

THE UNIVERSITY OF HULL

**Optimising the Prescription of Training for Post-Activation Potentiation in Rugby
League Players**

**being a Thesis submitted for the Degree of Doctor of Philosophy
in the University of Hull**

by

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There's not enough paper in the world” – Acrylic, Liam Fray - The Courteeners*

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DISSEMINATION

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LIST OF ABBREVIATIONS AND SYMBOLS

°	Degrees
$A_{inst.}$	Instantaneous acceleration
ANOVA	Analysis of variance
ARCT	Accommodating resistance complex training
ATP	Adenosine triphosphate
BF	Biceps femoris
B-mode	Brightness mode
BS	Back-squat
BSS	Bulgarian split squat
CA	Conditioning activity
Ca^{2+}	Calcium ion
CI	95% confidence interval
cm	Centimetres
CMJ	Countermovement jump
CON	Control
CSA	Cross-sectional area
CV	Coefficient of variation
d	Cohen's d effect size
DJ	Drop jump
EMG	Electromyography
g	Acceleration due to gravity
GCT	Ground contact time
GM	Gastrocnemius medialis

GRF	Ground reaction force
$\text{GRF}_{\text{inst.}}$	Instantaneous ground reaction force
GRF_{max}	Maximum ground reaction force
GTO	Golgi tendon organ
HBD	Hex-bar deadlift
H-reflex	Hoffman-reflex
Hz	Hertz
ICC	Intraclass correlation coefficient
ICRI	Intra-complex recovery interval
K^+	Potassium ion
kg	Kilograms
K_{leg}	Leg stiffness
L_f	Fascicle length
m	Metres
M_{adj}	Adjusted mean
MDC	Minimum detectable change
MHz	Megahertz
mm	Millimetres
ms^{-1}	Metres per second
ms^{-2}	Metres per second squared
MT	Muscle thickness
MTU	Muscle-tendon unit
N	Newtons
Na^+	Sodium ion
P_{ang}	Pennation angle

PAP	Post-activation potentiation
$P_{\text{inst.}}$	Instantaneous power
PPO	Peak power output
RDL	Romanian deadlift
RFD	Rate of force development
RLC	Regulatory light chain
RM	Repetition maximum
ROM	Range of motion
RSI	Reactive strength index
SENIAM	Surface Electromyography for the Non-Invasive Assessment of Muscles
SSC	Stretch-shortening cycle
TA	Tibialis anterior
TCT	Traditional complex training
TE	Typical error
$V_{\text{inst.}}$	Instantaneous velocity
VL	Vastus lateralis
W	Watts
Δz	Negative vertical displacement
π	Pi

ABSTRACT

Maximum lower-body muscular strength and power are key determinants of successful performance in rugby league (Baker & Newton, 2009; Johnston, Gabbett, & Jenkins, 2014). Due to large amounts of concurrent energy system training and the congested fixture schedule throughout the competitive season there is limited time available for strength training (McLellan, Lovell, & Gass, 2011; Moreira, Kempton, Aoki, Sirotic, & Coutts, 2015). Strength and conditioning coaches are therefore challenged to prescribe appropriate training modalities which aim to maintain highly developed levels of strength and power.

Complex training is a mixed resistance training modality which aims to address strength and power during a single training session by alternating heavy resistance exercise, set for set, with explosive plyometric exercise (Docherty, Robbins, & Hodgson, 2004). This training modality is underpinned by post-activation potentiation (PAP) which refers to the acute augmentation of force and power production following a heavy load conditioning activity (Hodgson, Docherty, & Robbins, 2005; Tillin & Bishop, 2009). Since PAP and fatigue are simultaneously induced, an appropriate recovery interval is required to enhance explosive performance when the muscle has partially recovered from fatigue but is still potentiated (Docherty et al., 2004) which may limit its practical application.

This thesis aimed to investigate methods of eliciting PAP at shorter recovery intervals to enhance its practical applicability for strength and conditioning coaches. The main aims of this thesis were:

1. To determine any differences in the PAP response between the hex-bar deadlift (HBD) and back squat (BS) exercises and identify the optimal recovery interval required for PAP to manifest.
2. To examine if moderately loaded HBD and BS exercises combined with accommodating resistance elicit PAP at shorter recovery intervals.
3. To examine the difference in the magnitude of the PAP response between stronger, more experienced and weaker, less experienced athletes.
4. To examine muscle activation as a result of the PAP response using surface electromyography.
5. To investigate the chronic adaptations to muscle architecture and athletic performance following two complex training interventions over a 6-week mesocycle.

Chapter 1: Introduction

1.1 Post-Activation Potentiation

Post-activation potentiation (PAP) is a phenomenon which is characterised by the acute enhancement of force and power production following a maximal, or near maximal, voluntary muscle contraction (Gourgoulis, Aggeloussis, Kasimatis, Mavromatis, & Garas, 2003; Hodgson, Docherty, & Robbins, 2005; Tillin & Bishop, 2009). The near maximal voluntary muscular contraction is typically referred to as a conditioning activity (CA) (Batista, Roschel, Barroso, Ugrinowitsch, & Tricoli, 2011). Scientific literature has demonstrated that near maximal voluntary CAs can acutely enhance subsequent muscular performance during bench press throw (Esformes, Keenan, Moody, & Bampouras, 2011; Kilduff et al., 2007), vertical jumping (Comyns, Harrison, Hennessy, & Jensen, 2006; Crewther et al., 2011; Kilduff et al., 2008; Seitz, de Villarreal, & Haff, 2014) horizontal jumping (Ruben et al., 2010) and sprinting (McBride, Nimphius, & Erickson, 2005; Seitz, Trajano, & Haff, 2014; Wyland, Van Dorin, & Reyes, 2015). However, conflicting evidence has reported little to no improvement during explosive activities following the completion of a near maximal voluntary CA (Andrews et al., 2011; Comyns et al., 2006; Duthie, Young, & Aitken, 2002; Esformes, Cameron, & Bampouras, 2010; Jensen & Ebben, 2003; Jones & Lees, 2003; McCann & Flanagan, 2010).

