ($p > 0.05$) difference was found following the free-weight resistance (FWR) and chain-loaded resistance (CLR) conditions.

		Eccentric Phase		**Concentric Phase**	
	Measure	FWR	CLR (Initial)	FWR	CLR (Initial)
QF EMG	Mean	51.9 ± 2.2	62.7 ± 3.6	71.2 ± 4.1	72.5 ± 4.1
	Peak	89.1 ± 3.9	101.7 ± 6.8	96.0 ± 4.5	106.7 ± 6.5
VL EMG	Mean	56.0 ± 3.3	63.5 ± 4.4	74.0 ± 4.6	75.2 ± 5.4
	Peak	93.3 ± 5.7	98.6 ± 10.1	94.1 ± 5.4	104.2 ± 10.2
VM EMG	Mean	50.4 ± 2.5	61.4 ± 4.6	68.0 ± 4.1	73.9 ± 5.0
	Peak	79.3 ± 4.8	91.4 ± 8.0	89.8 ± 5.1	98.6 ± 7.1
RF EMG	Mean	49.3 ± 3.2	63.2 ± 5.5	71.5 ± 6.7	67.3 ± 6.5
	Peak	94.6 ± 6.4	115.2 ± 9.2	104.0 ± 6.7	117.3 ± 9.7
ST EMG	Mean	54.5 ± 10.7	47.0 ± 5.9	74.4 ± 11.4	96.5 ± 21.0
	Peak	81.4 ± 12.6	75.8 ± 9.7	117.9 ± 17.4	158.4 ± 33.0
Velocity	Mean	54.3 ± 3.7	52.3 ± 3.0	60.5 ± 4.6	52.9 ± 4.6
	Peak	114.9 ± 7.8	109.7 ± 4.8	221.0 ± 15.4	180.2 ± 13.1

Final 1-RM attempt

Following the initial 1-RM attempt, the participants attempted a 5%, and if successful a further 5% (i.e. total 10%), increase of their initial 1-RM load. Whilst no participant successfully lifted a greater load following the FWR condition, 10 of the 16 participants (63%) were able to successfully increase their 1-RM (i.e. best) by up to 10% (mean 1-RM = 144.5 ± 6.0 kg) following the CLR condition (Figure 3.4), which resulted in a significantly greater 1-RM load in the CLR (6.2 ± 5.0%; $p < 0.01$) than the FWR condition.

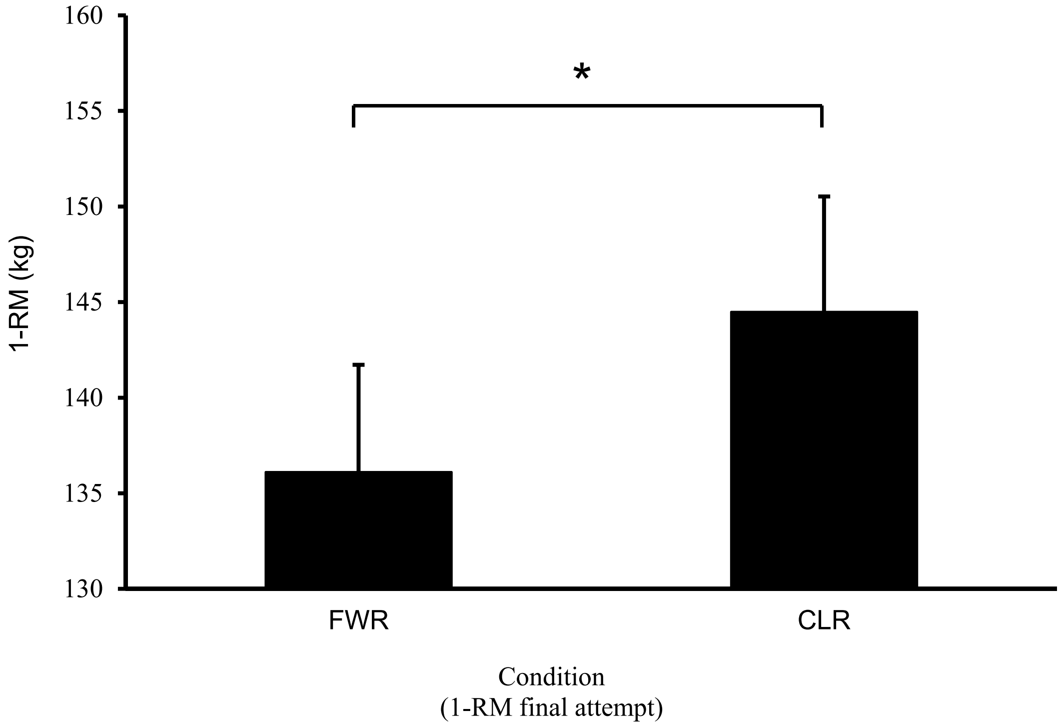

Figure 3.4. 1-RM load lifted following free-weight resistance (FWR) and chain-loaded resistance (CLR) conditions. Five minutes after the FWR and CLR warm-up conditions, free-weight one repetition maximum (1-RM) attempts were made. A 5% additional load was added for each successful lift, with a 5 min rest between attempts; the final successful attempt was considered their 1-RM. *Significantly (6.2 ± 5.0%; $p < 0.01$) greater free-weight back squat 1-RM was achieved following CLR than FWR.

Table 3.2. Mean and peak quadriceps femoris (QF), vastus lateralis (VL), vastus medialis (VM), rectus femoris (RF) and semitendinosus (ST) electromyogram (EMG) amplitude maximum voluntary contraction (%MVC) and knee angular velocities (°·s^{-1}) during the eccentric and concentric phases of the final one repetition maximum (1-RM) free-weight back squat attempt following the free-weight resistance (FWR) and chain-loaded resistance (CLR) conditions. *Significantly ($p < 0.05$) different than FWR.

		Eccentric Phase		**Concentric Phase**	
	Measure	FWR	CLR (final 10%)	FWR	CLR (final 10%)
QF EMG	Mean	48.2 ± 2.7	63.0 ± 3.9*	70.5 ± 6.3	78.6 ± 3.5
	Peak	85.8 ± 5.7	97.2 ± 6.3	93.9 ± 6.3	104.7 ± 6.2
VL EMG	Mean	51.7 ± 3.8	65.2 ± 4.8*	73.7 ± 6.6	80.7 ± 6.1
	Peak	88.5 ± 6.8	93.1 ± 6.9	93.9 ± 7.4	98.3 ± 7.1
VM EMG	Mean	47.4 ± 2.9	62.3 ± 4.6*	68.8 ± 6.4	79.1 ± 5.1
	Peak	76.4 ± 6.2	90.7 ± 9.9	87.3 ± 7.1	101.7 ± 8.2
RF EMG	Mean	45.5 ± 4.1	61.7 ± 6.5*	69.1 ± 9.0	76.1 ± 6.8
	Peak	92.5 ± 6.9	107.7 ± 9.9	100.5 ± 7.7	114.0 ± 13.6
ST EMG	Mean	54.0 ± 17.0	52.9 ± 6.4	75.7 ± 18.1	76.0 ± 11.2
	Peak	75.9 ± 18.9	85.9 ± 10.4	85.0 ± 12.8	125.7 ± 17.8
Velocity	Mean	48.7 ± 4.8	43.7 ± 4.8	66.7 ± 6.6	51.5 ± 4.9
	Peak	104.7 ± 10.8	95.8 ± 8.0	202.7 ± 17.9	180.1 ± 16.0

During the final (i.e. best) 1-RM attempt, a significantly ($p < 0.01$) greater mean eccentric EMG was found in QF (32.2 ± 6.7%), VL (30.3 ± 11.5%), VM (33.6 ± 10.7%), RF (41.1 ± 15.4%) following the CLR condition compared to FWR. However, no significant difference ($p > 0.05$) was detected in peak eccentric or concentric EMG between conditions (Table 3.2). No significant difference ($p > 0.05$) was found in peak or mean knee angular velocity during the eccentric or concentric phases of the lift (Table 3.2). Despite a greater load being lifted, no difference in peak knee flexion angle ($p > 0.05$) was found (Figure 3.3), indicating that a similar back squat depth was achieved and that a full repetition was performed.

3.5 Discussion

The purpose of the present study was to compare the acute effects of chain-loaded resistance (CLR) with free-weight resistance (FWR) warm-up conditions on a) subsequent free-weight 1-RM back squat performance (i.e. maximal load); b) lifting mechanics and c) neuromuscular activity. All participants lifted their previously determined 1-RM following both warm-up conditions, indicating that neither condition induced fatigue. During the initial 1-RM attempt, the peak knee flexion angle was significantly greater in the CLR condition, which indicates that participants voluntarily squatted to a greater depth, while no difference was found in EMG or knee angular velocities during the eccentric phase. Despite the greater squat depth, concentric movement velocity was similar after both conditions. Importantly, the greater squat depth likely required more work to be performed and placed the participants at a position of poorer mechanical advantage due to the larger external moment arms developed and requirement for force at different (longer) muscle lengths at the hip and knee (Anderson et al, 2008; Elliott & Wilson, 1989). These findings are indicative that subsequent 1-RM back squat attempts using the same load appeared to be more easily tolerated without compromising lifting mechanics.

The principal aim of the study was to compare the acute effects of a CLR warm-up with traditional FWR warm-up on 1-RM maximal back squat performance. The main finding was that 1-RM load (i.e. best attempt) was significantly greater (6.2%) following the CLR warm-up compared to the FWR warm-up, indicative of a potentiating effect, therefore the first experimental hypothesis can be accepted. Despite the increase in load lifted during these maximal attempts, there was no difference in peak knee flexion angle (0.3°) or peak and mean knee angular velocities when compared to the FWR condition. These data are indicative of strong evidence of a 'real increase' in 1-RM as the mechanics of the lift were not altered. Therefore, given that the squat depth and knee angular velocities were unchanged despite the greater load lifted, the second hypothesis can be partially accepted.

The reduction in eccentric knee angular velocities in some participants in the present study might be associated with the need to reduce the momentum of the bar during the downward movement, ensuring that sufficient impulse would be provided by the participants to decelerate and stop the bar. Equally, the additional load might have limited the concentric movement speed as predicted by the muscles' force-velocity relationships. The use of variable resistance during a 1-RM back squat exercise reduces the effective load near the sticking point in the early concentric phase of the lift whilst allowing greater loading later in the concentric phase where the joints are more extended, the internal moments arms are greater, external moment arms are smaller and optimal muscle lengths are achieved (Anderson et al., 2008). The variable resistance counteracts the increasing mechanical disadvantage from moment arm changes and force-length characteristics of the lower limb skeletal muscles at the hip and knee during the eccentric phase of the lift (Anderson et al., 2008; Elliott & Wilson, 1989), enabling the muscles to work closer to their maximum throughout the lift. This stimulus may have allowed for an enhanced potentiation effect and an increased 1- RM back squat performance.

The time period over which potentiation is induced is most notable within minutes of the conditioning contraction (Lowery et al., 2012; Sale, 2002). In the present study, 1-RM load following the CLR condition was increased 5 min after the conditioning contraction, which is consistent with previous studies that observed a maximal effect within 4–12 min (Lowery et al., 2012; Seitz et al., 2015). Despite significantly greater VL, VM and RF EMG activity being observed during the eccentric phase following CLR, no change occurred in the concentric propulsive phase, which may indicate that increased activity of the quadriceps was an unlikely mechanism underpinning the increased 1-RM. However, the increased eccentric EMG may be symptomatic of greater force enhancement (Edman et al., 1978) or increased stretch-shortening cycle activity (Doan et al., 2002), thus additional contribution from the quadriceps cannot be excluded. Alternatively, the contribution of other muscles such as the hip extensors (e.g. gluteus maximus) may have underpinned the enhanced 1-RM back squat performance as a greater mechanical contribution from the hip extensors, rather than the knee extensors, has been reported when greater loads are lifted during squatting (Flanagan & Salem, 2008). However, a limitation of the present study is that hip extensor EMG activity and the impact of variable resistance on other joint complex kinematics, such as hip flexion and torso angle, were not measured as participants in the present study were uncomfortable with placing electrodes on the gluteus. Also, whilst a reflective marker was placed on the bar, no marker was placed on the anterior superior iliac spine because it was completely obscured at peak hip flexion angles in the squatting position in pilot testing; therefore, changes in torso angle associated with spinal or pelvic adjustments were not determined. Whilst the knee joint complex and quadriceps activity were a focus in the present study, future studies should consider examining additional joints and muscle groups.

In summary, the present data are indicative that the use of chain-loaded resistance in warm-up routines provides a greater potentiating stimulus to enhance 1-RM capacity, without affecting the kinematics of the lift in the back squat exercise, than traditional non-variable free-weight exercise. Therefore, the incorporation of chain-loaded resistance could be beneficial to strength-based athletes (i.e. powerlifters, Olympic weightlifters) before training or competition to potentiate the neuromuscular system and enhance strength-based capacity. The results demonstrate a greater mean eccentric EMG in QF although no change was found in the concentric phase, which is indicative that the increased activity of the quadriceps is an unlikely mechanism affecting the increased 1-RM performance. However, the greater eccentric QF EMG activity may be symptomatic of a greater force production or increased stretch-shortening cycle. The use of chain-loaded resistance has practical limitations as they are difficult to attach or transport, therefore given the increase in performance an alternative method to vary the resistance (i.e. elastic bands) should be examined as elastic bands are smaller, light-weight and transportable, and may offer a more practical solution for ease of use.

Chapter 4

4 Study 2
Influence of elastic band variable resistance loading on subsequent free-weight maximal back squat performance

4.1 Abstract

The purpose of the study was to determine the potentiating effects of elastic bands (EB) during a warm-up on subsequent free-weight resistance (FWR) maximal squat performance. In the first session, 16 recreationally active men (age = 26.0 ± 7.8 years; height = 1.7 ± 0.2 m; mass = 82.6 ± 2.7 kg) were familiarised with the experimental protocols and tested for 1 repetition maximum (1-RM) squat lift. The participants then visited the laboratory on 2 further occasions under either control or experimental conditions. During these conditions, 2 sets of 3 repetitions of either FWR (control) or EB (experimental) squat lifts at 85% of 1-RM were performed; during the experimental condition, 35% of the load was generated from band tension. After a 5 min rest, 1-RM, 3D knee joint kinematics, and vastus medialis (VM), vastus lateralis (VL), rectus femoris (RF), and semitendinosus (ST) EMG signals were recorded simultaneously. A significantly greater 1-RM (mean = 7.7%; $p < 0.01$), lower peak and mean eccentric (16–19%; $p < 0.05$) and concentric (12–21%; $p < 0.05$) knee angular velocities were observed following EB when compared with FWR, however no differences in knee flexion angle (1.8; $p > 0.05$) or EMG amplitudes (mean = 5.9%; $p > 0.05$) occurred. As conditioning contractions using EB significantly increased 1-RM without detectable changes in knee extensor muscle activity or knee flexion angle, although eccentric and concentric velocities were reduced, EB resistance appear superior to FWR to potentiate the neuromuscular system and enhance subsequent maximal lifting performance.

Keywords: elastic bands, postactivation potentiation, preconditioning, 1-RM, strength training

4.2 Introduction

The free-weight back squat exercise is one of the most commonly performed exercises in powerlifting, Olympic lifting, and recreational strength and conditioning routines, with several review articles reporting that the lift can elicit a potentiating effect often referred to as postactivation potentiation (PAP) response (referred to in the present thesis as postactivation potentiation enhancement; PAPE which refers to increases in voluntary force production rather than electrically elicited (twitch) contractions) and improve functional performance when used in a warm-up (Hodgson et al., 2005; Rassier & MacIntosh., 2000; Tillin & Bishop, 2009). Exercises designed to elicit a potentiating effect during training and/or before competition have been shown to influence neuromuscular characteristics, including peak force or strength (e.g. 1-RM), joint range of motion, velocity and muscle activity during the exercise (Fletcher, 2010; Miyamoto, et al., 2010). Two mechanisms theorised to explain the PAP phenomenon include: a) upregulating Ca^{2+} sensitivity of the myofilaments and phosphorylation of the myosin regulatory light chains (Hanson et al., 2007; Hodgson et al., 2005; Sale, 2002), enhancing the excitation-contraction coupling process, and b) increasing descending neural drive via the recruitment and synchronisation of faster motor units, or a decreased presynaptic inhibition at the spinal level (Aagaard et al., 2002; Chiu et al., 2003; Güllich & Schmidtbleicher, 1996; Tillin & Bishop, 2009). Regardless of the mechanism, such changes could enhance mechanical power above previous capacity when induced using maximal or near maximal contractions during a warm-up (Chatzopoulos, et al., 2007; Chiu et al., 2003; Gourgoulis et al., 2003; Güllich & Schmidtbleicher, 1996; Miyamoto, et al., 2010) and utilised during a subsequent MVC.

However, during a maximal (1-RM) back squat exercise, the individual only operates maximally during a short period in the early ascending (concentric) phase, i.e. near the "sticking point", and operates sub-maximally during the remaining concentric and entire eccentric phase. This submaximal demand can be largely explained by the mechanics of the lift, where smaller internal and greater external moment arms are developed at the hip and knee during the eccentric phase of the lift. This results in a poor mechanical advantage and the force-length characteristics of lower limb muscles, which are sub-optimally long in the deep squat position (Anderson et al., 2008; Elliott and Wilson, 1989). Therefore, the characteristics of the free-weight back squat lift may limit the likelihood for potentiation, thus limiting acute increases in strength observed during a warm-up.

Warm-up routines are specifically designed to precondition the neuromuscular system to enhance performance and reduce injury risk during high-intensity physical activity (Bishop, 2003; Verhoshansky, 1986; Woods et al., 2007). In sports such as powerlifting and in strength and conditioning programs, such warm-up routines can act as a determining factor of the athlete’s performance. A possible means of improving the back squat exercise during a warm-up to enhance subsequent maximal strength is the use of variable resistance. Chains or the more recent use of elastic bands attached to a loaded barbell pull the bar down altering the mechanical loading and stresses placed through the musculoskeletal system during the lift, which may ultimately change movement patterns (Stevenson et al., 2010; Wallace et al., 2006). The magnitude of this variable loading is dictated by the weight of the chains or deformation of the bands, which is greater in the standing position (i.e. more chain linkages are off the ground or the elastic bands are stretched) but reduces as the athlete lowers the bar, thus changing the loading characteristics of the lift (Baker & Newton, 2009; Stevenson et al., 2010) and affecting neuromuscular demand. Accordingly, chains or bands can be used to increase resistance at ranges of motion where the muscles can produce their greatest force, as well as unload the system where the muscles are weaker. Therefore, because load manipulation can allow a larger overall impulse to be produced, which is purportedly an important factor influencing PAPE (Anderson et al., 2008), it may be possible to further enhance strength performance.

In the previous study in this thesis (Chapter 3), the effects of chains on subsequent 1-RM performance were examined where a significantly greater difference in 1-RM load and eccentric EMG activity were observed compared to free-weight resistance, while no difference in kinematics was detected. Similar studies have also reported that the use of elastic band resistance during the back squat also result in performance improvements by generating higher forces and power output compared to free-weight resistance alone (Wallace et al., 2006), with increased movement velocity also reported during the eccentric phase (Stevenson et al., 2010). Force production during the subsequent concentric phase is then likely enhanced via the combination of increased reflex amplitudes and a greater use of elastic energy stored in the muscle-tendon units during the eccentric phase (Stevenson et al., 2010), which ensures that the muscles work closer to their maximum through the lift. The increase in total muscle force production elicited by the variable resistance could increase the magnitude of the PAPE response, given that PAPE tends to be augmented when a greater work is performed by the muscles (Anderson et al., 2008; Wallace et al., 2006). Such an improvement in force production during training could subsequently increase muscular adaptation and strength development (Anderson et al., 2008; Simmons, 1996). However, equivocal data exist describing the influence of elastic band resistance exercise on the kinematics of squatting (Ebben & Jensen, 2002; Israetel et al., 2010). Furthermore, no research has examined the influence of elastic band resistance during squat lifting on subsequent free-weight lifting performance. Strength coaches incorporating these elements in a warm-up routine may both enhance acute performance (i.e. increase 1-RM) and impose a greater mechanical stimulus (i.e. training load). As such, identifying an effective warm-up routine to potentiate strength performance is of clear importance to strength coaches. Therefore, the purpose of the present study was to examine the influence of variable resistance exercise using elastic bands, and not chains, due to their practical efficiencies (i.e. cheaper, smaller, lighter and easily transportable) during a warm-up back squat exercise on subsequent free-weight back squat performance. It was hypothesised that the variation in resistance elicited by elastic band use during squatting in the warm-up would: a) enhance subsequent free-weight squat lift performance (measured as the 1-RM load) and b) alter lifting mechanics and neuromuscular activity during the 1-RM lift when compared to the traditional free-weight squat warm-up currently used by many athletes. Furthermore, elastic bands are more practical and may be a better solution for strength and conditioning practitioners to use during training or competition.

4.3 **Methods**

4.3.1 Participants

Sixteen physically active men (age mean = 26.0 ± 7.8 y, range 18 to 44 y; height = 1.7 ± 0.2 m; mass = 82.6 ± 12.7 kg) experienced in weight training (>3 years) volunteered to participate in the study after giving written informed consent (Appendix 4) and completing a pre-test medical questionnaire (Appendix 5). The participants were healthy, had no recent illness or injury in the lower limbs or lower back, were instructed to maintain their eating and drinking habits throughout the study and avoided strenuous exercise and dietary stimulant use for 48 h prior to testing. Ethical approval was granted by the ethics committee at the University of Northampton in accordance with the Declaration of Helsinki. Identical to Study 1 (Chapter 3, section 3.3.1), effect sizes (ES) were calculated from mean change in 1-RM back squat load (ES = 1.9). The analysis revealed that the initial sample size required for statistical power was 12, therefore considering the possibility of participant withdrawal and data loss, 16 participants were recruited with 16 participants completing the study.

4.3.2 Study design

A randomised cross-over study compared 1-RM back squat performance following two warm-up conditions; EB (experimental) or FWR squat (control). The study design was identical to that previously described in Study 1 (Chapter 3, section 3.3.2) with the exception that variable resistance was imposed using elastic band tension rather than chains.

4.3.3 Procedures and overview

Identical to Study 1 (Chapter 3, section 3.3.3), the participants visited the laboratory on three occasions for familiarisation, control and experimental sessions. During the control condition, the participants performed a 5 min warm-up on a cycle ergometer (Monark 874E, Sweden) at 65 rpm with a 1-kg resistance load producing a power output of 65 W followed by 2 sets of 10 back squat repetitions with an unloaded bar (i.e. 20 kg). After 5 min, the participants performed 2 conditioning sets (3 repetitions at 85% of the previously determined 1-RM) with 3 min of rest between sets to prepare for the

1-RM trial. After a further 5 min rest, the participants attempted their previously recorded 1-RM, and after a successful lift the participants attempted a lift with 5% greater load; any further successes resulted in an attempt with an additional 5% load (i.e. 10% total) to the nearest 1 kg. During the experimental condition, similar to previous studies (Wallace et al., 2006), variable resistance from the bands was 35% of the total load. To ensure a similar total load during the squat exercise, half of the 35% load was taken off the bar during the conditioning set, identical to that previously described in Study 1 (see Chapter 3, section 3.3.5 for explanation). Five minutes later, the participants attempted their previously recorded 1-RM; each successful lift was followed by further attempts with 5% greater load.

4.3.4 One-repetition maximum (1-RM) assessment

All participants were experienced at squatting (>3 yr) and completed 5-10 repetitions with appropriate and consistent technique during the familiarisation session using a light resistance set at approximately 50% of 1-RM. A successful squat was considered as the posterior thigh being approximately parallel to the floor, flexing the knee joint more than 90º (Baechle and Earle, 2000) before returning to a standing position. An experienced spotter was used throughout all testing procedures to ensure correct technique, safety during the lifts, and to provide uniform verbal encouragement to all participants. A specific squat depth was not dictated to the participants because an important aim of the research was to determine whether kinematics were influenced by the interventions. Squats were performed without the use of any supportive equipment (e.g. knee wraps, squats suits, weight lifting belts, etc.) and calibrated and certified Olympic standard weight lifting bar, plates, collars and rack (Eleiko, Sweden) were used throughout. In a method identical to Study 1 reported in Chapter 3 (section 3.3.4) and similar to that previously reported (Baechle and Earle, 2000), gradual adjustments were made where the load was increased by 10-20% and the participants then performed 3-5 repetitions, after a 2 min rest period the load was further increased by 10-20% and 2-3 repetitions performed. Two to 4 min later, the load was increased by 10% and participants attempted to perform a 1-RM lift. The load was then increased by 5% with 2-4 min rest between lifts until the participants failed to complete the squat; the previous successful lift was recorded as their 1-RM.

4.3.5 Intervention

In the FWR (control) condition, the load during the conditioning sets was adjusted to 85% of the previously determined 1-RM and the participants performed 2 sets of 3 back squat repetitions with 3 min rest between sets. However, elastic bands were used in conjunction with free-weight resistance in the EB experimental condition to generate variable resistance during the conditioning sets (Figure 4.1). To ensure that a similar load of 85% 1-RM was performed in the EB experimental condition, the mechanical properties of the elastic bands were determined to enable 35% of the load to be generated from elastic resistance.

Figure 4.1. Electromyogram (EMG) electrode and infrared reflective motion analysis marker placement during the back squat exercise. Infrared reflective markers were placed over the lateral malleolus, femoral epicondyle and greater trochanter of the right lower limb to enable knee kinematics to be recorded, while EMG electrodes were positioned over the muscle bellies of the rectus femoris, vastus lateralis and medialis, and semitendinosus enabled muscle activity to be recorded. Elastic bands attached to the barbell provided an average of 35% of the total loading during the squat exercise.

In the EB experimental condition, it was vital to subtract half of the band's resistance from the total free-weight load to ensure that the elastic bands had an identical average resistance as the FWR condition. Using methods previously reported in Study 1 (see

Chapter 3, section 3.3.5) and from other research groups (Wallace et al., 2006), the participants stood on a force platform (HUR, Finland) with 85% 1-RM loading to determine their combined load (kg); data were then directed to a personal computer running Research Line software (v.2.4). The bar was then unloaded and elastic bands were anchored to the floor with two custom-made weight stands, attached equidistant to the ends of the Olympic bar to ensure participant stability. The thicknesses and lengths of the elastic bands were adjusted so that the tension in them increased the force platform reading by 35% of the 85% load when the participants were standing but were slack in a full squatting position, and thus contributed no loading. Therefore, due to the linear force-length properties of the elastic bands, the average loading during the lift equated to 35% of the total load.

To determine the effect of free-weight (FWR) and elastic band (EB) conditioning sets on maximal squat performance, the participants attempted a 1-RM lift at their previously determined 1-RM after a passive (seated) 5 min rest. Similar to the 1-RM trials performed in the familiarisation session, participants then attempted lifts with successive 5% increases of their 1-RM load with 5 min rest until they reached their maximum lift; no participants were able to lift more than 10% of their initial 1-RM.

4.3.6 Muscle activity (Electromyogram [EMG])

Identical to Study 1 (see Chapter 3, section 3.3.6), skin-mounted bipolar double-differential active electrodes (model MP-2A, Linton, Norfolk, UK) constantly monitored the EMG activity of vastus medialis (VM), vastus lateralis (VL), rectus femoris (RF) and semitendinosus (ST). EMG signals were amplified (gain = 300, input impedance = 10 GΩ, common mode rejection ratio ≥100 dB at 65 Hz) and directed to a high-level transducer (model HLT100C, Biopac) before being converted from an analog to digital signal at a 2,000-Hz sampling rate (model MP150 Data Acquisition, Biopac). The signals were then directed to a personal computer running AcqKnowledge software (version 4.1), filtered using a 20-500 Hz band-pass filter, and converted to root-mean-squared (RMS) EMG with a 250-ms sample window. The RMS EMG data were then normalised as a percentage of the peak amplitude recorded during a maximal countermovement vertical jump; VL, VM, and RF data were then averaged to represent quadriceps femoris (QF) EMG. The normalised EMG amplitudes (%MVC) were used as a measure of neuromuscular activity during the squat exercises with peak and mean EMG activity recorded during the concentric and eccentric phases.

4.3.7 Motion analysis

Real-time motion analysis was performed using four ProReflex cameras (Qualisys, Sweden) operating Track Manager 3D (v.2.0) software. The position of three spherical infrared reflective markers (20 mm) placed over the greater trochanter, lateral femoral epicondyle and lateral malleolus were recorded in order to determine knee flexion range of motion (ROM) and both mean and peak eccentric and concentric knee angular velocities during the 1-RM trials. Similar to a previous study (Kay & Blazevich, 2009b), raw coordinate data were sampled at 100 Hz and smoothed using a 100-ms moving average before joint angle and velocities were calculated using Track Manager 3D (v.2.0) software. The positions of the markers were initially recorded with the participants in the anatomical position to enable knee angle data to be corrected (180° full extension) before knee flexion ROM and peak and mean eccentric and concentric knee velocity data were calculated.

4.3.8 Statistical analyses

All data were analysed using SPSS statistical software (version 17.0) with all data reported as mean ± SE. Normal distribution was assessed using the Shapiro-Wilk test; no significant difference ($p > 0.05$) was detected in any variable, indicating that all data sets were normally distributed. Separate repeated measures MANOVA's were used to determine if there was a significant difference in peak and average eccentric and concentric velocities and EMG activity during initial 1-RM trials (same load; 136.1 ± 5.6 kg) following control (FWR) and experimental (EB) conditions. Paired t-tests were then used to locate significant differences in peak knee flexion angle between conditions.

As some participants were able to increase their 1-RM, further analyses were conducted on the best 1-RM performance between conditions (greatest load). Again, separate repeated measures MANOVA's were used to determine if there was a significant difference in peak and average eccentric and concentric velocities and EMG activity during the greatest 1-RM performance following FWR and EB conditions. Paired t-tests were then used to locate significant differences in peak knee flexion angle and 1-RM load between conditions. Significance was accepted at $p < 0.05$ for all tests.

4.3.9 Reliability

Reliability for peak and average concentric and eccentric EMG, peak and average concentric and eccentric knee angular velocity, and knee flexion angle data were determined during two warm-up sets from the 2nd repetition of each set during the FWR condition warm-up. No significant difference was detected in any measure between repetitions ($p > 0.05$). As identical methods were used in Study 1, reliability data has already been established (see Chapter 3, section 3.3.9).

4.4 **Results**

Initial 1-RM attempt

The influence of FWR (control) and EB (experimental) warm-up sets on subsequent free-weight 1-RM kinematics and neuromuscular activity of the knee joint were examined initially at the same 1-RM load (i.e. to determine whether fatigue was induced and whether neuromuscular and kinematics were altered). All participants successfully lifted their previously determined 1-RM after FWR and EB conditions indicating that neither warm-up induced fatigue. No significant difference ($p > 0.05$) was found in peak or mean knee extensor EMG amplitudes during the eccentric or concentric phases of the lift (Table 4.1). Despite similar movement velocities being adopted in the eccentric and concentric phases under the same load, a deeper knee flexion angle (3.4°; $p < 0.05$) was achieved following the EB conditioning contractions compared to the FWR conditioning contractions (Figure 4.2). Thus, the participants squatted to a greater depth following the EB warm-up when measured under the same load.

Table 4.1. Mean and peak quadriceps femoris (QF), vastus lateralis (VL), vastus medialis (VM), rectus femoris (RF) and semitendinosus (ST) electromyogram (EMG) amplitude maximum voluntary contraction (%MVC) and knee angular velocities ($°·s^{-1}$) during the eccentric and concentric phases of the initial 1-RM free-weight back squat attempts. No significant ($p > 0.05$) difference was found following the free-weight resistance (FWR) and elastic band (EB) conditions.

		Eccentric Phase		**Concentric Phase**	
	Measure	FWR	EB (Initial)	FWR	EB (Initial)
QF EMG	Mean	51.7 ± 2.6	60.9 ± 2.1	70.6 ± 4.7	72.3 ± 4.9
	Peak	88.8 ± 4.4	94.6 ± 4.6	95.2 ± 5.1	100.5 ± 6.5
VL EMG	Mean	55.8 ± 3.8	62.2 ± 3.4	67.2 ± 4.7	78.3 ± 5.3
	Peak	93.0 ± 6.6	91.2 ± 6.0	93.5 ± 6.2	104.9 ± 6.9
VM EMG	Mean	50.2 ± 2.9	58.8 ± 3.8	67.2 ± 4.7	74.4 ± 4.8
	Peak	77.7 ± 5.2	88.3 ± 6.7	88.6 ± 5.7	96.3 ± 5.3
RF EMG	Mean	49.2 ± 3.7	61.8 ± 4.0	71.3 ± 7.7	64.3 ± 6.9
	Peak	95.6 ± 7.3	104.2 ± 6.4	103.4 ± 7.6	100.4 ± 10.3
ST EMG	Mean	53.1 ± 12.1	53.0 ± 8.0	74.8 ± 13.0	77.0 ± 12.1
	Peak	78.6 ± 14.1	85.3 ± 13.2	118.9 ± 20.0	131.3 ± 23.5
Velocity	Mean	53.9 ± 3.8	56.9 ± 4.3	61.7 ± 4.6	60.6 ± 3.4
	Peak	114.4 ± 8.1	117.8 ± 6.3	221.9 ± 15.9	210.8 ± 13.4

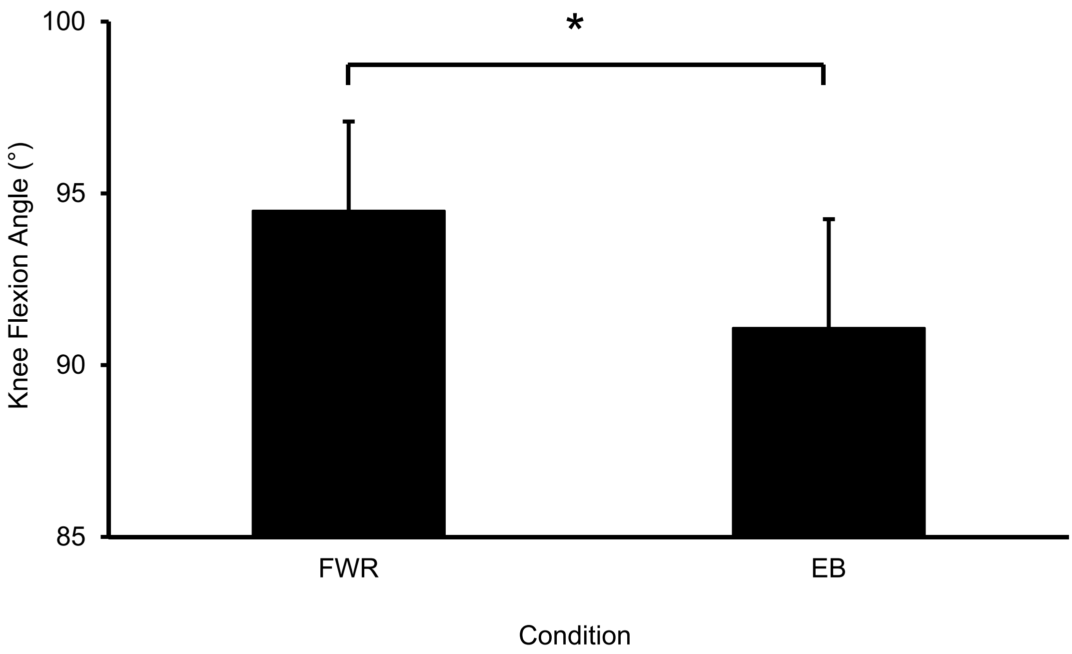

Figure 4.2. Mean knee flexion angle achieved during initial one-repetition maximum (1-RM) free-weight back squat exercise at the same load (136.1 ± 5.6 kg) following a free-weight (FWR) or elastic band (EB) warm-up set. *Significantly (3.4°; $p < 0.05$) greater (deeper) knee flexion angle was achieved following EB compared to FWR.

Final 1-RM attempt

Following the first 1-RM trial, the participants then attempted a 5% and, if successful, a 10% increase in loading to determine any potentiating effects of the warm-up conditions. No participant was able to successfully lift a greater load following the FWR warm-up condition. However, following the EB condition, 13 of 16 participants (81%) were able to successfully increase their 1-RM load by 5-10% (1-RM = 146.6 ± 5.7 kg). This resulted in a significantly greater 1-RM (Figure 4.3) following EB (7.7 ± 1.0%; $p < 0.01$) compared with FWR indicative of a potentiating effect on squat performance.

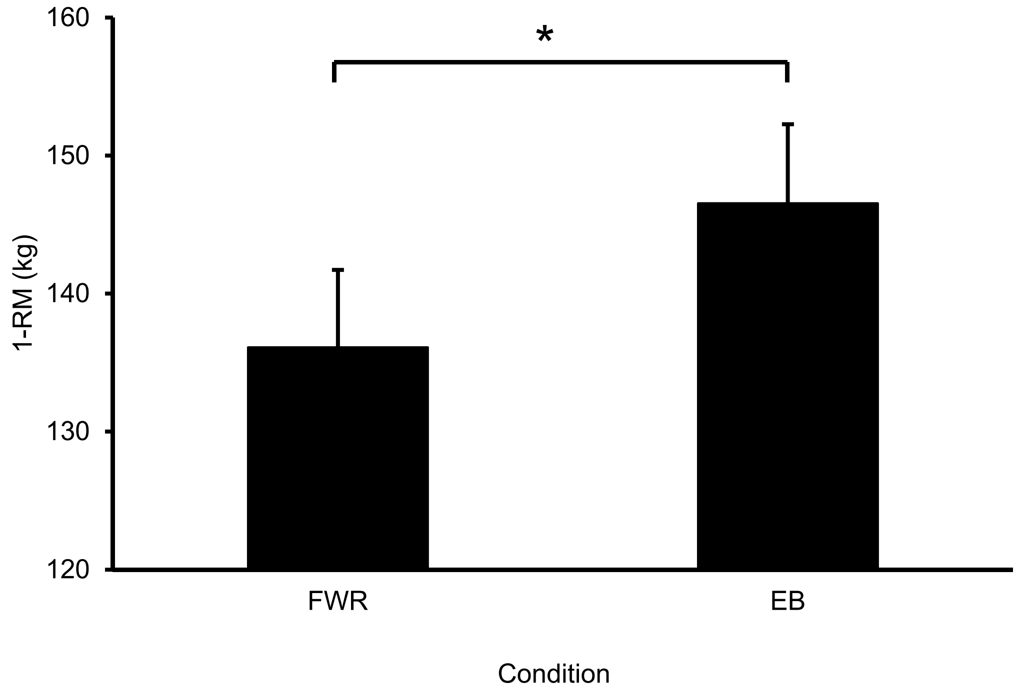

Figure 4.3. Mean 1-RM load achieved during a one repetition maximum (1-RM) free-weight back squat exercise following a free-weight (FWR) or elastic band (EB) warm-up set. *Significantly (7.7 ± 6.2%; $p < 0.01$) greater load was achieved following EB compared to FWR.

Significantly slower ($p < 0.05$) peak (22.6 ± 14.5%) and mean (16.0 ± 9.5%) eccentric knee angular velocities were found when measured during the maximum 1-RM load following EB than FWR, however no differences in EMG amplitudes ($p > 0.05$) were detected during the eccentric or concentric phases of the lift (Table 4.2). Similarly, significantly slower peak (24.7 ± 10.1%) and mean knee angular velocities (27.9 ± 8.5%) were found during the concentric phase in the EB condition, although again no difference in EMG was detected. Despite the greater load and slower movement, no difference in peak knee flexion angle (1.8°; $p > 0.05$) was found, indicating that a similar squat depth was achieved and that a full repetition was performed.

Table 4.2. Mean and peak quadriceps femoris (QF), vastus lateralis (VL), vastus medialis (VM), rectus femoris (RF) and semitendinosus (ST) electromyogram (EMG) amplitude maximum voluntary contraction (%MVC) and knee angular velocities (°·s^{-1}) during the eccentric and concentric phases of the final 1-RM free-weight back squat attempts following the free-weight resistance (FWR) and elastic band (EB) conditions. *Significantly ($p < 0.05$) different than FWR.