Moreover, empirical evidence has reported that a recovery interval of 0.3-18.5 minutes is required between the completion of the CA and the subsequent explosive exercise to mediate the voluntary PAP response (Kilduff et al., 2008; Seitz, de Villarreal, et al., 2014; Seitz & Haff, 2015b). As such, the practical application of PAP in training scenarios can be limited. There is a lack of conclusive evidence with respect to the extent to which PAP can be reliably elicited and the mechanisms which underpin the response. Consequently, further research is required to investigate the modulating factors of PAP so that clearer guidelines with regard to the practical implementation of PAP can be developed.

1.2 Complex Training

A common training modality used to take advantage of the PAP response is complex training. The concept of complex training is credited to Russian sport scientist Yuri Verkhoshansky and refers to the alternation of biomechanically similar heavy resistance exercise, or CA, and explosive plyometric exercise on a set for set basis (Ali et al., 2017; Docherty, Robbins, & Hodgson, 2004; Fleck & Kontor, 1986; MacDonald, Lamont, & Garner, 2012; Weber, Brown, Coburn, & Zinder, 2008). For example, a back squat (BS) followed by a box jump or a bench press followed by a medicine ball power drop. The coupling of such CAs and plyometric exercises is typically referred to as a complex pair (Carter & Greenwood, 2014; Docherty et al., 2004). This is thought to be an effective and time efficient training modality for developing maximum strength and power as it enables both extremes of the force-velocity curve to be trained during a single session (Comyns, Harrison, & Hennessy, 2010; Ebben, 2002; Ebben & Watts, 1998; Robbins, Young, Behm, & Payne, 2009).

Complex training is widely used by strength and conditioning coaches in practical settings and has been examined in a number of reviews (Ali et al., 2017; Carter & Greenwood, 2014; Docherty et al., 2004; Ebben, 2002; Seitz & Haff, 2015a). Whilst resistance training and plyometric training are both key elements of an athlete's training programme in the development of muscular strength and power (Ali et al., 2017; Ebben & Blackard, 1997; MacDonald et al., 2012), research investigating the efficacy of complex training has provided equivocal results. This is likely to be due to a multitude of factors since a number of training variables must be taken into consideration when implementing complex training, such as: exercise selection, intensity and volume of the CA, and recovery interval between the CA and subsequent plyometric activity (Carter & Greenwood, 2014; Robbins, 2005; Tillin & Bishop, 2009). In addition, training status and strength levels of

the individual may also influence the voluntary PAP response and consequently the effectiveness of complex training (Kilduff et al., 2008; Seitz, de Villarreal, et al., 2014).

According to Fleck and Kontor (1986), Yuri Verkhoshansky defined complex training as a series of several exercises performed in succession with the aim of enhancing the ability to produce power quickly. Complex training was initially described as performing several sets of various heavy resistance exercises early in a training session followed by completing several sets of various high velocity movements later in the session (Fleck & Kontor, 1986; Janz & Malone, 2008). Whereas, the term contrast training was used to describe a training session whereby heavy load resistance exercise and high velocity movements were performed in alternation on a set for set basis (Duthie et al., 2002; Janz & Malone, 2008). However, the term complex training later adopted the definition of contrast training and the term complex pair was introduced to describe the coupling of the exercises (Chu, 1996; Ebben, 2002; Ebben & Blackard, 1997; Ebben & Watts, 1998). Consequently, some confusion exists as these two terms have been used interchangeably within academic literature (Duthie et al., 2002; Janz & Malone, 2008; Jones, Bampouras, & Comfort, 2013). Although these terms are still used interchangeably, it is important to clearly state that for the purpose of this thesis complex training will be defined as the alternation of heavy load resistance exercise and plyometric exercise on a set for set basis.

1.3 Adaptations to PAP and Complex Training

Although there is a large body of literature which has reported acute increases in force and power production during explosive activities following the completion of a CA, the exact physiological mechanisms underpinning the voluntary PAP response are not completely understood (Carter & Greenwood, 2014; Docherty et al., 2004). It is thought that PAP may occur as a result of increased myosin regulatory light chain (RLC) phosphorylation in response to voluntary CA (Baudry & Duchateau, 2007; Docherty et

al., 2004; Hodgson et al., 2005). There is also evidence to suggest that increased neural activation influences the voluntary PAP response; this may occur through the recruitment of higher order motor units, increased motor unit synchronisation, decreased presynaptic inhibition and increased α -motor neuron excitability (Docherty et al., 2004; Güllich & Schmidtbleicher, 1996; Hodgson et al., 2005). Additionally, a short-term decrease in muscle fibre pennation angle (P_{ang}) has also been proposed as a contributing factor to the voluntary PAP response (Mahlfeld, Franke, & Awiszus, 2004; Reardon et al., 2014). Collectively, these temporary neuromuscular adaptations may explain the observed improvements in jump performance (Comyns et al., 2006; Crewther et al., 2011; Kilduff et al., 2008; Seitz, de Villarreal, et al., 2014), sprint performance (McBride et al., 2005; Seitz, Trajano, et al., 2014; Wyland et al., 2015) and throwing performance (Esformes et al., 2011; Kilduff et al., 2007) in acute studies.