		Eccentric Phase		**Concentric Phase**	
	Measure	FWR	EB (final 10%)	FWR	EB (final 10%)
QF EMG	Mean	50.8 ± 2.4	58.7 ± 2.4	69.7 ± 4.8	69.4 ± 4.7
	Peak	85.8 ± 4.2	95.9 ± 3.5	94.6 ± 5.2	100.8 ± 4.6
VL EMG	Mean	55.0 ± 3.4	59.9 ± 2.7	64.2 ± 4.3	76.0 ± 5.4
	Peak	88.3 ± 5.5	92.5 ± 5.9	95.2 ± 6.2	100.1 ± 5.8
VM EMG	Mean	48.6 ± 2.5	57.4 ± 3.4	64.2 ± 4.3	69.8 ± 4.5
	Peak	74.9 ± 5.2	87.0 ± 5.8	86.1 ± 5.8	95.3 ± 5.9
RF EMG	Mean	49.0 ± 4.0	58.6 ± 4.4	70.2 ± 8.1	62.4 ± 6.5
	Peak	94.3 ± 7.3	108.1 ± 6.1	102.6 ± 7.7	107.0 ± 8.1
ST EMG	Mean	41.6 ± 5.0	51.1 ± 7.9	64.0 ± 8.4	81.3 ± 13.8
	Peak	64.7 ± 7.6	77.4 ± 9.7	109.2 ± 18.6	137.6 ± 26.8
Velocity	Mean	54.3 ± 3.7	46.9 ± 4.4*	60.5 ± 4.6	49.7 ± 4.0
	Peak	114.9 ± 7.8	96.5 ± 8.9*	221.0 ± 15.4	185.2 ± 17.6

4.5 Discussion

The primary aim of the present study was to compare the influence of elastic bands (EB) and free-weight resistance (FWR) on: a) subsequent free-weight 1-RM performance (measured as the 1-RM load); b) lifting mechanics and c) neuromuscular activity during the 1-RM. During the initial 1-RM attempt following both interventions, all participants were able to lift their previously determined 1-RM with no differences found in eccentric or concentric velocities or EMG activity. However, a significantly greater knee flexion angle was achieved following EB warm-up, indicating that the participants volitionally squatted to a greater depth, a similar finding to Study 1 where the use of chains to induce variable resistance also resulted in a greater squat depth. Despite the greater squat depth placing the participants at further mechanical disadvantage due to internal and external moment arms and force-length properties of skeletal muscle (Anderson et al., 2008; Elliott and Wilson, 1989), concentric velocities were similar to the FWR condition. The greater squat depth while maintaining velocity is indicative of the participants more easily tolerating the same load while performing greater muscular work without limiting or compromising the mechanics of the lift.

While the choice to squat to a greater squat depth without reducing movement velocity provided some evidence that the participants more easily tolerated the same previously determined 1-RM load, the primary aim of this study was to determine whether a greater 1-RM load could be lifted following the EB warm-up. The main finding of the present study was that when compared to a standard warm-up using free-weight squats, subsequent squat lift 1-RM was greater when variable resistance was included using EB in the warm-up, therefore the experimental hypothesis that 1-RM would be increased can be accepted. EB training is typically used to reduce the effective load near the sticking point experienced early in the concentric phase of the squat lift, but then allows for greater loading later in the concentric phase when the joints are more extended, the internal moment arms are greater and optimal muscle lengths are achieved, and the load would therefore be easier to lift (Anderson et al., 2008). According to Anderson et al. (2008), a less acute sticking point may have allowed for greater muscle fibre recruitment and stimulation during the eccentric phase that may bring greater neuromuscular adaptations and Type IIx muscle fibre recruitment. Thus, the use of EB changes the loading pattern during the squat to allow for loading to be closer to the maximal capacity of the lower limb musculature as the capacity changes throughout the lift. The ability for muscles to operate closer to their maximum through a greater proportion of the lift may have allowed for an enhanced PAPE effect and an increased 1-RM capacity. Some authors have suggested that performance may be enhanced after chronic EB training due to improvements in muscular strength and power (Anderson et al., 2008; Baker & Newton, 2009; Israetel et al., 2010; Simmons, 1996; Stevenson et al., 2010; Wallace et al., 2006), however no study had previously examined the effects of EB as a conditioning exercise as part of a warm-up on a subsequent free-weight 1-RM squat performance. Accordingly, these are the first data confirming that an acute increase in free-weight 1-RM squat performance can be elicited by EB conditioning, which is clearly important for coaches and athletes where maximal strength development is crucial for performance.

The magnitude of PAP is suggested to be intensity dependent, with higher intensity contractions resulting in greater enhancement of motor unit recruitment and/or magnifying the phosphorylation of regulatory light chains (Sale, 2002). These effects are typically notable within minutes of the conditioning contraction being performed Lowery et al., 2012). However, several studies have indicated that PAPE is maximal 4-12 min after a conditioning contraction when measured during voluntary contractions (Jo et al., 2010; Kilduff et al., 2007; Lowery et al., 2012). Therefore, increased phosphorylation of regulatory light chains is an unlikely mechanism influencing the increased 1-RM during the squat exercise in the present study. Alternatively, changes in the magnitude of activation of the muscles, perhaps through changes in spinal excitability or influences from afferent projections (Güllich & Schmidtbleicher, 1996; Trimble & Harp, 1998), are more likely factors, although increases in temperature, motivation and acute improvements in motor control strategies cannot be discounted. In the present study, a clear increase in 1-RM was noted 5 min after the conditioning contractions, consistent with previous findings and within the timeframe normally associated with neural, but not muscular, changes (Jo et al., 2010; Kilduff et al., 2007; Lowery et al., 2012). Nonetheless, no change in knee extensor EMG amplitude was detected, although the lack of change in EMG despite increased loading is consistent with previous studies (Caterisano et al., 2002; Ebben & Jensen, 2002). Ebben and Jensen (2002) compared free-weight squats to VR of (10% of load supplied by elastic bands) and reported no difference in EMG activity from the quadriceps and hamstrings during these techniques. One possible explanation for this finding is that muscles other than the quadriceps, including the hip extensors, were activated differently after the EB squats. In fact, Flanagan & Salem (2008) examined hip and knee extensor contributions during the squat lift exercise and reported that increases in load required greater mechanical effort from the hip than the knee extensors. However, EMG activity of the hip extensors was not examined in the present study and joint torque measurements were not obtained, and while trends for greater EMG was observed within the semitendinosus, which contributes to hip extension, these increases were not statistically significant. Thus, the contribution of primary extensor muscle groups at the hip needs to be more explicitly examined in future studies.

An alternative possibility is that the improvement in 1-RM resulted from a modification in lifting technique whereby the participants failed to squat to the same depth and therefore did not complete a full repetition. However, no significant difference in peak knee flexion angle was observed after EB when compared to FWR during the maximal efforts, despite participants increasing their load after the EB condition. Nonetheless, although 1-RM increases occurred without a noticeable technique change (i.e. squat depth), peak and mean knee angular velocities during both the eccentric and concentric phases of squat exercise were reduced, indicating greater difficulty in completing the task. Therefore, given that squat depth was unchanged while knee velocities were reduced, the second hypothesis that lifting mechanics would be altered can be partially accepted. Previous research examining lifting mechanics during EB have reported increased eccentric velocity (Baker & Newton, 2009; Stevenson et al., 2010). However, these previous studies measured velocity during the variable resistance condition rather than after during free-weight exercise, using chains rather than bands, and during a bench press rather than back squat exercise, therefore substantial differences in methodology likely explain these disparate findings. The reduction in eccentric velocity likely resulted from the need to minimise the greater load's momentum during the descent so that the impulse provided by the participants was sufficient to decelerate, and then re-accelerate, the load. Similarly, the greater loading might have limited the maximal concentric velocity unless a substantial change in the muscles' force-velocity characteristics (Rahmani et al., 2001) occurred after the EB repetitions. While the reduction in eccentric and concentric knee velocities was likely a result of the greater loading (Rahmani et al., 2001), the participants were still able to squat to the same knee angle and complete the exercise. This clearly demonstrates that a full repetition was performed, and that 1-RM, mechanical output and force generating capacity were enhanced, which is of great importance to strength and conditioning coaches whose primary aim is to maximise the strength potential of their athletes.

In summary, performing free-weight resistance back squat exercise in combination with elastic bands enhances subsequent free-weight squat lift performance, similar to the findings of Study 1 where chain loaded resistance was employed. Despite the 1-RM enhancement following the EB condition there was no noticeable change in squat depth, although movement velocities were reduced. No change in knee extensor EMG activity was found in the EB condition although in Study 1 (Chapter 3), a significantly greater mean eccentric EMG was found in VL, VM, RF (QF) EMG in the CLR condition, therefore the mechanisms underpinning these improvements in performance following different modes of inducing variable resistance remain unclear. Although a significant increase in 1-RM was achieved in both studies, the EB condition influenced a greater number of participants with only 3 participants unable to improve performance compared to 6 in Study 1. To ensure these participants' data did not influence the statistical findings for EMG, velocity and knee flexion angle, subsequent analyses were undertaken without these participants included. Identical statistical outcomes were found compared with the original analyses, therefore inclusion of non-responders in the analysis did not influence the study's conclusions. Whilst Studies 1 and 2 have similar findings, Study 2 resulted in a greater mean increase in performance with a lower number of non-responders. Furthermore, elastic bands are more practical and may be a better solution for strength and conditioning practitioners to use during training or competition as they are cheaper, smaller, lighter and easily transportable. However, the positive effects observed presently require further research in other muscle groups (i.e.

hip extensors) and more applied athletic tasks, (e.g. countermovement jump), to more fully determine the influence of variable resistance on athletic performance.

Chapter 5

5 Study 3
Variable, but not free-weight, resistance exercise potentiates jump performance following a comprehensive warm-up

5.1 Abstract

Studies examining acute, high-speed movement performance enhancement following intense muscular contractions (frequently called ‘postactivation potentiation’; PAP) often impose a limited warm-up, compromising external validity. In the present study the effects on countermovement vertical jump (CMJ) performance of back squat exercises performed with or without elastic bands during warm-up were compared. After familiarisation, fifteen active men visited the laboratory on two occasions under counterbalanced experimental squat warm-up conditions: a) free-weight resistance (FWR) and (b) elastic bands (EB). After completing a comprehensive task-specific warm-up, three maximal CMJs were performed followed by three back squat repetitions completed at 85% of 1-RM using either FWR or EB. Three CMJs were then performed 30 s, 4 min, 8 min and 12 min later. During CMJ trials, hip, knee and ankle joint kinematics, ground reaction force data and vastus medialis (VM), vastus lateralis (VL) and gluteus maximus (Glut) EMG were recorded simultaneously using 3D motion analysis, force platform, and EMG techniques, respectively. No change in any variable occurred after FWR ($p > 0.05$). Significant increases ($p < 0.05$) were detected at all time points following EB in CMJ height (5.3-6.5%), peak power (4.4-5.9%), rate of force development (12.9-19.1%), peak concentric knee angular velocity (3.1-4.1%) and mean concentric vastus lateralis EMG activity (27.5-33.4%). The lack of effect of the free-weight conditioning contractions suggests that the comprehensive task-specific warm-up routine mitigated any further performance augmentation. However, the improved CMJ performance following the use of elastic bands is indicative that specific alterations in force-time properties of warm-up exercises may further improve performance.

Keywords: elastic bands, PAP, conditioning contraction, explosive strength, kinetics, kinematics

5.2 Introduction

Pre-exercise (i.e. warm-up) routines are typically designed to precondition the neuromuscular system to enhance performance and reduce injury risk during subsequent high-intensity physical activities (Tillin & Bishop, 2009; Woods et al., 2007). Performing maximal or near-maximal muscular contractions during a warm-up routine are important as they can induce short-term increases in force production and physical performance (Hodgson et al., 2005) through a number of mechanisms including, but not limited to, increases in muscle temperature (Racinais & Oksa, 2010), reductions in muscle thixotropy or viscosity (Woods et al., 2007), increases in myofilament calcium sensitivity (Moore & Stull, 1984), an increased neural drive (leading to higher-frequency motor unit discharge) and optimisation of motor control strategies (Trimble & Harp, 1998). Such changes lead to an increased mechanical power output (i.e. above previous maximal voluntary capacity), a state often referred to as postactivation potentiation (PAP), but which may not be synonymous with 'classic' PAP, which refers to an increase in muscular force production during an electrically elicited (twitch) contraction (Hamada et al., 2000; Vandervoort et al., 1983). Regardless of the mechanism, short-term improvements in performance (i.e. postactivation performance enhancements [PAPE]; Cuenca-Fernandez et al., 2017) are commonly reported following intense muscular contractions that have important implications for the design of warm-up strategies.

The acute augmentation of physical performance has been explored using different warm-up strategies including light muscle stretching, cycling, running and sub-maximal repetitions of the primary task (Jo et al., 2009) or no warm-up at all (Hamada et al., 2000). Consequently, a "comprehensive task-specific" warm-up (including progressively intense task-specific conditioning contractions) is often not provided prior to the specific activity being tested. Although warm-up strategies adopted to potentiate muscular force production have been shown to enhance athletic performance following a conditioning contraction, it is unclear whether the enhancement of athletic performance observed is a consequence of acute neuromuscular alteration relating to the conditioning contraction, or whether it simply reflects a standard warm-up itself (MacIntosh et al., 2012a). Heavy resistance exercise has been shown to acutely potentiate muscle force output, at least when a comprehensive task-specific warm-up is not completed (Hamada et al., 2000; Young et al., 1998), however force production can also be reduced as a result of fatigue or coordination interference (i.e. perseveration) processes, which may mask any potentiating effects (Tillin & Bishop, 2009). Some studies have reported that vertical jump performance enhancements can be detected after only 20 s (Arabatzi et al., 2014) and 90 s (Baker, 2008) following maximal isometric squats and heavy box squats, respectively. Findings from these studies are indicative that effects may be detected within the timecourse of "classic" PAP observed using muscle twitch examinations (Hamada et al., 2000; Seitz et al., 2015). Nonetheless, a meta-analysis of the literature revealed that minimal performance enhancement was likely when the rest period was less than 2 min, whereas longer rest periods of 3-7 min were more beneficial (Wilson et al., 2013). The equivocal findings likely result from disparate study methodologies including types of conditioning contraction (i.e. movement-pattern specificity), performance tasks, delay between the conditioning contraction and performance testing, study participant characteristics (e.g. experienced/novice lifters) and warm-up performed, which limit our understanding of the potentiating effects of these warm-up strategies.

Although previous research including Studies 1 and 2 of the present thesis examined the impact of variable resistance on squat performance, the countermovement vertical jump (CMJ) task is commonly performed in sport but is also a model commonly used to test power and muscle function in clinical research environment. Various high-intensity exercise types have been performed before maximal CMJ tests including resistance-, plyometric-, and electrical muscle stimulation-based exercises (Gourgoulis et al., 2003; Witmer et al., 2010). The back squat exercise is a fundamental exercise for the development of lower-limb strength and power (Young, 1998) and its use during a warm-up has been reported to improve subsequent functional performance including CMJ height (Hodgson et al., 2005; Tillin & Bishop, 2009); this enhancement is commonly attributed to the PAP effect. However, maximal voluntary muscle activity occurs only during a short period in the early ascending (concentric) phase, near the "sticking point" in successful maximal (1-RM) back squat attempts. The larger internal and smaller external moment arms developed at the hip and knee joints (resulting in a greater mechanical advantage) combined with the optimised force-length characteristics of lower-limb muscles, ensures that only a submaximal muscle activation is needed for successful completion of the remaining part of the lift (Elliott and Wilson, 1989). Thus, theoretically, variations of the exercise that evoke a greater muscle activation throughout the lift could result in a greater warm-up (i.e. PAPE) effect and improve CMJ performance. A possible means to alter the loading characteristics of the squat lift is the use of elastic bands to reduce the external load in the deepest part of the squat while increasing external load when the joints are more extended, the internal moment arms are greater and optimal muscle lengths are achieved (Elliott and Wilson, 1989; Israetel et al., 2010). Previous studies comparing elastic bands to free-weight squats for muscle activities (EMG), kinematics and kinetics has shown significantly higher EMG, movement velocity, and external power in the first quarter of the eccentric phase and the last quarter of the concentric phase of the squat exercise when using elastic bands (Israetel et al., 2010; Wallace et al., 2006). Accordingly, it has been found that conditioning contractions using elastic bands significantly increased subsequent 1-RM squat test performance without detectable changes in knee extensor muscle activity or knee flexion angle, although eccentric and concentric velocities were reduced. Accordingly, elastic bands can be used to increase resistance in ranges of motion where the muscles can produce the greatest relative force, as well as unload the system where muscle forces are compromised, and thus allow a larger overall impulse to be produced. Given the possibility for higher muscle activation and greater total work done during the lift, it might be hypothesised that these conditions would allow for a greater potentiating effect.

Individuals incorporating the use of elastic band-based strategies into a warm-up routine may observe an acute enhancement of performance, and thus benefit from a greater mechanical stimulus during training (Wallace et al., 2006). However, a common limitation in the literature is that brief or no warm-up has been provided before imposing the conditioning contraction (Hamada et al., 2000), limiting the practical application and external validity of the data. Therefore, the purpose of this study was to compare the influence of free-weight resistance (FWR) and elastic band (EB) squat exercises following a comprehensive task-specific warm-up on subsequent CMJ performance at different post-conditioning time points (i.e. 30 s, 4 min, 8 min, and 12 min). It was hypothesised that (i) FWR and VR would enhance subsequent CMJ performance; however the variation in resistance imposed by the elastic bands during the squat lift would (ii) further enhance subsequent CMJ performance, (iii) alter CMJ kinetic and kinematic parameters (i.e. peak power, peak eccentric kinetic energy, impulse- and time-based descent-to-ascent asymmetry indexes, vertical stiffness (K_{vert}), rate of force development (RFD), hip, knee and ankle joint kinematics), and (iv) increase the muscle activity of the lower-limb extensor muscles more than squatting without elastic bands.

5.3 Methods

5.3.1 Participants

Fifteen active men (age = 21.7 ± 1.1 y, height = 1.8 ± 0.1 m, mass = 77.6 ± 2.6 kg) with ≥5 y experience with heavy weight training of varying levels (from regional to elite) and training backgrounds volunteered to participate after providing written informed consent and completing a pre-test medical questionnaire. The participants' training protocols involved resistance training, sprint running, power exercises, dynamic/explosive exercises, agility drills and other specific exercises relevant to their sports. The participants had no recent illness or lower-limb injury, were instructed to maintain normal eating and drinking habits throughout the study, and avoided strenuous exercise and stimulant use at least 48 h prior to testing. Ethical approval was granted by the ethics committee at the University of Thessaly, Greece, with the study conducted in accordance with the Declaration of Helsinki. Effect size (ES) values (Cohen's d) were calculated from mean changes in variables (jump height, power, RFD and EMG) from previous studies using similar methods. To ensure an adequate population to reach statistical power (set at 0.8) was recruited, effect sizes were initially calculated from related research (Argus et al., 2011; Golas et al., 2017; Lowery et al., 2012) for jump height (ES = 1.5), peak power (ES = 1.5), RFD (ES = 1.3), and EMG (ES = 1.2). To ensure an adequate sample, the measure with the smallest ES (i.e. EMG [ES = 1.2]) was used to calculate sample size. The analysis revealed that the initial sample size required for statistical power was 13, therefore considering the possibility of participant withdrawal and data loss, 18 participants were recruited with 15 participants completing the study.

5.3.2 Study Design

A randomised, cross-over design was implemented to compare CMJ performance following two warm-up conditions: free-weight resistance (FWR) or elastic bands (EB) back squat exercise. Participants completed a familiarisation session one week prior to the two experimental sessions, each separated by 72 h and performed at the same time of the day. During familiarisation, anthropometric characteristics were recorded, one-repetition maximum (1-RM) back squat load was determined, and the participants were familiarised with all experimental procedures. During experimental conditions, following the comprehensive warm-up (described later) the participants performed three pre-intervention CMJs followed by back squats at 85% of 1-RM using either FWR or EB resistance. CMJ trials were then performed at 30 s, 4 min, 8 min and 12 min after the intervention. Peak power output, peak eccentric kinetic energy, impulse- and time-based descent-to-ascent asymmetry indexes, peak normalised (to body weight) K_{vert} and RFD, peak knee flexion angle, peak eccentric and concentric knee angular velocities, peak and mean eccentric and concentric EMG (vastus lateralis [VL], vastus medialis [VM], gluteus maximus [Glut]), and jump height were measured during all CMJ trials (described later).

5.3.3 Procedures and overview

5.3.3.1 Familiarisation session and one-repetition maximum (1-RM) back squat assessment

The 1-RM back squat protocol was adopted from Sheppard & Tripplet (2016). Participants initially performed a 5 min cycling warm-up (Monark 874E, Varberg, Sweden) at 65 rpm with a 1-kg resistance load producing a power output of 65 W followed 2 min later by 2 sets of 10 back squat repetitions using an unloaded 20-kg Olympic bar. The participants then completed 8-10 repetitions of the squat lift exercise at 50% of their estimated 1-RM load before the load was increased by 20% for 3-5 repetitions, and by a further 20% for 2-3 repetitions with a 2 min rest between sets. The load was finally increased by 5% movements with 2-4 min rest between lifts until participants failed to complete the lift; the previous successful attempt was recorded as their 1-RM load. To ensure correct technique, participants were instructed to place the bar above the posterior deltoids at the base of the neck and position the feet shoulder width apart with the toes pointed slightly outward and attempt to squat to a position where the knee was flexed to ~90° before returning to a standing position. This was visually assessed by an experienced, certified British Amateur Weight Lifting Association (BAWLA) spotter throughout all testing procedures to ensure correct technique and safety during the lifts, with participants receiving strong verbal encouragement to promote maximal effort.

5.3.3.2 Comprehensive warm-up and countermovement jump trials

During the experimental trials the participants performed a comprehensive task-specific warm-up consisting of 5 min of cycling followed by five continuous unloaded squats (i.e. non-jumping) at a rhythm of 2 s/ 2 s (eccentric/concentric) and a further 5 squats at a rhythm of 1 s/ 1 s after a 30 s rest. After 20-s rest, five continuous CMJs were performed at ~70% of the participants' perceived maximum and, after a further 30 s rest, maximal CMJs were performed every 30 s until three consecutive jumps were within 3% of jump height (4-7 jumps were performed in all trials). The CMJ was performed from a stationary upright standing position with hands positioned on the hips, making a preliminary downward movement with the hips and knees flexed, and immediately jumping vertically up as high possible (Young et al., 1998).

Two minutes after the completion of the warm-up, three maximal pre-intervention CMJ trials were performed to establish baseline (i.e. after warm-up) performance. A conditioning set of three repetitions of back squats at 85% of the previously determined 1-RM using either FWR or VR (described later) was then performed before the participants completed three CMJs 30 s, 4 min, 8 min and 12 min (Table 5.1) later with participants receiving verbal encouragement to jump as high as possible. The post-intervention intervals were selected from previous data describing the time-course of the performance augmentation (PAP) response (Kilduff et al., 2007; Lowery et al., 2012).

Table 5.1. Study design timeline.

Task	Time (min)
5 min cycle	0-5.0
5 unloaded squats (1 s/ 1 s)	5.0-6.0
5 unloaded squats (2 s/ 2 s)	6.0-7.0
5 CMJs (70%)	7.5-8.5
Single CMJs every 30 s (100%)	9.0-11.0
CMJ Test 1	13.0-13-5
FWR or EB squats	14.5-15.0
CMJ Tests (2-5)	15.5, 19.5, 23.5, 27.5

CMJ = countermovement vertical jump; FWR = free-weight resistance; EB = elastic bands.

5.3.4 Intervention

During the FWR condition, the load was adjusted to 85% of the previously determined 1-RM load with the participants performing one set of three-repetition back squats. In the VR warm-up condition, 35% of the total load was generated from band resistance. To ensure a similar load of 85% 1-RM across FWR and VR conditions, mechanical properties of the bands were determined to allow the band resistance to generate 35% of the total load. Half of the band's resistance was subtracted from the total free-weight load to ensure the elastic bands did not have substantially different average resistance compared with the FWR condition, thus both the FWR and VR warm-up conditions were equalised, as previously reported (Wallace et al., 2006). The participants stood on a force platform with 85% 1-RM load to determine the combined load (kg), the bar was then unloaded to adjust the band tension. The elastic bands were anchored to the floor with custom-made weight stands and attached equidistant to the ends of the Olympic bar to ensure the participant's stability. The thickness and lengths of the elastic bands were adjusted so that: (a) the tension in the bands increased the ground reaction force (measured by force platform) by 35% of the 85% load when the participants were standing, but (b) bands were slack in a full squatting position and thus provided no additional loading. The linear force-length properties of the bands ensured, therefore, that the average load during the lift equated to 35% of the total load. For example, a 100-kg load in the FWR condition would require 35-kg (35%) to be generated from the bands. Half of the 35-kg load (i.e. 17.5 kg) was removed from the bar with the 35-kg resistance added from the bands providing a total load of 117.5 kg in the standing position. As band tension reduced as the participant squats, 35 kg of load was removed leaving the 82.5 kg from the bar in the full squatted position. Thus, the average loading throughout the lift in this example is 100 kg, identical to the FWR condition whilst enabling 35% to be generated by band tension.

5.3.5 Kinetic and kinematic analyses

Kinematic data were collected during the CMJs using a Vicon motion analysis system (T-Series, Oxford Metrics LTDA, Oxford, UK) with 10 cameras operating at 100 Hz surrounding two force platforms (Bertec, FP4060-10-2000, Bertec Corporation, Columbus, OH, USA). Ground reaction forces were sampled at 1000 Hz and time-synchronised with the Vicon system (Figure 5.1). The data were then filtered using Woltring's quantic spline algorithm (Woltring, 1986) with a mean squared error setting of 15 before running the Plug-In-Gait biomechanical model (Vicon Plug-in-Gait, Oxford Metrics). The procedures identified by Davis et al. (1991) were followed to define Cardan angles and to reconstruct a system of embedded coordinates from the marker set to 0° at the three joints of the lower extremities (hip, knee and ankle) in a standing position. Lower-limb kinetic and kinematic data were captured by placing 16 reflective markers over the pelvis, left and right thigh, left and right shank in a straight line, and the left and right foot at a right angle to the leg. Data were analysed using Vicon Nexus (v.2.3) software to determine peak hip, knee and ankle flexion angle and angular velocity data during the pre- and post-intervention CMJ trials (Figure 5.1).

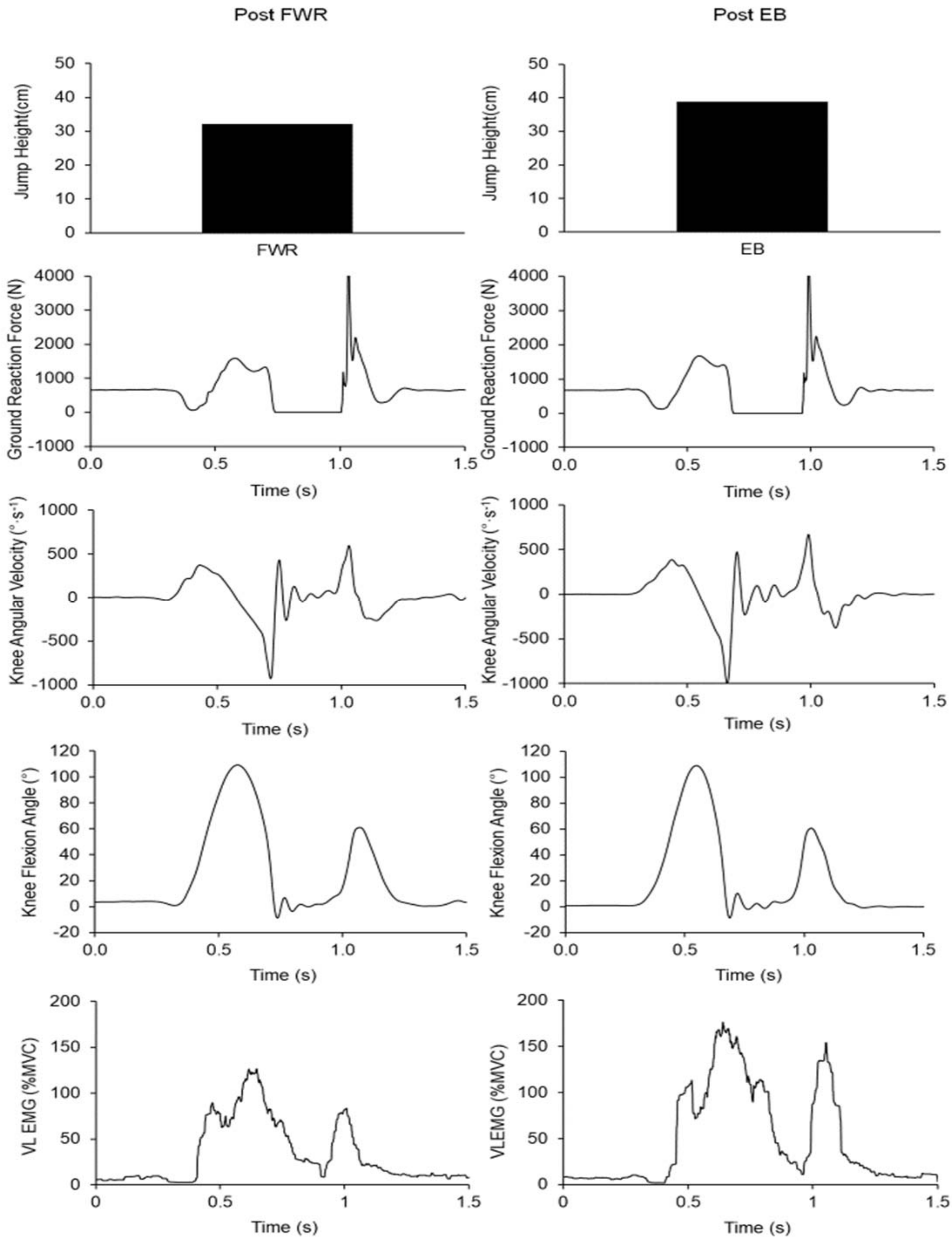

Figure 5.1. Exemplar data from a participant depicting countermovement vertical jump (CMJ) height, ground reaction force, knee angular velocity, knee flexion angle and

vastus lateralis (VL) EMG activity at 8 min following the free-weight resistance (FWR) and elastic band (EB) warm-up squat conditions.

All jumps were performed from the standing position with each foot in parallel on two force platforms providing a separate yet time-synchronised measurement of the force data for each leg. The participant's body weight was calculated by averaging the vertical force from each platform when the participants were stationary. The initiation of the jump (i.e. the beginning of the eccentric phase) was identified as the point when the ground reaction force (N) decreased 2 standard deviations (SD) below the mean baseline force. The vertical ground reaction force was integrated using the trapezoid method during the eccentric and concentric phases of the jump. The net impulse was calculated independently and summed from the left and right force platforms. Ground reaction forces were directly quantified by integrating the applied force over time (i.e. impulse), which is equivalent to the change in momentum of the body:

$$J = \int F \, dt = \Delta p$$

where J = impulse, F = force, t = time and Δp = change in momentum.

The take-off velocity was determined from impulse by dividing by body mass, and the jump height was calculated using standard equations for motion (Kibele, 1998). To calculate power, the impulse-momentum approach was used. Since the force, mass and initial velocity conditions were known, instantaneous velocity could be calculated. The instantaneous power was calculated as force × velocity and the peak values were determined for the propulsive phase of the CMJ:

$$V_{(0)} = 0$$

$$F(\mathrm{i})t = m(v_{(\mathrm{i}+1)} - v_{(\mathrm{i})})$$

$$\Delta v = (F_{(\mathrm{i})}t)/m$$

$$P_{(\mathrm{i})} = F_{(\mathrm{i})} \times V_{(\mathrm{i})}$$

where F = force, t = 1/sampling frequency, m = mass of body, load, v = velocity, and P = power.

The peak eccentric kinetic energy (KE) developed during the jumps was calculated as:

$$KE = ½mv^2$$

where *m* is the participant's mass and *v* is the velocity of the countermovement phase.

The impulse-based asymmetry index was calculated by dividing the negative and positive impulses, where the negative impulse describes the impulse that negatively accelerates the body downwards and the positive impulse accelerates the body upwards. The index was calculated to estimate the efficiency of the metabolic energy conversion into mechanical work (i.e. storage of elastic energy during eccentric contraction) performed during the CMJ from the force applied by the body to the ground (Cavagna, 1977) and subsequently released energy during the concentric phase of the stretch-shortening cycle. The time-based asymmetry index was calculated as the quotient of times A + B, where A is the time from force first rising above 1 body weight to the peak vertical force and B is the time from peak force until force drops below 1 body weight. K_{vert} was calculated by dividing the peak vertical ground reaction force by the maximal vertical displacement of the centre of mass during contact with the ground (Boullosa et al., 2013)

$$K_{vert} = F_{max} / \Delta y$$

where Fmax = maximum vertical force, and Δy = maximum vertical displacement of the centre of mass. The vertical displacement was determined by the double integration of the vertical force trace according to methods of Cavagna (1985).

The peak RFD (normalised to body weight) was calculated from the initiation of the jump (i.e. first rise in force during the eccentric phase) using the average force-time curve with a 50-ms time window.

5.3.6 Muscle activity (Electromyogram [EMG])

EMG data were collected wirelessly using a Myon MA-320 EMG system (Myon AG, Schwarzenberg, Switzerland) from vastus lateralis (VL), vastus medialis (VM) and gluteus maximus (Glut). The skin was shaved, abraded and cleansed with alcohol before bipolar adhesive surface electrodes (Noraxon Dual Electrodes, Ag-AgCl, Noraxon USA, Inc, Scottsdale, AZ) were placed over the muscle belly with an inter-electrode distance of 2 cm according to SENIAM guidelines. EMG data were sampled at 2000 Hz and imported into ProEMG software (version 4.1) and filtered using a Butterworth (20-500 Hz bandpass) filter before using a symmetric moving root-mean-square algorithm with a 50-ms sampling window. The Myon EMG software was integrated with an optimal tracking device for synchronisation between the systems (Vicon motion analysis system, Oxford, UK). The normalised EMG amplitude during isometric squat lifts (% maximal voluntary contraction [MVC]) for each muscle was used as a measure of neuromuscular activity during the jumps (Figure 5.1), with peak and mean EMG activity recorded during the eccentric and concentric phases.

5.3.7 Statistical analyses

All data were analysed using SPSS statistical software (version 24.0; IBM, Chicago, IL, USA); all data are presented as mean ± SE and Cohen's *d* was used to calculate effect size (ES). Normal distribution was assessed using Shapiro-Wilks test; no significant difference ($p > 0.05$) was detected in any variable indicating that all data sets were normally distributed. Separate multivariate analyses of variance (MANOVAs) were used to compare (a) jump height and peak power, and (b) EMG. Where significant differences were detected, separate two-way repeated measures ANOVAs (time × condition) were used to determine differences in (a) jump height, (b) peak power, (c) peak eccentric kinetic energy, (d) impulse- and time-based descent-to-ascent asymmetry indexes, (e) peak normalised RFD, (f) peak hip, knee and ankle flexion angle, (g) peak eccentric and concentric hip, knee and ankle angular velocities, (h) peak and mean eccentric and concentric EMG activities during CMJ trials. Significance was accepted at $p < 0.05$ for all tests.

5.3.8 Reliability

Reliability for all measures was determined during the pre-intervention vertical jumps from the EB and FWR warm-up conditions. No significant differences ($p > 0.05$) were detected in any measure and high intraclass correlation coefficients (ICCs) calculated for jump height (0.95), peak power (0.98), peak eccentric kinetic energy (0.99), impulse- (0.96) and time-based (0.91) asymmetry indexes, peak RFD to 50 ms (0.92), peak hip, knee and ankle flexion angle (0.67-0.96), and peak angular velocities ranged for hip (0.76-0.85), knee (0.95-0.95) and ankle (0.79-0.85), respectively. ICCs for the EMG data ranged for VL (0.73-0.89), for VM (0.85-0.92) and for Glut (0.85-0.92), respectively. Coefficients of variation (CoV) expressed as a percentage of the mean were also calculated for jump height (8.0%), peak power (6.2%), peak eccentric kinetic energy (8.5%), impulse- (4.9%) and time-based (14.6%) asymmetry indexes, K_{vert} (8.7%), peak RFD to 50 ms (12.5%), peak hip, knee and ankle flexion angle (3.8-7.6%), peak angular velocities for hip (5.0-5.6%), knee (3.4-5.2%), and ankle (6.3%-14.8%) . CoVs for EMG data were also calculated for VL (9.0-14.3%), VM (11.3-14.1%), and Glut (14.9-22%).

5.4 **Results**

In FWR, no significant changes ($p > 0.05$) were found in jump height (range = 3.0-4.9%) at any time point compared with pre-intervention data. Also, no significant changes ($p > 0.05$) were observed in peak power (0.1-3.6%), peak eccentric kinetic energy (0.5-4.9%), impulse- (0.6-2.0%) and time-based (4.5-14.8%) asymmetry indexes K_{vert} (3.1-5.8%) or peak normalised RFD (3.1-11.8%) at any time point (Table 5.2). No changes ($p > 0.05$) were detected in peak eccentric hip (0.5-2.6%), knee (0.5-2.6%), ankle (2.2-9.0%) or concentric hip (1.2-3.7%), knee (0.5-1.7%), ankle (1.4-4.7%) angular velocities, or peak hip (1.5-3.4°), knee (0.1-1.7°), ankle (0.1-0.6°) flexion angle (Table 5.3). Furthermore, no changes in peak or mean eccentric EMG eccentric activity ($p > 0.05$) in VL (peak = 2.4-7.2%; mean = 0.7-7.3%), VM (peak = 0.6-8.3%; mean = 8.9-10.9%), Glut (peak = 0.9-8.7%; mean = 2.3-10.7%) or concentric EMG in VL (peak = 0.4-9.4%; mean = 2.2-7.0%), VM (peak = 0.5-7.1%; mean = 1.2-9.5%) or Glut (peak = 1.3-10.4%; mean = 2.1-8.3%) were detected (Table 5.4).

Table 5.2. Kinetic measures of vertical jump performance across all time points following the free-weight and elastic band resistance warm-up conditions (values are reported as mean ± SE; *$p < 0.05$ compared to pre-intervention and FWR condition).

Measure	Condition	Pre	30 s	4 min	8 min	12 min
Peak Power (W)	FWR	49.3 ± 1.9	50.3 ± 1.5	50.8 ± 1.7	49.2 ± 2.2	50.3 ± 1.7
	EB	49.0 ± 1.7	51.3 ± 1.8*	51.8 ± 1.6*	51.0 ± 1.7*	51.2 ± 1.7*
Peak Eccentric Kinetic Energy (J)	FWR	87.4 ± 7.7	95.8 ± 9.0	90.8 ± 9.4	90.3 ± 7.7	88.0 ± 9.0
	EB	94.3 ± 8.0	93.6 ± 7.3	87.9 ± 7.2	88.8 ± 6.9	82.4 ± 5.9
Impulse asymmetry index (N·s)	FWR	2.9 ± 0.1	2.8 ± 0.1	2.9 ± 0.1	2.9 ± 0.1	2.9 ± 0.1
	EB	2.8 ± 0.1	2.9 ± 0.1	2.9 ± 0.1	2.9 ± 0.1	2.9 ± 0.1
Time asymmetry index (ms)	FWR	1.5 ± 0.1	1.4 ± 0.2	1.5 ± 0.2	1.3 ± 0.2	1.2 ± 0.2
	EB	1.4 ± 0.2	1.5 ± 0.2	1.1 ± 0.2	1.4 ± 0.2	1.2 ± 0.2
K_{vert} ($N \cdot m^{-1} \cdot kg^{-1}$)	FWR	70.8 ± 6.0	72.6 ± 3.8	70.5 ± 3.6	69.0 ± 3.7	72.0 ± 3.8
	EB	69.9 ± 5.0	73.3 ± 3.9	73.5 ± 4.5	74.6 ± 3.7	74.4 ± 4.5
Peak normalised RFD ($N \cdot s^{-1}$)	FWR	134.2 ± 11.3	147.1 ± 12.2	132.5 ± 10.8	141.8 ± 13.5	118.2 ± 7.5
	EB	126.1 ± 6.7	149.8 ± 12.8*	143.2 ± 11.7*	149.2 ± 9.0*	147.7 ± 13.7*

Pre = pre-intervention; FWR = free-weight resistance; EB = elastic bands; K_{vert} = vertical stiffness; RFD = rate of force development.