A common goal for strength and conditioning practitioners is to implement training programmes which induce chronic sport-specific adaptations (Tredrea, 2017). The chronic adaptations to resistance and plyometric training alone are well documented within scientific literature (Folland & Williams, 2007; Markovic & Mikulic, 2010; Potach & Chu, 2016). Research has consistently demonstrated that heavy resistance training enhances maximal force development, whereas more explosive exercise impact high velocity movements (Cormie, McGuigan, & Newton, 2010a, 2010c; Haff & Nimphius, 2012; Taber, Bellon, Abbott, & Bingham, 2016). Consequently, a mixed methods approach is recommended to induce optimal adaptations and enhance the transfer of the training effect due to a greater range of loading conditions enabling the development of the entire force-velocity curve (Figure 1.1) (Cormie, McGuigan, & Newton, 2011b; Haff & Nimphius, 2012; Haff, Whitley, & Potteiger, 2001). Therefore, complex training may be an effective training modality within sporting environments.

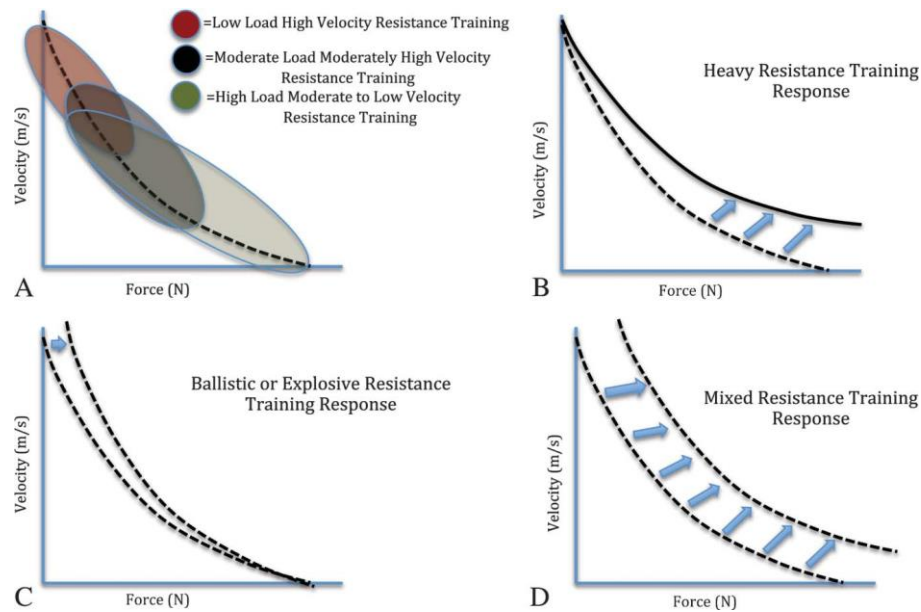


Figure 1.1 The potential impact of various training modalities on the force-velocity curve (Haff & Nimphius, 2012).

Despite research continually demonstrating acute enhancements in explosive performance due to the voluntary PAP response, there is limited evidence with respect to the chronic adaptations of complex training. Empirical evidence has reported that complex training may enhance athletic performance, or at worst show no decrement, in comparison to conventional training modalities (Dodd & Alvar, 2007; MacDonald et al., 2012; MacDonald, Lamont, Garner, & Jackson, 2013). Specifically, complex training related studies have found this training modality to improve levels of 1 repetition maximum (RM) strength (MacDonald et al., 2012; Stasinaki et al., 2015; Walker, Ahtiainen, & Häkkinen, 2010), power outputs (Dodd & Alvar, 2007; MacDonald et al., 2013; Stasinaki et al., 2015; Walker et al., 2010) and speed (Alves, Rebelo, Abrantes, & Sampaio, 2010; Dodd & Alvar, 2007). However, there is little literature reporting the chronic muscular adaptations due to complex training, which may explain the observed enhancements in athletic performance. The limited evidence has reported increases in muscle thickness (MT) and P_{ang} of the vastus lateralis (VL), increased P_{ang} of the gastrocnemius medialis (GM), decreased muscle fascicle length (L_f) of the GM and

increased type II muscle fibre cross-sectional area (CSA) (Stasinaki et al., 2015). The ability to take advantage of the voluntary PAP response may induce favourable adaptations therefore, further research is required to examine the chronic muscular and performance adaptations of complex training.

1.4 Strength, Power and Rate of Force Development

Power is a key element of athletic performance and is a determinant of success in various sports (Baker, 2001a, 2001b; Baker & Newton, 2009). There is a strong correlation between muscular strength and power therefore, the use of heavy resistance training appears to be crucial in the development of power (Baker, 2001b; Baker & Newton, 2009; Baker & Nance, 1999; Bompa & Buzzichelli, 2015). However, heavy resistance exercises typically involve slow contraction velocities (Baker & Newton, 2005, 2009; Newton, 2011). Given that power is a product of force and velocity, it has been recommended that a multifaceted approach is adopted to enhance power output (Baker & Newton, 2005, 2009). Although it has been reported that stronger individuals produce greater power outputs (Baker, 2001b; Baker & Nance, 1999) individuals who possess lower strength levels are still able to improve power output, emphasising that it is not just adaptations to maximum strength which contribute to overall power production (Cormie, McGuigan, & Newton, 2010b; Cormie et al., 2010c).