In EB, significant increases ($p < 0.05$) in CMJ height were detected at 30 s (5.9 ± 1.2%), 4 min (5.6 ± 1.8%), 8 min (6.5 ± 2.6%) and 12 min (5.3 ± 2.5%) time points compared with pre-intervention data (Figure 5.2). Significant increases ($p < 0.05$) were also observed in peak power at 30 s (4.7 ± 1.2%), 4 min (5.9 ± 1.3%), 8 min (4.4 ± 1.7%) and 12 min (4.8 ± 1.7%) time points compared to pre-intervention data. These changes in CMJ height and power were also statistically different to FWR ($p < 0.05$). Similarly, significant increases ($p < 0.05$) were found in peak normalised RFD at 30 s (18.9 ± 7.8%), 4 min (12.9 ± 5.9%), 8 min (19.1 ± 5.0%) and 12 min (16.0 ± 8.1%) compared to pre-intervention data. However, no significant change ($p > 0.05$) in peak eccentric kinetic energy (0.4-5.2%) or impulse- (1.4-4.6%) or time-based (7.4-13.0%) asymmetry indexes, K_{vert} (6.6-8.9%) were found following the VR warm-up condition at any time point (Table 5.2).

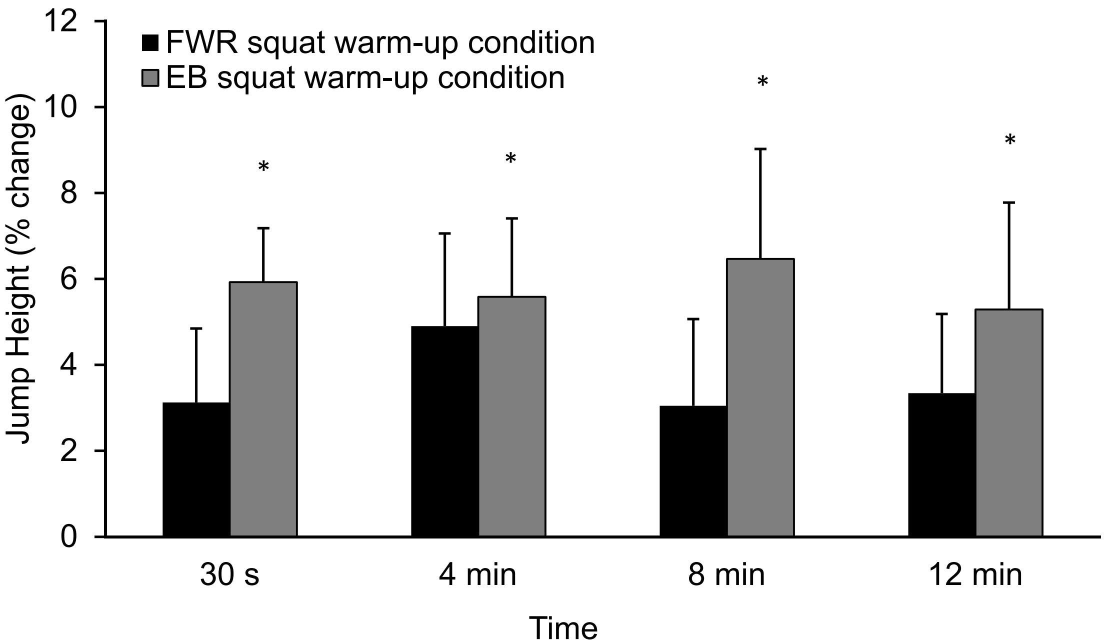

Figure 5.2. Percentage (%) change of the countermovement vertical jump height following free-weight resistance (FWR) and elastic band (EB) warm-up squat conditions. *Significant increases (5.3-6.5%; $p < 0.05$) in vertical jump performance were achieved across all time points following the EB warm-up condition compared to pre-intervention and the FWR warm-up condition.

Table 5.3. Kinematic measures of vertical jump performance across all time points following the free-weight and elastic band warm-up conditions (values are reported as mean ± SE; *$p < 0.05$ compared to pre-intervention).

Measure	Mode	Condition	Pre	30 s	4 min	8 min	12 min
Peak hip angular velocity (°·s^{-1})	ECC	FWR	301.1 ± 9.5	302.2 ± 10.0	294.4 ± 9.8	291.4 ± 6.9	292.8 ± 9.2
		EB	298.2 ± 7.1	305.2 ± 8.3	300.2 ± 8.3	302.6 ± 8.8	297.3 ± 8.7
	CON	FWR	584.6 ± 15.6	605.4 ± 18.8	591.9 ± 20.2	575.7 ± 20.7	576.2 ± 15.8
		EB	572.2 ± 17.1	591.9 ± 20.2	593.0 ± 22.1	588.2 ± 19.3	580.8 ± 21.7
Peak knee angular velocity (°·s^{-1})	ECC	FWR	343.2 ± 13.6	341.0 ± 11.4	332.6 ± 11.9	343.8 ± 13.7	340.5 ± 14.3
		EB	352.1 ± 14.3	364.9 ± 15.7	353.5 ± 13.9	363.0 ± 15.0	347.5 ± 16.6
	CON	FWR	956.4 ± 23.6	971.6 ± 24.6	969.3 ± 26.7	939.6 ± 27.9	959.6 ± 25.1
		EB	937.0 ± 23.8	966.0 ± 28.8*	975.7 ± 29.7*	966.9 ± 26.2*	964.2 ± 24.5*
Peak ankle angular velocity (°·s^{-1})	ECC	FWR	108.1 ± 10.0	117.6 ± 12.0	109.7 ± 12.2	112.0 ± 10.9	114.4 ± 10.8
		EB	121.1 ± 12.8	118.7 ± 9.8	120.3 ± 9.0	112.8 ± 7.1	104.5 ± 5.0
	CON	FWR	745.4 ± 23.4	733.7 ± 25.5	728.2 ± 18.9	707.9 ± 25.3	721.5 ± 27.0
		EB	717.9 ± 21.3	723.6 ± 22.2	731.7 ± 23.6	735.1 ± 28.1	739.4 ± 19.1
Peak hip flexion angle (°)		FWR	79.3 ± 2.0	82.7 ± 2.1	81.8 ± 1.7	82.1 ± 2.4	81.8 ± 2.2
		EB	81.5 ± 1.9	83.2 ± 1.4	83.3 ± 1.9	83.4 ± 1.5	82.8 ± 1.5
Peak knee flexion angle (°)		FWR	71.7 ± 2.9	73.3 ± 3.0	71.1 ± 2.8	72.0 ± 2.7	71.9 ± 3.3
		EB	71.8 ± 3.5	72.6 ± 3.4	74.2 ± 3.3	75.2 ± 2.8	75.4 ± 3.5
Peak ankle flexion angle (°)		FWR	32.7 ± 1.6	32.6 ± 1.4	32.7 ± 1.4	33.0 ± 1.4	33.2 ± 1.4
		EB	33.8 ± 1.6	34.7 ± 1.6	34.8 ± 1.6	35.2 ± 1.6	34.8 ± 1.8

Pre = pre-intervention; FWR = free-weight resistance; EB = elastic band; ECC = eccentric; CON = concentric.

No significant change in peak hip (1.3-1.9°), knee (0.9-4.1°), ankle (0.9-1.47°) flexion angles were observed in EB at any time point. Similarly, no changes ($p > 0.05$) were found at any time point (Table 5.3) in peak eccentric hip (0.2-2.5%), knee (0.04-2.6%), ankle (0.1-6.7%) or concentric hip (1.5-3.6%) or ankle (1.1-3.5%) angular velocities or peak or mean eccentric EMG amplitudes for VL (peak = 0.5-3.1%, mean = 4.9-9.2%), VM (peak = 2.1-9.6%, mean = 4.9-6.7%) or Glut (peak = 2.2-4.6%, mean = 3.5-4.9%). However, a significant increase ($p < 0.05$) was found in peak concentric knee angular velocity at 30 s (3.1 ± 1.4%), 4 min (4.1 ± 1.7%), 8 min (3.2 ± 1.0%) and 12 min (3.1 ± 1.5%) and mean concentric VL EMG activity at 30 s (28.1 ± 10.5%), 4 min (31.5 ± 11.0%), 8 min (33.4 ± 15.9%) and 12 min (27.5 ± 14.5%). No changes ($p > 0.05$) in mean concentric VM (3.7-12.7%) or Glut (0.3-7.0%) EMG or peak concentric VL (0.6-4.5%), VM (0.3-9.2%) or Glut (0.2-7.1%) EMG were observed at any time point (Table 5.4).

Significant ($p < 0.05$) correlations were observed between the change in CMJ height (pre-intervention to 8 min post-intervention, i.e. where the greatest mean increase in jump height occurred) and changes in peak power (r = 0.82) during EB. No significant correlations ($p > 0.05$) were found between change in CMJ height and changes in peak normalised RFD (r = 0.27), peak knee angular velocity (r = -0.21), mean concentric VL EMG (r = 0.17) or peak eccentric kinetic energy (r = 0.32).

Table 5.4. Normalised mean and peak vastus lateralis (VL), vastus medialis (VM), gluteus maximum (Glut) electromyogram (EMG) amplitudes maximum voluntary contraction (%MVC) measured during vertical jumps across all time points following free-weight resistance (FWR) and elastic band (EB) warm-up squat conditions (values are reported as mean ± SE; *p < 0.05 compared to pre-intervention (Pre) and FWR condition).

Measure	Mode	Condition	Pre	30 s	4 min	8 min	12 min
Mean VL EMG (%MVC)	ECC	FWR	31.9 ± 2.1	31.5 ± 3.4	30.5 ± 3.0	30.0 ± 2.0	29.5 ±2.9
		EB	28.5 ± 2.1	30.2 ± 2.2	31.9 ± 2.3	31.5 ± 1.8	32.0 ± 2.2
	CON	FWR	82.4 ± 6.1	83.9 ± 6.4	78.4 ± 8.5	72.5 ± 4.6	73.4 ± 6.0
		EB	85.4 ± 7.8	108.2 ± 13.3*	110.2 ± 12.2*	107.5 ± 10.5*	102.6 ± 9.4*
Peak VL EMG (%MVC)	ECC	FWR	89.2 ± 6.7	94.7 ± 8.0	90.4 ± 6.9	85.0 ± 6.7	84.0 ± 6.0
		EB	91.6 ± 4.9	95.0 ± 8.0	94.2 ± 6.1	90.7 ± 4.7	90.6 ± 5.9
	CON	FWR	112.4 ± 8.0	123.7 ± 9.6	116.9 ± 7.1	112.8 ± 6.7	112.2 ± 6.3
		EB	114.3 ± 5.8	115.8 ± 10.2	117.4 ± 7.6	111.2 ± 6.6	108.1 ± 6.6
Mean VM EMG (%MVC)	ECC	FWR	36.3 ± 2.7	33.9 ± 4.1	32.6 ± 3.3	32.2 ± 2.6	33.0 ± 3.4
		EB	37.9 ± 3.8	40.2 ± 3.8	38.1 ± 3.3	39.9 ± 2.9	38.1 ± 3.3
	CON	FWR	94.9 ± 5.0	95.3 ± 10.9	85.1 ± 8.4	85.1 ± 6.4	87.7 ± 7.3
		EB	90.2 ± 9.2	96.0 ± 7.9	94.7 ± 7.5	88.8 ± 5.9	87.2 ± 6.2

Peak VM EMG (%MVC)	ECC	FWR	98.6 ± 7.9	96.9 ± 7.4	92.9 ± 6.7	88.0 ± 6.1	89.0 ± 6.1
		EB	111.3 ± 9.5	114.4 ± 11.2	108.1 ± 10.2	104.7 ± 8.1	97.3 ± 6.7
	CON	FWR	132.0 ± 12.2	128.7 ± 11.5	120.5 ± 9.5	118.2 ± 8.6	118.8 ± 9.1
		EB	150.6 ± 12.8	149.0 ± 14.4	143.4 ± 12.5	140.8 ± 11.8	127.7 ± 8.9
Mean Glut EMG (%MVC)	ECC	FWR	20.0 ± 1.9	22.4 ± 2.8	21.3 ± 2.3	19.7 ± 1.7	21.2 ± 1.9
		EB	21.7 ± 2.5	23.2 ± 2.6	22.5 ± 2.4	22.5 ± 2.2	21.7 ± 2.0
	CON	FWR	81.1 ± 10.2	84.4 ± 14.8	83.9 ± 12.1	78.6 ± 8.7	75.1 ± 9.2
		EB	84.4 ± 14.0	87.1 ± 14.2	78.3 ± 10.1	77.4 ± 8.5	76.8 ± 9.8
Peak Glut EMG (%MVC)	ECC	FWR	72.6 ± 7.0	78.3 ± 7.5	76.4 ± 7.2	74.6 ± 7.1	71.7 ± 6.9
		EB	79.1 ± 9.4	82.0 ± 9.5	76.7 ± 8.9	74.7 ± 5.5	71.7 ± 7.3
	CON	FWR	103.4 ± 10.8	111.3 ± 14.0	112.7 ± 12.5	103.3 ± 12.1	103.1 ± 9.6
		EB	115.9 ± 9.9	118.5 ± 10.7	110.8 ± 11.7	100.3 ± 7.9	99.7 ± 7.6

VL = vastus lateralis; VM = vastus medialis; Glut = gluteus maximum; EMG = electromyogram; MVC = maximum voluntary contraction; FWR = free-weight resistance; EB = elastic bands; ECC = eccentric; CON = concentric.

5.5 Discussion

The primary aim of the present study was to assess the magnitude and time-course of changes in countermovement vertical jump (CMJ) performance after traditional free-weight (FWR) and elastic band (EB) resistance squat exercises were performed following a comprehensive task-specific, warm-up routine. The first hypothesis can be partially rejected as the lack of change in any measure following the FWR condition suggests that no additional benefit (i.e. PAP/PAPE effect) was derived from the inclusion of intense loading from FWR exercise (i.e. the conditioning contractions), contrary to the improvement in jump height following the use of elastic bands. This finding contrasts those of previous studies where the performance of heavy squat lifts increased CMJ height (Lowery et al., 2012; Sotiropoulos et al., 2010), and other literature reporting an increase in tasks including sprint running performance (Chatzopoulos et al., 2007). However, those previous studies either did not report the use of other warm-up activities or only included a light cardiovascular warm-up rather than a more comprehensive task-specific warm-up including progressively intense task-specific muscular contractions. The current finding of a lack of effect of a free-weight back squat conditioning contraction after a comprehensive task-specific warm-up (Figure 5.2) is, however, consistent with a previous report of an absence of change in vertical jump performance when dynamic warm-up exercises were employed prior to a set of back squats (Witmer et al., 2010). These data are indicative that a lack of a comprehensive task-specific warm-up may enable further augmentation of performance after squats were performed, but may be of limited relevance to athletes, strength trainers and recreational exercisers who would customarily perform a thorough warm-up. That is, the high-intensity conditioning contractions might only increase performance when the warm-up would otherwise be insufficient to promote maximal performance. Collectively, these findings indicate that the previously reported 'potentiating' effects of heavy free-weight back squat exercise on subsequent CMJ performance (Gourgoulis et al., 2003; Lowery et al., 2012) may be a consequence of study design, where the limited use of warm-up protocols provided an opportunity for further performance augmentation after the baseline tests. Furthermore, inconsistencies in PAP responses (Gourgoulis et al. 2003; Witmer et al., 2010; Young et al. 1998) may depend on fatigue-potentiation or perseveration-potentiation interactions and their influence on subsequent performance, therefore new strategies for designing warm-up protocols and effective recovery periods following conditioning contractions are vital in order to induce a potentiation effect.

Despite FWR squat lifts having no effect on CMJ performance, a significant increase in jump height was achieved following the EB conditioning contractions at all time points (30 s, 4 min, 8 min and 12 min; Figure 5.2), which suggests a prolonged ‘potentiating’ effect was evoked, i.e. postactivation performance enhancement; PAPE (Kilduff et al., 2007). Thus, the second experimental hypothesis, that jump height would be further increased following the EB intervention, can be accepted. These data are consistent with previous studies (Buttifant and Hrysomallis, 2015; Seitz et al., 2016b) in which box squats incorporating elastic band resistance acutely increased power output during subsequent CMJ tasks. However, in the present study it was shown that this effect can be evoked even after completion of a comprehensive, task-specific warm-up, which was not included in previous studies. Although each maximal CMJ may possibly potentiate the next one, no significant improvement occurred in the FWR condition, therefore these jumps were unlikely to explain the increased performance in VR. Previous studies showed that only seconds or a few minutes are needed to recover from a short bout of maximal-effort exercise, e.g. less than 1 min for recovery from a maximal squat (Hitchcock, 1989) or bench press lifts (Matuszak et al., 2003), thus it is unlikely that fatigue is a factor influencing the findings of the present study as a significant increase was observed across all time points. The use of elastic bands reduces the effective load near the “sticking point” in the early concentric phase of the squat lift, but then allows for greater loading later in the lift as the effective mechanical advantage is increased (Anderson et al., 2008). The ability for muscles to operate closer to their maximum force capacity through a greater proportion of the lift may therefore enhance subsequent muscle force output and elicit a greater dynamic muscle performance (i.e. increase in CMJ height), even when a comprehensive task-specific warm-up is already completed. Collectively, these data indicate that the use of elastic bands, which alter the loading strategy during the lift, provides a more effective warm-up than either warm-up alone or warm-up that also includes traditional free-weight resistance exercises.

In the present study significant changes in force production (peak power and RFD; Table 5.2) at all time points in the EB warm-up condition were consistent with the changes in jump height. However, peak hip, knee and ankle, flexion angle, peak eccentric kinetic energy, and the impulse- and time-based asymmetry indexes remained unchanged and no change was detected in K_{vert} (Tables 5.2 and 5.3), which is consistent with previous research (Boullosa et al., 2013). Accordingly, changes in jump kinematics cannot explain the changes in force production or jump height. The third hypothesis, that both kinetic and kinematic parameters would be altered by elastic band-resisted squat lifts, can therefore only be partially accepted. The changes in peak jump power were significantly correlated with the changes in CMJ height, however a poor relationship was identified between changes in RFD and CMJ height. This latter finding is consistent with a previous report (Wilson et al., 1995) in which stretch-shortening cycle test performances were not statistically related to RFD measured during the test. The poor relationship may be partly explained by the participants being well strength-trained yet relatively untrained in explosive power-based exercises, and thus unable to rapidly reach peak force (Moir et al., 2005). However, further research on power-trained athletes is needed to fully elucidate the importance of training status.

A number of mechanisms relating to stretch-shorten cycle efficiency may have contributed to the increased jump height, including a more rapid muscle stretch resulting from force potentiation (Rassier & Herzog, 2004), greater elastic energy storage in the muscle (Finni et al., 2003), an increased time of muscle activation (Bobbert et al., 1996; Finni et al., 2003), an augmented pre-load effect (Finni et al., 2001), force and stiffness augmentation from stretch reflexes (Bobbert et al., 1996), and changes in relative contributions of muscle and tendon allowing the muscle to operate at lower shortening speeds and over shorter distances (Hill, 1938). Whilst it is difficult to assess the effects of each, the peak eccentric kinetic energy and both impulse- and time-based asymmetry indexes remained unchanged after EB, indicating that the total energy available for storage in elastic structures (eccentric kinetic energy), the kinematic pattern adopted to make use of it (asymmetry indexes; Cavagna, 1977), as well as the time for force application and likely contribution of stretch reflexes, were also unchanged. Nonetheless, increases in peak power and concentric knee angular velocity were observed.

A more plausible explanation for the increase in force production, and thus jump height, may be found in the increased knee extensor muscle activity detected in the concentric phase (VL EMG increased 27.5-33.4% across time points; Table 5.4). Thus, the fourth hypothesis, that extensor muscle activity would be increased, can be accepted. The greater increase in EMG activity in VL than VM or Glut is consistent with previous reports of greater VL EMG in the concentric phase of a CMJ after both low- and moderate-intensity squat warm-ups (Sotiropoulos et al., 2010), and would likely have resulted from an increased motor unit firing frequency (Heckman & Enoka, 2012). In fact, Nikolaidou et al. (2017) found that a greater jump height was achieved during CMJ compared to squat jump which was consistent with an increased VL activation during the push off phase. Increased phosphorylation of the myosin light chain leading to an increase in myofilament Ca^{2+} sensitivity and force output (i.e. classic PAP) may have contributed to the increase in CMJ, although it resolves completely within about 5 min (MacIntosh et al., 2012a), thus its effect at 4 – 12 min would have been negligible. Although other mechanisms such as increases in muscle temperature (not examined in the present study) may have contributed to the increase in jump height it remains likely that the change in muscle activation was the major factor influencing the improvement in CMJ performance. The increased muscle activity and consequent increase in peak power output in the concentric phase would have allowed a greater jump height without changes in kinematics or stretch-shorten cycle efficiency (i.e. without changes in eccentric knee angular velocity, eccentric kinetic energy, impulse- and time-based asymmetry indexes or K_{vert}). The most likely explanation for the finding is that the variation in muscle force requirements imposed by the use of elastic band resistance influenced muscle recruitment patterns and ultimately increased concentric force output (Israetel et al., 2010). The current findings are suggestive that manipulation of loading strategies during warm-up exercises might beneficially alter muscle recruitment amplitude or timing and result in greater performances than achieved through traditional high-intensity, task-specific warm-ups alone; this hypothesis should be explicitly examined in future studies. It is important to note that it was not possible to measure muscle temperatures in the current study, however muscle temperature would likely have increased substantially during the comprehensive task-specific warm-up so temperature may have remained constant (i.e. in an optimum zone) for a longer time, and any further small increase in temperature from the conditioning contractions would have been similar between conditions. This may have allowed the improved muscle activation to result in a greater jump performance and for the increased activation to persist for a longer time. However, muscle temperature would likely have increased substantially during the comprehensive task-specific warm-up so temperature may have remained constant (i.e. in an optimum zone) for a longer time, and any further small increase in temperature from the conditioning contractions would have been similar between conditions. This may have allowed the improved muscle activation to result in a greater jump performance and for the increased activation to persist for a longer time. Thus, although it remains to be explicitly examined in future, it can be considered unlikely that muscle temperature differences could explain the between-condition differences in jump performance.

In summary, the completion of brief, high-load free-weight squat exercise following a comprehensive task-specific warm-up failed to alter CMJ height, force/power production or movement pattern. These findings are suggestive that the previously-observed 'potentiating' effect of squat exercise may be a consequence of limited warm-up. The beneficial effect of a free-weight squat strategy to potentiate the system may therefore be minimal in athletic populations that typically perform high-intensity, task-specific warm-up routines prior to maximal exercise tasks. However, the use of elastic band resistance during these squats resulted in significant increases in jump height, peak power, peak concentric knee angular velocity and peak RFD, as well as increased VL EMG activity in the concentric (propulsive) phase of the jump, which did not return to baseline after 12 min despite a comprehensive task-specific warm-up being completed. The results suggest that the inclusion of tasks in which force-time parameters differ from the outcome task (CMJ in the current study) might evoke positive acute adaptations in addition to those achieved through warm-up alone. Further research is required to determine whether similar effects are observed following different warm-up strategies and in different athletic tasks, as well as in other populations.

Chapter 6

6 General Discussion

The present research compared the acute effects of two forms of VR (i.e. chains [CLR] and elastic bands [EB]) with free-weight resistance (FWR) during a warm-up on subsequent free-weight 1-RM back squat performance as well as the impact of a comprehensive warm-up prior to using EB and FWR on counter movement jump (CMJ) performance. These are the first data to describe the impact of VR exercise on subsequent free-weight back squat performance, and it was found that the use of both CLR and EB as part of a warm-up elicited a significant improvement on subsequent free-weight back squat performance compared to FWR exercise alone. The CLR potentiating effects occurred without changes in knee flexion angle or eccentric and concentric knee angular velocities or knee extensor muscle activity, thus a real 1-RM increase was achieved as the mechanics of the lift were not altered. Similarly, using EB as a conditioning contraction also significantly increased 1-RM without detectable changes in knee extensor muscle activity or knee flexion angle, although eccentric and concentric velocities were reduced. The eccentric velocity reduction may have resulted from the need to minimise the momentum of the lift so that the impulse provided was sufficient to decelerate and then re-accelerate, although the eccentric velocity reduction is likely a result of the greater loading (Rahmani et al., 2001). Nonetheless, participants were still able to squat at the same knee angle, and thus complete a full repetition with the mechanical output and force production being enhanced, which shows a true enhancement of the subsequent lifting performance. The results are indicative of a potentiating effect of the VR warm-up that may benefit athletes in tasks where high-level of strength is required. Despite the comparable findings observed in the CLR and EB warm-ups, importantly elastic bands are more practical to use compared to chains, are relatively inexpensive, easily implemented and transportable, and thus may provide a cheaper and more practical tool for use by athletic or clinical populations. Regardless, the key message for strength and conditioning coaches is that the use of VR repetitions can be used as a training modality to improve performance and thus its use in strength-based athletes should be encouraged.

Whilst Studies 1 and 2 examined whether VR in warm-up exercises might affect 1-RM load, it was also a purpose of the research to determine whether the addition of VR squat lifts to a full, comprehensive warm-up could enhance subsequent vertical jump performance. A common limitation in the literature examining the effects of conditioning activities on performances in 'high power' tasks (e.g. sprint running, sprint cycling, vertical jumping) is that brief, or no warm-up, protocols were often implemented prior to a conditioning contraction that subsequently resulted in an enhancement in performance (Duthie et al., 2002; Hamada et al., 2000). Thus, the practical application of the research findings have been unclear. Previous studies that reported increases in CMJ height after the performance of free-weight heavy squat lifts, for example, often did not report the use of other warm-up activities or only included brief cardiovascular warm-up (Lowery et al., 2012; Sotiropoulos et al., 2010) rather than a comprehensive task-specific warm-up. In contrast to these previous studies, when a comprehensive task-specific warm-up was included in Study 3 of the present thesis, CMJ height was not improved following the FWR condition, suggesting that the previously reported additional benefits (PAPE effect) derived from the inclusion of intense loading from FWR were removed following a comprehensive warm-up. However, the current findings revealed a significant PAPE effect even after a comprehensive warm-up was completed, as following the EB condition an increased CMJ height (~6%) was achieved when 85% 1-RM total load of which 35% was imposed by elastic resistance to alter the magnitude of force applied through the lifting (concentric) phase. In Studies 1 & 2, changes in torque and force production and muscle activities around joints and in muscles other than the knee flexors did not allow a broad examination of the effects of VR on whole lower-limb function. However, these limitations were overcome in Study 3 where knee and hip extensor EMG activity was measured. The results showed an increase in VL EMG only, which occurred in the concentric (propulsion) phase of the CMJ and were associated with increases in knee extension angular velocity and jump power output. Together, these results suggest that increases in CMJ height resulted from a greater activation of the quadriceps and increase in knee angular velocity during the concentric phase of the CMJ after the VR (elastic band) squat warm-up. These data are consistent with previous studies showing an increase in VL EMG activity and CMJ performance (Nikolaidou et al., 2017; Sotiropoulos et al., 2010). Collectively, these findings highlight current limitations and possible misconceptions in the literature regarding PAPE effects of high-intensity FWR exercises and the beneficial effects of utilising variable resistance exercises in a warm-up routine to further augment performance.

The lack of PAPE effect induced by FWR squats following the comprehensive warm-up suggests that the task-specific warm-up was probably not sufficient to maximally influence performance, or at least did not allow the squats to further enhance performance. Importantly, the previously reported potentiating effects of high-intensity free-weight muscular contractions on CMJ performance (Chiu et al., 2003; Jensen & Ebben, 2003), may possibly be due to limited or no, warm-up being done by the study participants, which has important implications for the external validity of those findings. The findings in the present thesis can inform not only the need to use VR to further improve performance under some conditions, but also that current recommendations for intense contractions using FWR alone to further enhance performance may be questionable. These data indicate that EB may be an effective warm-up strategy offering a prolonged potentiating effect compared with either warm-up alone or warm-up that also includes traditional FWR exercises.

Recent studies that used a previously performed ‘task-specific’ warm-up found increases in physical performance (Feros et al., 2012; Hancock et al., 2015; Munro et al., 2017; Kontou et al., 2018), thus a relevant PAPE effect was observed although no evidence was provided to link such increases to PAP. It was unclear whether the testing occurred within a reasonable time following the warm-up and a description of the standard warm-up was not provided (Feros et al., 2012; Hancock et al., 2015; Munro et al., 2017; Kontou et al., 2018). However, the conditioning contractions performed in other studies did not enhance athletic performance following a warm-up (Samarian et al., 2015; Marshall et al., 2019); the causes for the equivocal findings in the literature remain unclear. Further studies are therefore required to determine whether the duration of the warm-up and the exercise intensity are additional factors that should be considered to ensure that an appropriate or a full warm-up is performed prior to a conditioning contraction.

The series of present studies may provide an insight into the possible mechanisms responsible for performance enhancement following variable resistance exercises as the different temporal profiles differ from other PAP studies where twitches were evoked. The enhancement of 1-RM load observed in Studies 1 and 2 occurred 5 min after the conditioning contractions, which is consistent with previous studies reporting a maximal effect within 4-12 min, a timeframe normally associated with neural but not muscular changes (Lowery et al., 2012; Seitz et al., 2015). Therefore, increased phosphorylation of regulatory light chains is an unlikely mechanism influencing the performance enhancement instead changes in muscle temperature and muscle water are more likely factors since increased muscle temperature may augment subsequent muscle force and power production/velocity (Bergh & Ekblom, 1979), and muscle water can possibly increase muscle fibre force and shortening velocity (Edman & Anderson, 1968) following high-intensity exercise. However, the performance enhancement in the CMJ height (Study 3) was achieved at all time points (30 s, 4 min, 8 min and 12 min), with concomitant increase in knee extensor (VL) EMG activity during the concentric phase of the jump. The PAPE effect may be largely explained by increases in muscle activation detected at all time points although other mechanisms may have contributed to the performance enhancement. Previous studies showed that only seconds or a few minutes are needed to recover from a short bout of maximal-effort exercise (Hitchcock, 1989; Matuszak et al., 2003), therefore fatigue is an unlikely factor influencing the present findings as a significant increase was observed across all time points. This finding confirms that enhancement in muscular force production (PAPE) has a longer window of action than PAP, lasting seconds to several minutes. Therefore, other mechanisms such as increases in muscle temperature or intra-muscular fluid accumulation (Edman & Hwang, 1977; Sargeant, 1987) may have also contributed to the enhancement in performance, although this possibility can't be tested using the current data. There is little evidence of a strong fibre-type dependence since muscle temperature increases function in both Type I and Type II fibres, although increases in intramuscular fluid tend to show a clear fibre-type dependence as it is found to be greater in individuals with higher Type II fibres (Blazevich & Babault, 2019; Fink et al., 1986). Regardless of the mechanism, while PAPE can be affected by PAP in the short time period following a conditioning contraction, in the present thesis PAPE was observed at time-points where PAP was expected to have dissipated; thus further research is required to fully determine the likely mechanisms affecting PAPE.

Considering the popularity of VR, the somewhat limited and equivocal scientific evidence (Baker, 2008; Baker & Newton, 2009; Cronin et al., 2003; Ebben & Jensen, 2000; Israetel et al., 2010; Wallace et al, 2006) clearly demonstrates the need for continued study, as using such methods of enabling VR to alter loading patterns may be a useful training tool for enhancing athletic performance. Specific to the present thesis, equivocal data exist describing the influence of VR on squat lift kinematics (Ebben & Jensen, 2002; Israetel et al., 2010), and while activities designed to evoke a PAPE response have been consistently shown to enhance explosive activities of different types, the presence of PAPE has not always been observed (Chiu et al. 2003; Jensen & Ebben, 2003; Young et al., 1998). Ultimately, various methodological issues limit the external validity of previous research findings and may explain the disparate findings in the literature. For example, the effects of exercise type, including bench press, clean, back squat (Anderson et al., 2008; Baker & Newton, 2009; McMaster et al., 2010; Wallace et al., 2006), the selected magnitude of VR (10%, Ebben & Jensen [2002]; 15% and 30%, Stevenson et al. [2010]; 35%, Wallace et al. [2006]), exercise volume (e.g. sets, repetition and rest intervals) and participant characteristics (i.e. experienced vs novice lifters [Chiu et al., 2003; Young et al., 1998]) are factors that appear to influence the PAPE response, and likely explain the equivocal findings.

In summary, the key findings reported in the present thesis were that 1) practice of the squat lift under conditions of VR (either CLR or EB) increased subsequent free-weight 1-RM performance compared to performing FWR alone, and that 2) CMJ height was improved after an EB squat exercise conditioning task even after a comprehensive task-specific warm-up was performed, 3) the increase in CMJ height was observed at all time points from 30 s to 12 min, and 4) the lack of change in any measure following the FWR condition suggests that no additional benefit (PAPE effect) was derived from the inclusion of intense FWR loading following a comprehensive warm-up. As the time course of potentiation effects observed in all three studies differed to the previously-reported time course of PAP (measured as the muscle twitch force response), it is likely that the PAPE effect was relatively unaffected by mechanisms that underpin the PAP effect, although more data are required to explicitly test this hypothesis. The use of VR as part of a warm-up can lead to prolonged acute improvements in performance and has obvious implications for coaches and specialists in sport sciences to enable athletes to more rapidly and efficiently achieve acute enhancements in performance compared to traditional FWR resistance training methods (Anderson et al., 2008, Wallace et al., 2006). VR incorporated into warm-up routines before training or competition by strength-trained individuals can clearly enhance function of the neuromuscular system and facilitate greater strength capacity even after a comprehensive warm-up is performed, providing the strength and conditioning practitioner greater flexibility in designing warm-up routines and exercise variety.

6.1 **Limitations and future directions**

Two methodological limitations of Studies 1 & 2 are that changes in torque and force production and muscle activities around joints and in muscles other than the knee flexors were not performed, which did not allow a broad examination of the effects of VR on whole lower-limb function. As a greater mechanical contribution is thought to come from the hip extensors, rather than the knee extensors, at greater loads during squatting (Flanagan & Salem, 2008), determining hip extensor EMG activity and the impact of VR on other joint complex kinematics, such as hip flexion and torso angle, would have potentially been valuable. Whilst a reflective marker was placed on the bar, no marker was placed on the anterior superior iliac spine because it was completely obscured at peak hip flexion angles in the squatting position in pilot testing; therefore, changes in torso angle associated with spinal or pelvic adjustments were not determined due to methodological restrictions. However, these limitations were overcome in Study 3 where knee and hip extensor EMG activity was measured during the vertical jump task. Whilst the knee joint complex and quadriceps activity were a primary focus in the present thesis, future studies should consider examining additional joints and muscle groups, particularly the contribution of primary extensor muscle groups at the hip needs to be more explicitly examined.

A limitation of the current literature examining the effects of conditioning activities on performances in ‘high power’ tasks (e.g. sprint running, sprint cycling, vertical jumping) is that brief, or no warm-up, protocols were often implemented prior to a conditioning activity that subsequently resulted in an enhancement in performance

(Duthie et al., 2002; Hamada et al., 2000). These study designs do not replicate current athletic activity and restrict the preparedness of the individual for maximal efforts. However, a comprehensive task-specific warm-up was included in the present thesis and dynamic performance was not enhanced following the FWR condition. This finding highlights the possible misconceptions in the literature regarding PAPE effects of high-intensity FWR exercises. However, following the EB condition a significant PAPE effect (even after a comprehensive warm-up) was observed, i.e. increased 1-RM squat and CMJ performances were achieved, highlighting the beneficial effects of utilising VR in a warm-up routine to further augment performance. Further research is required to determine whether similar effects are observed following different warm-up strategies and in different athletic tasks, as well as in other populations. Finally, a further limitation of the present thesis and the current literature is that several of the proposed mechanisms (i.e. myofilament light chain phosphorylation, muscle-tendon stiffness, muscle temperature, increase neural drive, muscle blood flow/water inflow) suggested to contribute to the increase in performance in dynamic tasks following a conditioning activity have not been directly examined following VR; thus whilst a PAPE effect is often observed, future research is required to fully elucidate the mechanisms underpinning PAPE.

7 References

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8 Appendices

8.1 Appendix 1: Participant information sheet (Study 1)

PARTICIPANT INFORMATION SHEET

About The Researcher:

My name is Minas Mina and I am a PhD student at Derby University undertaking collaborative research at the Division of Sport & Exercise School of Health at the University of Northampton. The marks awarded for this study will contribute towards my PhD. Dr Tony Kay at the University of Northampton, is supervising this study.

Title: Influence of chain-loaded variable resistance exercise on subsequent free-weight maximal back squat performance

Aim of Study: The purpose of the present study is to examine the acute effects of chain-loaded resistance (CLR) on a) subsequent free-weight 1-RM back squat performance; b) lifting mechanics and c) muscle activity, compared to free-weight resistance (FWR) alone.

What the study involves:

Agreeing to take part in this study will mean that you will be asked to attend a familiarisation session (approx. 1-hour in duration) prior to 3 separate assessment occasions (40 min each; 72h between them). Each participant will be present at the same time in all three trials.

Familiarisation: Height and weight will be recorded and 1 maximum repetition (1-RM) will be assessed. Participants will familiarise themselves in performing squat exercise with chain-loaded resistance with the correct technique.

Experimental conditions: Participants will perform a 5 min warm-up on a stationary bicycle. Infrared reflective markers were placed over the lateral malleolus, femoral epicondyle, and greater trochanter of the right lower limb to enable knee kinematics to be recorded. EMG bipolar surface electrodes will be placed along the longitudinal axis of the quadriceps (rectus femoris, vastus lateralis and vastus medialis). Measurements will be taken pre- and post-intervention.

Intervention: All participants will perform squat exercise either CLR in combination with free-weights or FWR alone. These will be randomised.

The information required:

You will be asked to give information by completing a questionnaire to gather data on each participant's training activity and their health history. Through the questionnaire participants must indicate no current lower extremity or other related injuries and no apparent limits in knee ROM.

What are the benefits of taking part?

By taking part in this study you will have the opportunity to be involved in a research study which can benefit athletes in different sports by incorporating chain resistance during a warm-up protocol. This method of training may potentiate the athletes' performance in the future.

What are the risks of taking part?

By taking part in this study you should be aware that there is a limited potential risk associated following weight lifting exercise, however, participants will have a certain level of fitness of 2-3 years weight lifting experience. Participants will be screened prior to accepting participation in the study by completing a health questionnaire and a familiarisation trial will be undertaken before testing. There are no known risks associated with equipment used in this study (i.e. electromyography "EMG", force plate and motion capture system) or from testing, although a small risk of muscle tendon injury always exists when maximal contractions are performed.

What will happen to the information?

Any personal and/or confidential information disclosed by the participant in this study will be treated as confidential and only handled by the individuals relevant to the performance of the study and the storing of information thereafter. Any personal and/or confidential information relating to health issues or otherwise will not be disclosed without the participants consent in any event. Where information concerning the participant is published his identity will remain anonymous throughout. Information collected in this study will be stored in the Biomechanics laboratory at Northampton University for 4 years from the date of collection and will be then destroyed.

Not sure about participating?

If you choose not to participate, you have the right to do so. Participants have the right to change their mind at any point of the research and are free to withdraw from the study at any time by communicating such intent to the Researcher prior to doing so.

Your valued input:

I can make my results available to you when I have finished my study by sending you a short summary. Please let me know if you would like me to do this.

Contact the Researcher:

If you have any questions about the research, you can contact myself or my supervisor as follows:

Minas Mina
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1 Devonshire Road
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Dr. Anthony Kay

Senior Lecturer in Sport & Exercise Biomechanics
The University of Northampton
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Tel: +44 (0) 1604 892577
Fax: +44 (0) 1604 720636

Who has checked this research?

The School of Health Ethics Committee has approved this study.

The University of Northampton's Combined Liability Insurance Policy provides indemnity for students of the institution carrying out research work (such as questionnaires and interviews) as part of their course.

8.2 Appendix 2: Participant information sheet (Study 2)

PARTICIPANT INFORMATION SHEET

About The Researcher:

My name is Minas Mina and I am a PhD student at Derby University undertaking collaborative research at the Division of Sport & Exercise School of Health at the University of Northampton. The marks awarded for this study will contribute towards my PhD. Dr Tony Kay at the University of Northampton, is supervising this study.