A vital component in optimising the transfer of power to athletic performance is rate of force development (RFD) (Aagaard, Simonsen, Andersen, Magnusson, & Dyhre-Poulsen, 2002a; Haff & Nimphius, 2012; Taber et al., 2016). RFD is a measure of explosive muscle strength which refers to the rate at which force is generated during a sporting movement (Aagaard et al., 2002a; Haff & Nimphius, 2012; McBride, Triplett-McBride, Davie, & Newton, 1999). Explosive movements such as jumping, sprinting, throwing, kicking and change of direction, are associated with fast contraction times of

30-250 milliseconds (Haff & Nimphius, 2012; Taber et al., 2016). However, it is unlikely that maximal force can be applied during these sport specific actions since it can take >300 milliseconds to generate maximum force (Figure 1.2) (Aagaard et al., 2002a; Haff & Nimphius, 2012; Taber et al., 2016). Consequently, RFD is arguably the most important characteristic which underpins athletic performance since it is the conduit between maximal strength and power (Aagaard, 2003; Stone, Moir, Glaister, & Sanders, 2002; Taber et al., 2016).

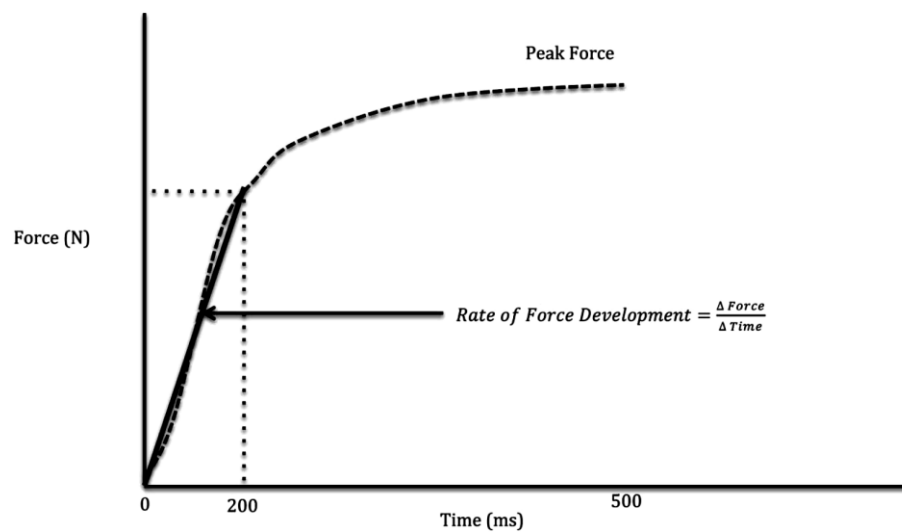


Figure 1.2 Isometric force-time curve (Haff & Nimphius, 2012).

Heavy resistance training enhances maximal force production and RFD capabilities of an athlete however, the reserve for adaptation is greater in weaker, less experienced athletes in comparison to their stronger, more experienced counterparts (Cormie et al., 2011; Haff & Nimphius, 2012; Newton & Kraemer, 1994). Although more explosive exercises have demonstrated greater increases in RFD in comparison to heavy resistance exercises, maximal force production is not improved to the same extent (Figure 1.3) (Cormie et al., 2010a, 2010c; Haff & Nimphius, 2012; Taber et al., 2016). Therefore, it is recommended that strength and conditioning practitioners adopt a mixed method approach when aiming to enhance maximal force production, power and RFD of their athletes (Haff & Nimphius,

2012; Haff et al., 2001; Taber et al., 2016). This involves the appropriate design and implementation of training programmes which incorporate a range of multi-joint heavy resistance and explosive exercises.

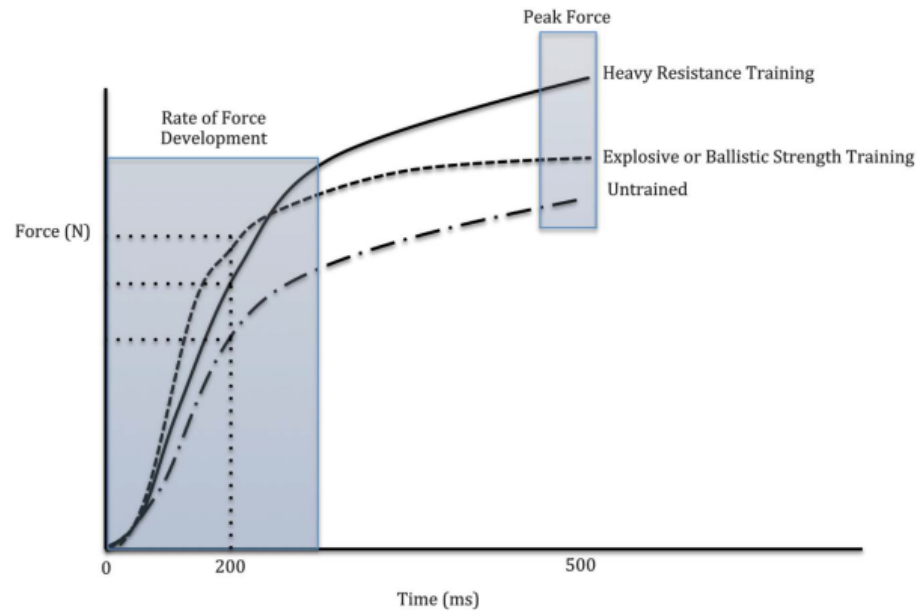


Figure 1.3 Isometric force-time curve demonstrating the rate of force development and maximum force generating capabilities in response to heavy resistance training and explosive training (Haff & Nimphius, 2012).