Title: Influence of elastic band variable resistance loading on subsequent free-weight maximal back squat performance.

Aim of Study: The purpose of the present study is to examine the acute effects of elastic band (EB) resistance on a) subsequent free-weight 1-RM back squat performance (i.e. maximal load); b) lifting mechanics and c) neuromuscular activity, compared to free-weight resistance (FWR) alone.

What the study involves:

Agreeing to take part in this study will mean that you will be asked to attend a familiarisation session (approx. 1-hour in duration) prior to 3 separate assessment occasions (40 min each; 72h between them). Each participant will be present at the same time in all three trials.

Familiarisation: Height and weight will be recorded and 1 maximum repetition (1-RM) will be assessed. Participants will familiarise themselves in performing squat exercise with elastic band resistance with the correct technique.

Experimental conditions: Participants will perform a 5 min warm-up on a stationary bicycle. Infrared reflective markers were placed over the lateral malleolus, femoral epicondyle, and greater trochanter of the right lower limb to enable knee kinematics to be recorded. EMG bipolar surface electrodes will be placed along the longitudinal axis of the quadriceps (rectus femoris, vastus lateralis and vastus medialis). Measurements will be taken pre- and post-intervention.

Intervention: All participants will perform squat exercise either with elastic band (EB) resistance in combination with free weighs or FWR alone. These will be randomised.

<u>The information required</u>:

You will be asked to give information by completing a questionnaire to gather data on each participant's training activity and their health history. Through the questionnaire participants must indicate no current lower extremity or other related injuries and no apparent limits in knee ROM.

<u>What are the benefits of taking part?</u>

By taking part in this study you will have the opportunity to be involved in a research study which can benefit athletes in different sports by incorporating chain resistance during a warm-up protocol. This method of training may potentiate the athletes' performance in the future.

<u>What are the risks of taking part?</u>

By taking part in this study you should be aware that there is a limited potential risk associated following weight lifting exercise, however, participants will have a certain level of fitness of 2-3 years weight lifting experience. Participants will be screened prior to accepting participation in the study by completing a health questionnaire and a familiarisation trial will be undertaken before testing. There are no known risks associated with equipment used in this study (i.e. electromyography "EMG", force plate and motion capture system) or from testing, although a small risk of muscle tendon injury always exists when maximal contractions are performed.

What will happen to the information?

Any personal and/or confidential information disclosed by the participant in this study will be treated as confidential and only handled by the individuals relevant to the performance of the study and the storing of information thereafter. Any personal and/or confidential information relating to health issues or otherwise will not be disclosed without the participants consent in any event. Where information concerning the participant is published his identity will remain anonymous throughout. Information collected in this study will be stored in the Biomechanics laboratory at Northampton University for 4 years from the date of collection and will be then destroyed.

Not sure about participating?

If you choose not to participate, you have the right to do so. Participants have the right to change their mind at any point of the research and are free to withdraw from the study at any time by communicating such intent to the Researcher prior to doing so.

Your valued input:

I can make my results available to you when I have finished my study by sending you a short summary. Please let me know if you would like me to do this.

Contact the Researcher:

If you have any questions about the research, you can contact myself or my supervisor as follows:

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Who has checked this research?

The School of Health Ethics Committee has approved this study.

The University of Northampton's Combined Liability Insurance Policy provides indemnity for students of the institution carrying out research work (such as questionnaires and interviews) as part of their course.

8.3 Appendix 3: Participant information sheet (Study 3)

PARTICIPANT INFORMATION SHEET

Title: Variable, but not free-weight, resistance exercise potentiates jump performance following a comprehensive warm-up

Lead Investigators:

Minas Mina: M.Mina@derby.ac.uk

Ass Prof Giannis Giakas: G.Giakas@gmail.com

Ass Prof Tony Kay: Tony.Kay@northampton.ac.uk

Prof Anthony Blazevich: a.blazevich@ecu.edu.au

Information to Potential Participants

The purpose of this study was to compare the influence of free-weight resistance (FWR) and elastic band (EB) squat exercises following a comprehensive warm-up on a) subsequent CMJ performance at different post-conditioning time points (i.e. 30 s, 4 min, 8 min, and 12 min); b) CMJ kinetic and kinematic parameters and c) muscular activity of the lower-limb extensor muscles, compared to free-weight resistance (FWR) alone.

Why have I been selected to take part in this study?

We are looking to assess healthy trained individuals with previous experience (> 3 years) in squatting, a category to which your preliminary details have placed you.

About the researcher

My name is Minas Mina and I am a Phd student at Derby University undertaking collaborative research with the University of Thessaly, Greece. This study marks awarded for this study will contribute towards my Phd.

What will I have to do?

You will be asked to attend a familiarisation session (approx 45 min in duration) and 2 separate testing sessions (30 min each; 48 h between them) at the University of Thessaly (Trikala).

Familiarisation Session

During familiarisation, anthropometric characteristics will be recorded, one-repetition maximum (1-RM) back squat load will be determined, and the participants will be familiarised with all experimental procedures.

Testing Sessions

During the experimental conditions, following a comprehensive warm-up (see below), the participants will perform three pre-intervention CMJs followed by back squats at 85% of 1-RM using either FWR or EB warm-up. CMJ trials were then performed at 30 s, 4 min, 8 min and 12 min after the intervention.

Comprehensive warm-up

- 5 min of cycling followed by five continuous unloaded squats (i.e. non-jumping) at a rhythm of 2 s/ 2 s (eccentric/concentric) and a further
- 5 squats at a rhythm of 1 s/ 1 s after a 30 s rest.
- after 20 s rest, five continuous CMJs were performed at ~70% of the participants' perceived maximum
- after a further 30 s rest, maximal CMJs were performed every 30 s until three consecutive jumps were within 3% of jump height (4-7 jumps were performed in all trials).

Information required

You will be asked to give information by completing a Health Questionnaire to gather data on your training activity and health history. Through the questionnaire you must indicate no current lower extremity or other related injuries.

Benefits of taking part?

By taking part you will have the opportunity to be involved in a research study that will potentially assist stength and conditioning coaches in designing new alterantive warm-up protocols to improve athletic performance in different sports.

What are the risks of taking part?

By taking part in this study you should be aware that there is a potential risk, although extremely rare, associated following weight lifting exercise (i.e. back or muscle injury).

Minimising potential risks

Participants will be screened prior to accepting participation in the study by completing a health questionnaire and a familiarisation trial will be undertaken before testing where an appropriate 1-RM protocol will be followed with a gradual increase in load. For the protection of participants, they must follow a warm-up procedure and a modified squat rack will be used with adjustable safety bars and catchcups. An experienced spotter will be used throughout all testing procedures to ensure correct technique, safety during lifts, and provide verbal encouragement to the participants. In addition, all participants recruited for this study will have weight lifting experience of more than 3 years and will be familiar with performing the squat exercise.

What will happen to the information?

Any personal and/or confidential information disclosed in this study will be treated as confidential and only handled by the lead investigatorsrelevant to the performance of the study and the storing of information thereafter. Any personal and/or confidential information relating to health issues or otherwise will not be disclosed without your consent in any event. Where the information and/or data collected in this study is published your identity will remain anonymous throughout.

Not sure about participating?

If you choose not to participate, you have the right to do so. Participants have the right to change their mind at any point of the research and are free to withdraw from the study at any time by communicating such intent to the Researcher, Minas Mina, prior to doing so.

Your valued input:

I can make my results available to you when I have finished my study by sending you a short summary. Please let me know if you would like me to do this.

Contact the researcher:

If you have any questions about the research, you can contact me as follows:

Minas Mina
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Tel: +44 (0) 7709001757

8.4 Appendix 4: Informed consent form (Studies 1, 2 and 3)

INFORMED CONSENT FORM

Please read and complete this form carefully.

Please tick the boxes

	Yes	***No***
I have read and understood the Participant Information sheet	☐	☐
I have had an opportunity to ask questions and discuss this study and I have received satisfactory answers	☐	☐
I understand that all information I provide will be treated in confidence and that my data will be destroyed or returned to me after being collated.	☐	☐
I understand that my participation is voluntary and that I am free to withdraw at any time without giving a reason	☐	☐
I agree to participate in this study	☐	☐
I confirm that I have completed the health questionnaire and I know of no reason, medical or otherwise, that would prevent me from participating in this study	☐	☐
I understand that failure to attend the testing session(s) will require my removal	☐	☐
I know that the results may be published, but they will not be linked to me	☐	☐
I would like to receive feedback on the results of the study and get a copy of the research summary at the email address given below Email address..	☐	☐

Signature of the participant…………………………..Date: ………………………….

NAME IN BLOCKS………………………………………………………….………….

Contact phone number……………………………………………………………..

Contact Address……………………………………………………………………….

Signature of researcher ……………………………. Date: …………………………..

NAME IN BLOCKS…………………………………………………………………..

8.5 Appendix 5: Health Questionnaire (Studies 1, 2 and 3)

HEALTH QUESTIONNAIRE

To be completed by the participant.

NAME:	Age:
Date: __/__/__	

Please read the questions carefully and answer each one honestly, ticking the appropriate box or adding information if necessary. All information given will be retained in strictest of confidence.

1. How long have you been training (in years)?				
2. Have you ever been diagnosed with a heart problem?	Yes		No	
3. Have you ever encountered chest pain while exercise or any other activity?	Yes		No	
4. Have you ever encountered chest pain while resting?	Yes		No	
5. Are you currently taking any medication or supplements?	Yes		No	
6. Are you currently taking any medication for any other problems?	Yes		No	
7. Do you suffer from any bone, muscle or joint conditions or back conditions or other injuries?	Yes		No	
8. Have you had any major illness or major surgery?	Yes		No	
9. Have you ever been diagnosed with diabetes?	Yes		No	
10. Have you ever been diagnosed with epilepsy?	Yes		No	
11. Have you ever been diagnosed with asthma?	Yes		No	
12. Have you ever been diagnosed with any other health problems?	Yes		No	
13. Are you presently pregnant?	Yes		No	
14. Have you recently had a baby?	Yes		No	
15. Do you ever lose your balance because of dizziness or lose consciousness?	Yes		No	
16. Are you feeling unwell at present due to cold, flu or headache etc?	Yes		No	
17. Do you have a high blood-pressure?	Yes		No	
18. Do you suffer from any condition which hinders you from performing exercises/tasks of maximal capacity?	Yes		No	
19. Have you had any cause not to train in the past two weeks for reasons relating to your health?	Yes		No	

If you have answered yes to any of the questions above, you must inform Minas Mina (E: M.Mina@derby.ac.uk, M: 07709001757) as soon as possible

Question Number	Give details

Other health problems or issues to disclose?

Insert details

I confirm that the information above is correct and current to the best of my knowledge. It is my understanding that my participation in this study will be denied due to a medical condition found in this Health Questionnaire.

Participant [Print name]: Signature:	Date:

8.6 Appendix 6: Ethical Approvals (Studies 1, 2 and 3)

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University of Thessaly
Department of Physical Education and Sport Science

Internal Ethics Committee

Trikala: 11/2/2015
Protocol Number: **958**

Approval of research entitled: Effect of high and low velocity variable resistance back squat and triple-extension squat loading on subsequent vertical jump and sprint performance.

Scientist responsible – supervisor: Giannis Giakas, Anthony Kay (University of Northampton (UK))
Associate Professor of Biomechanics/ Associate Professor of Biomechanics
University of Thessaly Trikala
Department of Physical Education & Sport Science

Main researcher – student - Minas Mina
PhD Candidate
University of Derby (UK)
Department of Sport, Outdoor and Exercise Science

The proposed research relates to a: Independent research

Contact phone: +44 7709001757
Contact email: m.mina@derby.ac.uk

The Internal Ethics Committee (IEC) of the Department of PE and Sport Science (DPESS), University of Thessaly, examined the proposal in its 4-1/11-2-2015 meeting and approves the implementation of the proposed research.

The Chair of the IEC – DPESS

College of Life and Natural Sciences
Life Sciences Research Ethics Committee (LSREC)

ETHICAL APPROVAL GRANTED

Dr Callum Osler
N606, Kedleston Road
University of Derby
DE22 1GB
Tel: 01332 59 1725
Email: c.osler@derby.ac.uk

Date: 20th March 2015
Ref number: LSREC_1415_04

Dear Minas Mina

Thank you for resubmitting your request for ethical approval to the Life Sciences Research Ethics Committee. The amendments and clarifications have been reviewed by the Committee Chair and we are pleased to grant ethical approval for the study.

If any changes to the study described in the application or supporting documentation are necessary, then you must notify the Committee and may be required to submit your request for ethical approval again.

As the study will be undertaken at the University of Thessaly, we advise you to also gain permission from this organisation before recruiting participants and proceeding with the research.

I wish you all the best with the study.

Yours sincerely

Dr Callum Osler
On behalf of the Life Sciences Research Ethics Committee

UNIVERSITY of DERBY

Request for Ethical Approval for Individual Study by Post-graduate Researcher

Please complete this form and return it to Callum Osler (Chair of the Life Sciences Research Ethics Committee) via email (c.osler@derby.ac.uk). The document should first be scrutinised by an academic member of staff (normally the research supervisor) to ensure that it is appropriate for submission. Your proposal will then be screened at the next committee meeting and a decision on ethical clearance will be made. Once approval has been given, you will be eligible to commence data collection.

1. Student name:	Minas Mina	**2a. School, Subject Area/ Research centre/group:** *Department of Life Sciences, College of Life and Natural Sciences* **2b. Current programme: PhD**
3. Contact Info:	**Email:** m.mina@derby.ac.uk **Tel Number: +44 7709001757**	
4. Name of supervisor(s):	*Prof. Nick Draper, University of Derby* *Assoc. Prof. Giannis Giakas, University of Thessaly Trikala, Greece* *Assoc. Prof. Anthony Kay, University of Northampton*	

5. Title or topic area of proposed study

Effect of high and low velocity variable resistance back squat and loaded jump squat exercises compared to free-weight resistance (FWR) on subsequent vertical jump and sprint performance

6. What is the aim and objectives of your study?

Aim:
This study aims to examine the potentiating effects of variable resistance back squat and loaded jump squat exercises using elastic bands compared to free-weight resistance (FWR) alone on subsequent vertical jump and sprint performance

Objectives:

- To investigate the changes of vertical jump performance (jump height) and 30 meter sprint (time) performance following the use of variable resistance using elastic bands during either a back squat exercise or a loaded jump squat as a warm-up compared to FWR
- To examine the biomechanical changes of vertical jumping between the conditions: (a) changes in ground reaction forces and the rate of force development using a force platform; (b) changes of movement mechanics (i.e. knee angular velocities) using a 3D motion capture system; and (c) measure changes in muscle activity of the lower limb muscles using electromyography (EMG).

To develop the research and further the knowledge of coaches and athletes of various sports considering that such warm-up techniques can act as a determining factor of the athlete's performance.

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7. Brief review of relevant literature and rationale for study (attach on a separate sheet references of approximately 6 key publications, it is not necessary to attach copies of the publications)

The proposed research aims to investigate variable resistance using elastic bands at high/low velocity back squat and loaded jump squat compared to free-weight resistance alone on subsequent vertical jump and sprint performance. This will be achieved through the use of biomechanical research techniques including, electromyography (EMG) measuring the muscle activity of the lower limb muscles, 3D motion capture system to evaluate any changes in movement (i.e. knee angular velocities) and force platform to determine the ground reaction forces.

Variable resistance strength training using elastic bands attached to a loaded barbell has been widely used in competitive powerlifting and, more recently, in strength and conditioning programs for the development of strength and power (Baker & Newton, 2006; Ebben & Jensen, 2002; Wallace et al., 2006). Warm-up routines are specifically designed to precondition the neuromuscular system to enhance performance and reduce injury risk during high-intensity physical activity. In sports such as powerlifting and in strength and conditioning programs, such warm-up routines can act as a determining factor of the athlete's performance. A possible means of improving the squat exercise during a warm-up to enhance subsequent maximal strength and power performance is the use of variable resistance using elastic bands.

Previous research has shown that the use of elastic bands in combination with free-weight resistance results in performance improvements generating higher forces and power output compared with free-weight resistance alone (Wallace et al., 2006) with increased movement velocity during the eccentric phase (Stevenson et al., 2010). Force production during the subsequent concentric phase is then likely enhanced through the combination of increased reflex amplitudes and a greater use of elastic energy stored in the muscle-tendon units during the eccentric phase (Stevenson et al., 2010), which allows the muscles work closer to their maximum through the lift. The increase in total muscle force production elicited by the use of bands should thus increase the magnitude of the post-activation potentiation (PAP) response, given that PAP tends to be augmented when a greater work is performed by the muscles (Anderson et al., 2008; Sale, 2002; Wallace et al., 2006). Such an improvement in force production during training could subsequently increase muscular adaptation and strength development (Anderson et al., 2008).

However, equivocal data exist in the current literature on the influence of variable resistance exercise. To date no research has examined the influence of elastic band use as a warm-up to vary the resistance during squat and loaded jump squat compared to free-weight resistance alone on subsequent vertical jump or sprint performance. Strength coaches incorporating these elements in a warm-up routine may both enhance acute performance and impose a greater mechanical stimulus (i.e., training load). As such, identifying the optimal warm-up routine to potentiate strength performance is of clear importance to strength coaches.

There are a number of studies within the literature on the use of variable resistance as a training tool but to date no research has examined the preconditioning effects of elastic band variable resistance on more dynamic activities such as, vertical jump and sprint performance. Therefore, identifying the optimal warm-up routine to enhance athletic performance is of clear importance to strength coaches.

8. Outline of study design and methods

This study, for which ethical approval is sought, builds upon previous research under the same aim (as per section 6) that was collected in isolation at the University of Northampton prior to registration for this PhD

Subjects

Twenty active men will participate in this study. All subjects will be experienced in weight training (>3 y) including the squat exercise. The subjects will be informed of the intended aims and procedures prior to completing a written informed consent and pre-test medical questionnaire, reporting no recent illness or injury in the lower limbs or lower back, and should avoid strenuous exercise and dietary stimulant use for 48 h prior to testing. They will also be informed of their right to withdraw at any time and that they are free to withhold any personal information. The investigation will be conducted in accordance with the Declaration of Helsinki (1964) and with ethical approval granted by the ethics committee of the University of Derby.

Overview of Methods

A randomized cross-over study will be implemented to investigate the effects of variable resistance using elastic bands as a warm-up during either a 55% jump squat (high velocity) or 85% back squat exercise (low velocity) followed by vertical jumping and sprint performance. Subjects will visit the laboratory on five separate occasions. During the first session, the subjects will be familiarized with the experimental procedures and their 1-RM back squat load, vertical jump and sprint performance will be determined. Upon arrival at the laboratory the participants will perform a 5-min warm-up on a cycle ergometer (Monark, Sweden). During the next four sessions, subjects will perform 2 sets of 3 submaximal repetitions with 2-4 minutes rest at either 55% (high velocity) or 85% (low velocity) of their 1-RM during the back squat and loaded jump squat exercise, or the same total load will be lifted with 35%

of the 55% and 85% load being generated via elastic bands as a conditioning warm-up. Following the conditioning warm-up, subjects will then perform either three vertical jumps with 30 seconds rest between each jump and a 30 meter sprint.

To ensure a similar total load will be lifted during the loaded loaded jump squat and the back squat exercises across conditions, half of the 35% load will be taken off the bar during the two preconditioning sets. Following a further 5 min rest, subjects will perform a vertical jump or sprint performance. Similar to previous studies, the elastic band resistance will be at 35% (Mina et al., 2014; Wallace et al., 2006); to ensure a similar total load is used across conditions half of the 35% load will be removed from the bar during the preconditioning set. Motion analysis will be used to determine the mean/peak concentric and eccentric knee angular velocities, EMG activity of the knee/hip extensors will be recorded in both conditions and force platform to determine the ground reaction forces/rate of force development.

9. Research Ethics

PROPOSALS INVOLVING HUMAN PARTICIPANTS MUST ADDRESS QUESTIONS 9 - 13.

Does the proposed study entail ethical considerations Yes ~~/ No~~ (please circle as appropriate)

If 'No' provide a statement below to support this position.
If 'Yes' move on to Question 10.