1.5 Complex Training in Rugby League

Rugby league is an international collision sport which originated in the North of England in the 1890s. The game is played predominantly in European, Australasian and Pacific countries at amateur, semi-professional, and professional level (Gabbett, 2002, 2005b, 2008; Gabbett, Jenkins, & Abernethy, 2011). Rugby league is played over two 40 minute halves (at senior level) separated by a 10 minute rest interval. Throughout match-play, players are subjected to frequent bouts of high intensity activities (e.g. high-speed running, sprinting, passing, tackling and high-impact collisions) separated by bouts of low intensity activities (e.g. standing, walking and jogging) and is therefore of a prolonged intermittent nature (Gabbett, 2000, 2002, 2005a). Playing positions in rugby league can be typically classified as forwards or backs. The specific playing positions

within each team (i.e. fullback, wing, centre, halfback, prop, hooker, second row and loose forward) can be split into four subgroups which reflect commonalities in position and playing role (i.e. hit-up forwards, wide-running forwards, outside backs, and adjustables/pivots) (Johnston et al., 2014; King, Jenkins, & Gabbett, 2009; Waldron, Twist, Highton, Worsfold, & Daniels, 2011). The specific playing positions within rugby league vary in physical demands due to their differing amount of game related activities (Gabbett, 2005b; Gabbett, King, & Jenkins, 2008; Sirotic, Knowles, Catterick, & Coutts, 2011). Regardless of playing position, rugby league players are required to possess highly developed levels of maximal aerobic power, speed, agility, strength, muscular endurance and power (Gabbett, 2005b; Gabbett et al., 2008). Consequently, strength and conditioning practitioners are challenged to appropriately implement multiple training modalities with the aim of enhancing these physical qualities.

Maximal strength, power and RFD are vital for successful performance in rugby league (Johnston et al., 2014; McLellan & Lovell, 2012; McLellan et al., 2011; McMaster, Gill, Cronin, & McGuigan, 2013). Additionally, these physical qualities are associated with reduced risk of injury (Gabbett & Domrow, 2005; Gabbett, Ullah, & Finch, 2012). Throughout the competitive rugby league season, it is challenging to maintain maximal strength and power due to the large amount of concurrent energy system training induced by multiple training modes (Baker, 2001a; McLellan et al., 2011; Moreira et al., 2015) (Table 1.1). Research has demonstrated that maximal strength can be maintained for up to 3-weeks of detraining (no resistance training) but the decay rate will increase thereafter (Issurin, 2008; McMaster et al., 2013). Power is most susceptible to interference as a result of conflicting neural patterns, fibre recruitment, and hormonal outputs (Baker, 2001a; Kraemer & Nindl, 1998; Kraemer et al., 1995). Empirical evidence suggests that

power requires an appropriate training stimulus (e.g. plyometric training) every 5-8 days to be maintained (Issurin, 2008; McMaster et al., 2013).

Table 1.1 Training modalities in rugby league (McLellan et al., 2011; Moreira et al., 2015)

Training Type	Description
Matches	Official rugby league matches
Skills	Individual rugby league skills and team tactics and strategy
Skills/Conditioning	Small-sided games, high-intensity conditioning drills designed to improve rugby league-specific fitness
Conditioning	Running sessions aimed at improving players' aerobic fitness, rugby league-specific endurance, weight training, and match fitness
Wrestle	Body-contact sessions aimed at improving both tackling and wrestling techniques
Speed	Short, intense drills aimed at improving speed, agility, and running technique
Recovery/Rehabilitation	Rehabilitation training, recovery, proprioception, and Pilates/core training

The maintenance of maximum strength and power is further complicated by the congested fixture schedule throughout the season, the turn-around time between games, the quality of the opposition, and whether the game involves significant away travel (Gamble, 2006; Kelly & Coutts, 2007; Moreira et al., 2015). Given the importance of strength and power in rugby league and the limited time available for strength training within a typical training week (Table 1.2) it is important that effective training strategies are implemented to maintain high levels of these physical attributes (Gamble, 2006; Kelly & Coutts, 2007; Moreira et al., 2015). This is essential in avoiding negative outcomes such as reduced performance and injury (Gabbett, 2016; Gamble, 2006; Kelly & Coutts, 2007; Moreira et al., 2015).

Table 1.2 An example of a typical training week in rugby league (McLellan et al., 2011; Moreira et al., 2015)

Day	AM	PM
Match day	OFF	Match 50-80 minutes
Day 1	Pool recovery/Massage 45 minutes	OFF
Day 2	Active recovery	OFF
Day 3	Skills/Conditioning 70 minutes	Weights 50 minutes
Day 4	Prehab/Weights 65 minutes	Skills/Speed 50 minutes
Day 5	Active recovery	OFF
Day 6	Skills 45 minutes	OFF

Complex training may be an advantageous training modality in rugby league since it enables both extremes of the force-velocity curve to be trained within a single session. This may be an effective and time-efficient training strategy to maintain high levels of muscular strength and power throughout the competitive season due to the limited amount of time strength and conditioning practitioners have available to work with their athletes. However, complex training is confounded by the PAP phenomenon since the recovery interval required to enhance subsequent explosive performance following the completion of a CA is reported to lie between 0.3-18.5 minutes (Kilduff et al., 2008; Seitz, de Villarreal, et al., 2014; Seitz & Haff, 2015b). Furthermore, there are multiple training variables which must be carefully considered when implementing complex training to ensure PAP is elicited, enabling athletes to take advantage of the enhanced force and power production capabilities in this heightened neuromuscular state. These include exercise selection, the intensity and volume of the CA, the recovery interval between the CA and subsequent plyometric activity as well as the strength level of the individual

(Carter & Greenwood, 2014; Kilduff et al., 2008; Robbins, 2005; Seitz, de Villarreal, et al., 2014; Tillin & Bishop, 2009). As a result, the major aim of this thesis is to investigate methods of eliciting the voluntary PAP response at shorter recovery intervals therefore increasing the efficacy of complex training and enhancing its practical value for strength and conditioning coaches.

1.6 Aims of the Thesis

Although both upper and lower body force and power production are key determinants of successful performance in rugby league (Baker & Newton, 2006, 2008; Gabbett, Jenkins, & Abernethy, 2010, 2011b; Johnston et al., 2014), the lower extremity arguably has a greater contribution to the movement demands of rugby league. For example, highly developed levels of lower body strength and power are required for match-play activities such as, high-speed running, sprinting, acceleration, deceleration, change of direction, jumping and kicking (Cronin & Hansen, 2005; Gabbett & Seibold, 2013; Johnston et al., 2014; Waldron, Worsfold, Twist, & Lamb, 2014). Whilst the upper body may be predominant in contact (i.e. tackling, wrestling, grappling, and collisions), lower body strength and power play a vital role in tackle success since the rapid development of momentum, effective leg drive and acceleration into the contact zone are important predictors of tackle success (Cronin & Hansen, 2005; Gabbett, Jenkins, & Abernethy, 2011a; Hendricks & Lambert, 2010). Therefore, this thesis will focus on the voluntary PAP response in the lower extremity and the following literature review will predominantly discuss research which has examined exercises to elicit PAP in the lower body.

The specific aims of this thesis are:

1. To determine the differences in the voluntary PAP response between the hex-bar deadlift (HBD) and BS exercises and identify the optimal recovery interval required for PAP to manifest.
2. To examine if moderately loaded HBD and BS exercises combined with accommodating resistance can elicit the voluntary PAP response at shorter recovery intervals of more practical value in real-world scenarios.
3. To examine the difference in the magnitude of the voluntary PAP response between stronger, more experienced and weaker, less experienced athletes.
4. To examine muscle activation as a result of the voluntary PAP response using surface electromyography (EMG).
5. To investigate the chronic adaptations to muscle architecture and athletic performance following two different 6-week complex training interventions where the recovery intervals implemented are based on scientific evidence.

Chapter 2: Literature Review

2.1 Purpose of Literature Review

The aims of this literature review are: (1) to provide an overview of the mechanical and architectural characteristics of skeletal muscle which are key with respect to force and power production; (2) to discuss the mechanisms of the voluntary PAP response and fatigue. The relationship between PAP and fatigue will be explored; (3) to critically examine the current knowledge base in relation to the training variables which influence the voluntary PAP response; (4) to critically examine the current knowledge base with respect to the practical application of PAP during complex training interventions.

2.2 Mechanical Characteristics of Muscle

2.2.1 Force-Velocity Curve

The force-velocity relationship refers to the properties of skeletal muscle which determines its power production capabilities (Cormie, McGuigan, & Newton, 2011a; Knudson, 2007). The inverse relationship between force and velocity during concentric muscle actions is attributed to Hill (1938) and explains how the force generated by an activated muscle fluctuates with respect to velocity. The force-velocity curve advocates that as the velocity of a concentric muscle action increases, the force generation capability of the muscle decreases (Figure 2.1). In contrast, the force a muscle can resist increases during high-velocity eccentric muscle actions (Knudson, 2007). This is due to actin-myosin cross-bridge cycling as it takes a constant amount of time for actin-myosin cross-bridges to attach and detach. The force produced by skeletal muscle is dependent on the number of cross-bridges; consequently, the force generating capability of skeletal muscle is reduced as the velocity of the concentric contraction increases (Cormie et al., 2011a). Therefore, power output can be optimised at a combination of submaximal forces and velocities (Lieber, 2010). This characteristic property of skeletal muscle is a limiting factor in all human movements (Komi, 1973; MacIntosh & Holash, 2000).

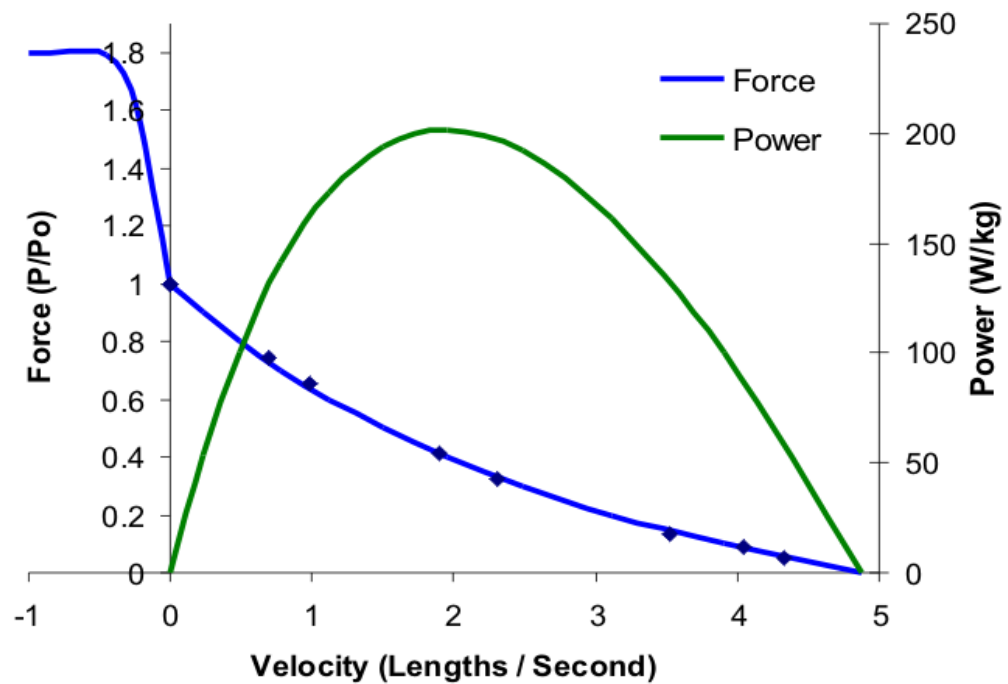


Figure 2.1 Force-velocity-power relationship of skeletal muscle (Newton, 2011).