10. Ethical Considerations Please indicate how you intend to address each of the following in your study. Points a - i relate particularly to projects involving human participants. Guidance to completing this section of the form is provided at the end of the document.

a. Consent

Participants will be asked to sign a written informed consent form based upon an appreciation of the details of the study and an understanding of participant information sheet in terms of how the study will develope.

b. Deception

No deception of any form will be employed. The participants will be aware of all aspects of the study. All questions will be answered in full when asked.

c. Debriefing

Participants will be provided with a briefing sheet outlining how the study will develop and the participant's criteria for selection. An oral explanation will also be given prior the start of testing, followed by an opportunity to ask any further questions. Obtained through a signed consent form. Following the data collection, participants will be able to ask questions and will be offered the opportunity to contact the researchers to discuss the results at a later date, after analysis.

d. Withdrawal from the investigation

Participants will have the right to withdraw at any time and are not obliged to continue if they do not wish to. Participants have the option to withdraw their data up to two weeks after collection.

e. Confidentiality

Participants' confidentiality and anonymity will be maintained, and their personal privacy protected. The collection, storage, disclosure and use of research data will comply with the Data Protection Act 1998. The data will be held securely, and will only accessible by Minas Mina, Prof. Nick Draper, Assoc. Prof. Giannis Giakas, Assoc. Prof. Anthony Kay. Any personal and/or confidential information disclosed by the participant in this study will be treated as confidential and only handled by the individuals relevant to the performance of the study and the storing of information thereafter. Any personal and/or confidential information relating to health issues or otherwise will not be disclosed without the participants consent in any event. Where information concerning the participant is published his identity will remain anonymous throughout.

f. Protection of participants

As with any form of weight lifting exercise there is a very minimal, but a potential risk to participants, which is explained fully in the Participant Information sheet. Participants will be screened via a health history questionnaire confirming weight lifting experience of more than 3 years and a participant activity readiness questionnaire. (Note: the testing protocols will be performed submaximally, back squat exercise at 85% load and jump squat exercise at 55% load with the exception of the 1-RM assessment during the familiarisation session where an appropriate 1-RM protocol will be followed with a gradual increase in load)

The experimental trial will include recognised and well established physical exercise methods and exercises that will be demonstrated during the familiarisation session. For the protection of participants they will follow a warm-up procedure and will be administered with appropriate safety equipment (weight-lifting belt, knee wraps). During the back squat and jump squat exercises, a modified squat rack will be used with adjustable safety bars and catchcups. An experienced spotter will be used throughout all testing procedures to ensure correct technique, safety during lifts, and provide verbal encouragement to the participants.

g. As well as being able to withdraw at any time, participants will be supervised during all protocols and if at any time participants safety is at risk testing will be immediately halted and appropriate measures taken.

Observation research [complete if applicable]

No observational research will be completed.

h. Giving advice

No advice will be given.

i. Research undertaken in public places [complete if applicable]

Biomechanics Laboratory at the University of Thessaly, Trikala.

j. Data protection

The researchers will comply with the Data protection act and the standards set out by University of Derby. The data will be held securely, and will only accessible by Minas Mina, Prof. Nick Draper, Assoc. Prof Anthony Kay. Data with identifying information (physical paper copies) will be stored in the locked office of Minas Mina. Anonymised data will be stored on Minas Mina personal computer (encrypted and password protected). Participant's identity will never be made public.

k. Animal Rights [complete if applicable]

Not applicable.

l. Environmental protection [complete if applicable]

Not applicable.

11. Sample: Please provide a detailed description of the study sample, covering selection, number, age, and if appropriate, inclusion and exclusion criteria.

A quota sample (~20 participants) will be recruited from the university and general population. Participants will be selected on the basis that they are experienced in weight training (>3 y) including the squat exercise. All participants will be over the age of 18.

12. Are payments or rewards/incentives going to be made to the participants? If so, please give details below.

No

13. What study materials will you use? (Please give full details here of validated scales, bespoke questionnaires, interview schedules, focus group schedules etc and attach all materials to the application).

3-D Motion Capture system (Vicon) integrated with Force Plate (Bertec) and Electromyography (EMG)-(Myon)
Health questionnaire and an informed consent form will be administered prior to the study – see attached.

14. What resources will you require? (e.g. psychometric scales, equipment, such as video camera, specialised software, access to specialist facilities, such as microbiological containment laboratories).

All data collection will take place in the Biomechanics Laboratory at the University of Thessaly, Trikala. Data will be collected using 3-D Motion Capture system (Vicon) integrated with Force Plate (Bertec) and Electromyography (EMG)-(Myon). Data will be analysed using Vicon Nexus 2 software.

15. Have / Do you intend to request ethical approval from any other body/organisation? Yes ~~/ No~~
(please circle as appropriate)

If 'Yes' – please give details below.

As explained in Q14 above, the collection of data will take place in the Biomechanics Lab at the University of the Thessaly so ethical approval will also be obtained.

16. The information supplied is, to the best of my knowledge and belief, accurate. I clearly understand my obligations and the rights of the participants. I agree to act at all times in accordance with University of Derby Code of Practice on Research Ethics http://www.derby.ac.uk/research/ethics/policy-document

Date of submission......9/02/2015..............................

Signature of applicant......Minas Mina...

Signature of first project supervisor ....Tony Kay..........................

Signature of second project supervisor ....

School of Health
Research Proposal and Ethics Form

Please ensure that you complete all relevant parts of this form. In case something is not relevant to your project, please insert N/A in the appropriate text box. Don't forget to insert your name/sign the ethics form before emailing your documents to your supervisor for consideration for approval by the ethics committee.

I confirm that the following have been included as part of this proposal before submission for consideration by the ethics committee:

Please tick ALL that apply:

☒	Completed research proposal and ethics form part A and B
☒	Consent form(s)
☒	Participant information sheet(s)
☐	Recruitment letter(s) to the organisation
☐	Recruitment poster(s)
☒	Questionnaires used
☐	Interview schedules used
☒	Risk assessment
☐	COSHH (Control of Substances Hazardous to Health) form
☐	In case of resubmission, completed Part E from the original proposal

Name/signature of the student: Minas Mina

Date: 21.11.11

My contact details are as follows:

Name:	Minas Mina
Student Number:	
Degree Title:	Phd
Email address:	M.Minas@derby.ac.uk

My supervisors contact details are as follows:

Name:	Dr Tony Kay
Address:	Northampton University : Health - Sport & Exercise
Phone number:	01604 89 2577
Email address:	tony.kay@northampton.ac.uk

Part A Details of the Project

To be completed by student:

1. Project title:

Post-activation potentiation effects of compensatory acceleration training using elastic bands and chains on back squat performance.

2. Project introduction and rationale (max 300 words):

Human performance can be affected after exercise as muscle performance decreases after a fatiguing session but increases after a warming up with a submaximal or high force activity (Chatzopoulos et al, 2007). This muscle performance augmentation is known as post activation potentiation (PAP), which may increase muscle mechanical output by increasing muscle twitch properties by increasing the phosphorylation of the myosin light chain and increasing the actimyosin sensitivity to calcium, which in turn increases crossbridge cycling during muscular contraction (Hanson et al. 2007; Sale et al. 2000).

The use of variable resistance training (elastic and chain resistance), combined with free weight resistance and their incorporation in a warm-up may produce performance improvements via PAP. During the lift of a load, proprioceptive feedback makes the athlete aware that the load changes and voluntarily intervenes in the loading process by accelerating/decelerating the bar to increase/decrease the force involved (Mell Siff, 2000), a method known as compensatory acceleration training (CAT). CAT can be useful in alternating muscle tension or movement velocity to achieve a specific training goal, the additional tension of the elastic bands and chains can improve acceleration, strength and power, elevate neural drive and as a result increase velocity (Mell Siff, 2000).

Both acute and chronic effects in muscle strength and power may be enhanced by performing an explosive exercise while the affected muscle is in the potentiating state. The acute effects of free-weight heavy resistance stimulus alone on squat performance have been previously examined (Weber et al. 2008), however, no studies have assessed the possible PAP effects of elastic and or chain resistance combined with free weights on back squat performance.

3. Project aim(s) and objective(s) (max 4 bullet):

- Examine the acute effects of PAP using elastic bands and chains in combination with free weight resistance on back squat performance.
- Develop optimal warm-up protocols that will maximise athletes ability to perform the necessary movements and improve performance through PAP.
-
-

4. Research question(s)/hypotheses:

Experimental hypothesis:
There will be a significant difference in back squat performance (peak power, peak force, peak EMG) after squat exercise, squat with elastic bands, and squat with chains conditions.

Null hypothesis:
There will be no significant difference in back squat performance (peak power, peak force, peak EMG) after squat exercise, squat with elastic bands, and squat with chains conditions.

5. Description of the participant sampling procedures (max 200 words):

Fifteen male (n = 15) weight trainees between 20-35 years of age will be recruited internally and externally to Northampton University. All participants will read and sign a University approved informed consent-form before participating in the study. Participants will be healthy and recreationally active with 2-3 years experience with strength training). The test will be conducted in the Biomechanics laboratory at NU. During the investigation participants will be instructed to minimise physical activity involving the lower body and avoid performance-enhancing substances, such as caffeine.

6. Description of the materials/measures/apparatus used in this study (max 200 words): Copies of any questionnaires, interview schedules, systematic literature review protocol etc MUST be attached as an appendices.

FREE WEIGHT BACK SQUAT (Eleiko) with a 20kg Olympic bar and weight plates will be used to perform the squat exercise and assess 1RM.
EMG electrodes of WBA Wireless Bioamplifier System (Finland) will measure the EMG activity from the rectus femoris, vastus lateralis and vastus medialis of each subject's right leg during back squat pre and post intervention.
FORCE PLATE (HUR Labs, Tampere, Finland) will record the peak and mean ground reaction forces (GRF) to determine the tension of the elastic bands. All data will be collected on a personal computer using Research Line (v. 2) software.
ELASTIC BANDS (Pullum Sport) of medium thickness (green) with resistance 50-120lbs will be used as an intervention prior to the testing.
The 3D MOTION ANALYSIS will be performed using ProReflex Motion Capture System (Qualisys, Sweden) at 240 Hz. Data will be transferred to Windows-based data acquisition software (Qualisys Track Manager). The recording will calculate the peak velocities, joint angles, and movement times.
A Questionnaire will be administered to gather data on each subject's training activity and health history.

Please see Appendix 1.

7. A detailed description of the data collection procedures to be used in this study (max 500 words). This section should provide sufficient information so that the study could be replicated:

Preliminary Testing

Measurements of height to the nearest 0.1cm and weight to the nearest 0.1kg will be taken. Participants will then perform a 5 minute warm-up on a cycle ergometer (Monarch, Sweden) set at 70W. One maximum repetition (1RM) will be determined, which will be used to set the tension of the elastic bands in the subsequent testing sessions. Participants will familiarise themselves in performing squat exercise with elastic bands & chains with the correct technique according to the National Strength & Conditioning Association guidelines (Earle & Baechle, 2000). Squat depth will be determined when the thigh will be parallel to the floor, placing the knee joint in approximately 90º of knee flexion. Visual inspection from the researcher will ensure the desired depth is reached.
1RM Assessment
During the first session subjects will perform a general warm-up and then 1RM will be assessed for the back squat. Each subject will choose a weight that commensurate with his ability to warm up with light resistance completing 5-10 reps, with a proper and consistent technique. Gradual load adjustments will then be estimated depending on each subjects' training status according to an orderly testing sequence of (3-5 reps - load 10-20%, 2 min rest period, 2-3 repetitions - load 10-20%, 2-4 min rest period, load 10-20% - attempt to perform 1RM). The load will increase or decrease until the athlete completes 1RM with proper exercise technique. An instructor to subject ratio 1:1 will be provided throughout all testing procedures and uniform verbal encouragement will be offered to all subjects.
Kinetic measurements
Bands
After assessing the 1RM of each participant in the preliminary testing, the band tension will be assessed using a force plate. The free weight resistance (FWR) load selected will be 85% of each participant's 1RM. This % was chosen because it falls near the average % that has been reported in the literature to be most effective in eliciting maximal power production (Stevenson et al. 2010; Baker et al. 2001). Bands will be attached on each side of the bar (in a symmetrical and equidistant fashion) with 50kg dumbbell on each side of the bar. The upper end of each band will be looped around the bar. During squat exercise with bands (WB), the band tension will be determined at 35% of the 85% 1RM in the fully erect starting/ finishing position and zero tension in the bottom position to equalise the loads at zero velocity point of the reversal phase. Participants will initially stand on the force plate with just the empty bar and then the band tension will be determined by the number of loops of the bands around the bar. These will be increased/ decreased until the tension is 35% of 85% 1RM.

Please see Appendix 2.

8. A description of the data analysis procedures to be used in this study (max 200 words):

Data from this investigation will be analyzed using SPSS statistical analysis (version 17.0, SPSS, Inc. Chicago, IL). All data will be reported as means and standard deviation. Seperate ANOVA with repeated measures will be used to test for differences in 1) WB 2) WC 3) FWR in peak EMG amplitude between muscles pre and post intervention. Post hoc t-tests will be used to further examine changes in measures where statistical significance will be reached.

9. Project timescale
Insert a realistic timescale for the completion of your project to the Gant chart below.

Put your list of tasks in the left hand column
Add the months across the top shaded row
Check the boxes corresponding to the task and the month(s) in which it will be undertaken

Task	Month											
	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT
Completion of Ethical Application	☒	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Preparation of Experimental design	☒	☒	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Pilot Study 1	☐	☒	☒	☐	☐	☐	☐	☐	☐	☐	☐	☐
Pilot Study 2	☐	☐	☒	☐	☐	☐	☐	☐	☐	☐	☐	☐
Pilot Study 3	☐	☐	☐	☒	☐	☐	☐	☐	☐	☐	☐	☐
Collection of data	☐	☐	☐	☒	☒	☐	☐	☐	☐	☐	☐	☐
Analysis of data	☐	☐	☐	☐	☒	☒	☐	☐	☐	☐	☐	☐
Research paper draft	☐	☐	☐	☐	☐	☐	☒	☐	☐	☐	☐	☐
Make necessary amendments of paper as advised	☐	☐	☐	☐	☐	☐	☒	☐	☐	☐	☐	☐
Send paper for peer review	☐	☐	☐	☐	☐	☐	☒	☒	☐	☐	☐	☐
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	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

Part B Ethical Considerations

To be completed by student:

10. Study design

a. Tick one of the following:

☒ I am conducting empirical research
☐ I am conducting a systematic literature review (Completed form needs to go to supervisor but does not need to go to the ethics committee)

b. Tick one of the following:

☐ I am using qualitative methods
☒ I am using quantitative methods
☐ I am using mixed methods

11. Need for formal SOH meeting (supervisor to tick one of the following boxes)

☐ **I, as the supervisor for this project confirm that I have seen the completed Part A and that I am satisfied with the proposed research plan. I can also confirm that no formal SOH ethics meeting will be required. The student will not be required to complete Parts B, C, D and E of this form.**

☐ **I, as the supervisor for this project confirm that I have seen the completed Parts A, B C, and D and that I am satisfied with the proposed research plan. I can also confirm that this project will need formal SOH ethics approval prior to any data collection can take place.**

12. Participants

a. Tick one of the following:

☒ I am using human participants.
☐ I am using archival data where individuals are identifiable
☐ I am **not** using human participants or data where individuals are identifiable (go to section 11).

b. Tick the box which most accurately describes the age range of your sample:

☐ Children and young people under 16 years
☐ Individuals 16-19 years old
☒ Individuals 20-64 years old
☐ Individuals over 65 years old

c. Tick the box which most accurately describes your sample:

☐ Members of the public (general) (e.g., shoppers, audiences, commuters)
☐ Members of the public (specific) (e.g., professionals, volunteers, describe here:)
☐ Members of vulnerable groups (e.g., Children, the elderly, individuals with disabilities and chronic health issues, describe here:)
☐ Members of my own team (e.g., work place, sport, church, describe here:)
☒ Staff/Students from the University of Northampton (describe here: 2-3 years experience with Resistance Training)
☒ Other. (describe here: Gym members and students from the University of Derby will be asked to volunteer as participants in this study)

13. Recruitment process. Tick the process that best describes how you plan to recruit participants. Full details of how you will recruit and where it will happen, should be provided above in section 7.

☐ Poster in a public place such as a library or community centre
☐ 'Packs' will be provided to named person in an organisation/group to be distributed on my behalf
☐ 'Packs' will be provided to an organisation and distributed to the individuals by the researcher

☒ Asking personal contacts to pass my information packs to their contacts
☒ Asking friends to be participants
☐ Asking family to be participants
☐ Cold calling
☐ Other. If other, state here:

14. Recruitment material. Tick all the recruitment material you will be using. You **must** use the School of Health templates to produce those. In addition, they **must not** be used until seen and approved by your supervisor.

☐ Recruitment poster(s)
☐ Recruitment letter(s) to named person in an organisation/group who will be distributing 'Packs' on your behalf
☐ Recruitment letter(s) to potential participants
☒ Participant Information Sheet(s)
☒ Consent form(s)
☐ Other. If other, state here:

15. Incentives or payment for participating: Please tick the box which applies to your research:
☒ Participants will not receive any incentive or payment for participating in this research (go to section 11)
☐ Participants will receive an incentive or payment for participating in this research
☐ Type of incentive/payment:
☐ Justification for incentive/payment:

16. A description of how the participant anonymity and/or confidentiality will be protected (max 200 words)

Any personal and/or confidential information relating to health issues or otherwise will not be disclosed without the participants consent in any event. Any personal and/or confidential information disclosed by the participant in this study will be treated as confidential and only handled by the individuals relevant to the performance of the study and the storing of information thereafter. Where information concerning the participant is published his identity will remain anonymous throughout.

17. A description of how the data will be stored (where, how, and for how long data and participant consent forms (data and consent forms should be stored separately) will be stored and destroyed) **(max 200 words):**

Information collected in this study will be stored on a security password protected computer at Northampton University for at least 5 years from the date of collection.

18. Risk assessment: Some projects will require risk assessment for participants and/or researchers. In other words, there is a possibility that participants and/or researchers will get hurt collecting data. If so, a risk assessment must be conducted. Tick the appropriate box below concerning your need for risk assessment.

☐ There is **no** risk of injury to participants and/or researchers, so **no** risk assessment will be conducted.
☒ There is a potential of injury to participants and/or researchers, so risk assessment has been (or will be) conducted.
☐ A copy of the completed risk assessment has been attached within the appendices
☐ A copy of COSHH (Control of Substances Hazardous to Health) form has been attached within the appendices (go to section 16)

19. Issues for ethical concern: Tick below any ethical issue that relates to this research.

☐ Involves invasive techniques (e.g. Taking blood)
☐ Involves participants undertaking tasks they would not normally undertake
☐ Involves any activity that might be described as an 'invasion of privacy'
☐ Involves deception
☐ Involves a topic that would be considered 'sensitive'
☐ Involves the collection of data that is not anonymised (contains identifying information such as name and address)
☒ Requires participants to have a certain level of fitness.

20. If any boxes in sections 18 and/or 19 have been ticked you MUST provide a detailed description (max of 500 words) of these potential concerns and how they would be addressed and managed:

There is a limited potential risk associated following weight lifting exercise, however, participants will have a certain level of fitness of 2-3 years weight lifting experience. Participants will be screened prior to accepting participation in the study by completing a health questionnaire and a familiarisation trial will be undertaken before testing and subjects will be supervised at all times during the testing.

21. A description of how the study findings will benefit the participants/subject area (max 200 words):

Participants: Opportunity to be involved in a research study.

Subject area: The use of variable resistance training (VRT) (i.e. elastic and chain resistance) combined with free weight resistance (FWR) has become increasingly popular amongst coaches and strength & conditioning practitioners as a new method of training which can help athletes enhance their performance. Therefore, the study findings will benefit athletes in different sports by incorporating elastic bands and chain resistance as a warm-up protocol. This method of training may potentiate the athletes performance.

Elastic bands and chains will find a place in many strength programs because of the purported performance benefits. Research suggests that the additional tension of the elastic bands and chains can improve acceleration, strength and power, elevate neural drive and as a result will increase velocity during the concentric phase of the lift.

22. A description of how the study findings will be disseminated (max 200 words):

The findings of this study may be disseminated as a research poster in conferences and a research paper published in a scientific journal.

- THE END -