Although maximal power output is governed by the force-velocity relationship, improvements in maximal power output can be achieved by increasing maximal force production and maximal velocity of concentric contraction through specific training (Knudson, 2007). Whilst the nature of the force-velocity curve cannot be altered, heavy resistance training can shift the curve upwards whereas lighter loads lifted at high velocities shift the curve to the right (Knudson, 2007). Furthermore, the force-velocity relationship displays differences in muscular performance based on muscle fibre composition (Knudson, 2007; MacIntosh & Holash, 2000), muscle architectural characteristics (Cormie et al., 2011a; Herbert & Gandevia, 1995), anatomical joint configuration (MacIntosh & Holash, 2000), and levels of neural activation (Caiozzo, Perrine, & Edgerton, 1981; Perrine, 1986). The ability of strength and conditioning coaches to understand this information and apply it in practical settings is essential in developing maximal power and RFD in athletes. Training modalities which enable both

extremes of the force-velocity curve to be trained, such as complex training, may be favourable for developing maximal power and RFD.

2.2.2 Length-Tension Relationship

The force generation capability of skeletal muscle is affected by sarcomere length (Knudson, 2007; Lieber, Loren, & Friden, 1994). The length-tension relationship illustrates how muscle force production varies at different sarcomere lengths (Figure 2.2). This variation in the potential force generating capability at different muscle lengths is influential in maximal power production (Cormie et al., 2011a; Knudson, 2007). The ability of skeletal muscle to produce the greatest amount of active tension is associated with the potential number of cross-bridges between actin and myosin filaments (Bartlett, 2007; Knudson, 2007; Lieber et al., 1994). This occurs when the sarcomere length provides an optimal overlap between actin and myosin filaments (Cormie et al., 2011a). The optimal length of skeletal muscle to produce maximal tension is approximately at the resting length of the muscle fibre (Bartlett, 2007; Knudson, 2007). In contrast, the shortening of sarcomeres to below optimal length reduces the ability of skeletal muscle to generate force as a result of actin filaments from opposite ends of the sarcomere overlapping and the compression of the myosin filament as the Z-lines are pulled towards the centre of the sarcomere (Knudson, 2007; Lieber, 2010). Similarly, if a sarcomere is stretched beyond its optimal length, the number of cross-bridges is decreased due to less overlapping between actin and myosin (Bartlett, 2007; Knudson, 2007; Lieber et al., 1994) therefore, force production is impaired. Finally, passive tension contributes to the total tension produced when the elastic components of the muscle are stretched (Bartlett, 2007; Knudson, 2007).

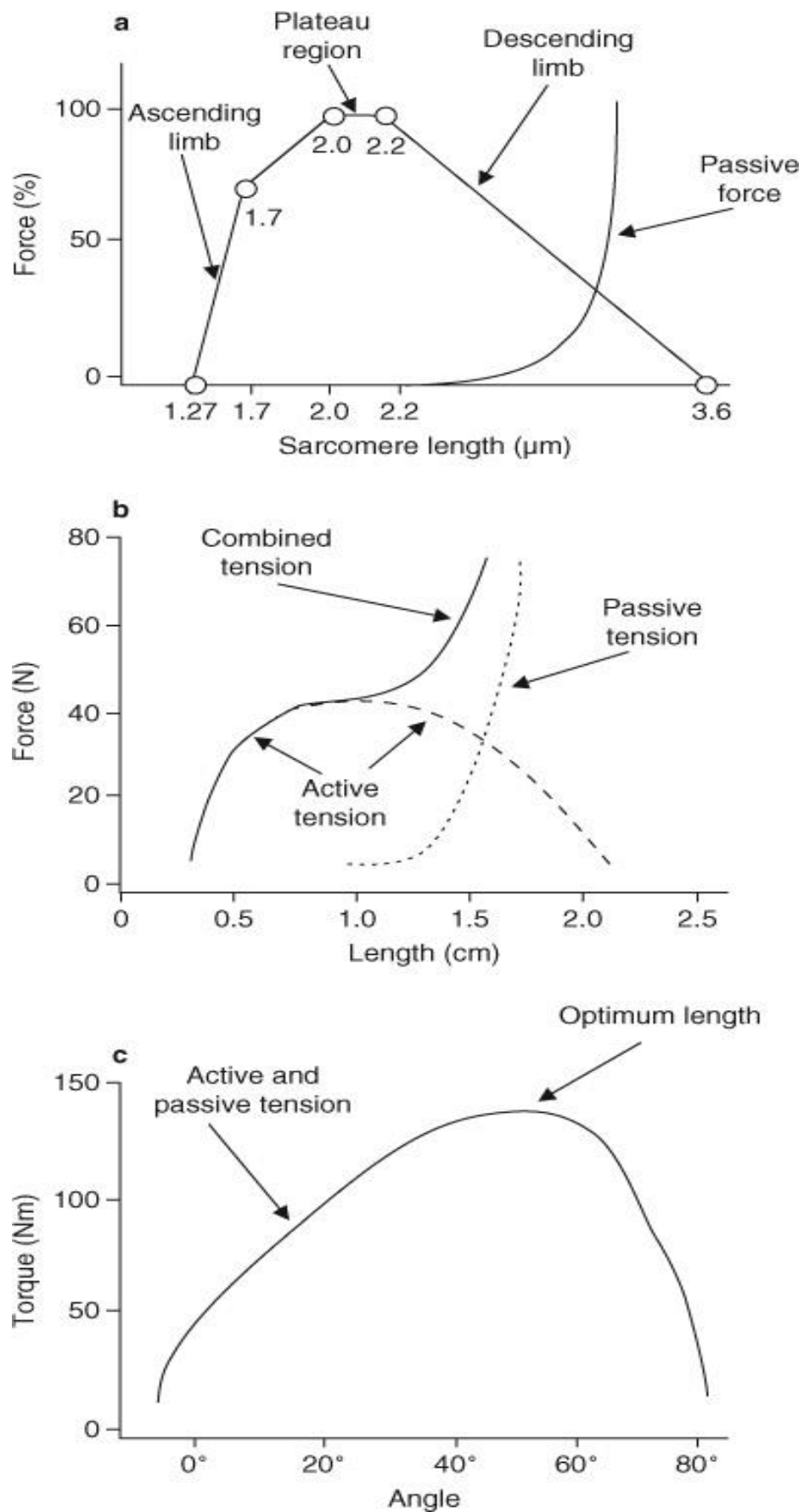


Figure 2.2 a) length-tension curve of a single muscle fibre; b) length-tension curve of a whole muscle; c) torque-angle curve (Brughelli & Cronin, 2007).

Although the peak force of the length-tension curve is identical between muscles, the operating ranges are different (Lieber & Fridén, 2000). Some muscles operate across the ascending and descending limbs of the length-tension curve whereas other muscles operate solely on the ascending or descending limbs of the curve (Brughelli & Cronin, 2007; Lieber & Fridén, 2000). More specifically, the VL muscle operates across the ascending, plateau and descending limbs of the curve (Son, Indresano, Sheppard, Ward, & Lieber, 2018). For example, during the BS exercise there is limited overlapping between actin and myosin filaments at the end range of the eccentric phase where the VL is operating on the descending limb of the length-tension curve. This creates a biomechanically disadvantageous position, commonly referred to as a “sticking point”, which reduces the production of force and acceleration (Anderson, Sforzo, & Sigg, 2008; Nijem, Coburn, Brown, Lynn, & Ciccone, 2016; Wyland et al., 2015). Towards the end range of the concentric phase there is a short period of time where the force generating capability of the muscle is at its greatest (Mina, Blazeovich, Giakas, & Kay, 2014; Nijem et al., 2016). This corresponds to the plateau region of the length-tension curve where the overlapping of actin and myosin is optimal. It has been reported that the optimum knee angle for peak force generation for the VL occurs at approximately 20° flexion, where 0° is full extension (Son et al., 2018).

The GM muscle, however, operates on the ascending limb and plateau of the length-tension curve (Maganaris, 2001; Maganaris, 2003). Research has reported that the optimum angle for peak force generation is approximately 15-20° dorsiflexion, where 0° is a neutral anatomical position with the foot at right angles to the shank (Maganaris, 2001; Maganaris, 2003). When the ankle is in this position the overlapping between actin and myosin is optimal and the GM is operating on the plateau region of the length-tension curve. As the ankle dorsiflexion angle decreases and progresses into plantarflexion, the

force production of the GM gradually decreases due to the overlapping of actin from opposite ends of the sarcomere (Maganaris, 2001; Maganaris, 2003). Consequently, the GM is operating on the ascending limb of the length-tension curve. This explains the importance of dorsiflexion of the ankle joint prior to ground contact during explosive activities such as sprinting or lower body plyometric training to generate maximum force (Phillips & Flanagan, 2015).

The length-tension curve can be shifted to the right through appropriate training modalities, in particular eccentric training, which may have beneficial implications for athletic performance and injury prevention (Brughelli & Cronin, 2007; Byrne, Eston, & Edwards, 2001). A shift in optimal length could mean that the descending limb of the length-tension curve, a region of instability where force production levels decrease, is not reached during eccentric activities (Brughelli & Cronin, 2007; Byrne et al., 2001). Therefore, the muscle will maintain stability at longer lengths; this may occur due an increase in fibre length as a result of a greater number of sarcomeres in series (Brughelli & Cronin, 2007). It is important for strength and conditioning coaches to understand the length-tension relationship and implement appropriate training strategies which could enhance athletic performance whilst reducing the risk of injury.

2.2.3 Stretch-Shortening Cycle

In accordance with the force-velocity relationship, human skeletal muscle cannot produce large forces when contracting rapidly (Cormie et al., 2011a; Knudson, 2007; Taber et al., 2016). Research has demonstrated that the shortening velocity of human skeletal muscle is limited since it takes a fixed amount of time for myosin to associate and dissociate from actin (Cormie et al., 2011a; Nyitrai et al., 2006; Sargeant, 2007). Therefore, there is a decreased number of cross-bridges attached at high shortening velocities (Cormie et al., 2011a). In practical sporting scenarios, force production is hindered by the time

constraints of sport specific actions (Cormie et al., 2011a; Taber et al., 2016). Consequently, human skeletal muscle relies on the stretch-shortening cycle (SSC) to maximise force production during high velocity movements (Knudson, 2007). The SSC is a natural type of muscle function which occurs in various actions, such as jumping, running and throwing (Komi, 2003). Although the exact mechanism underpinning the SSC remains unclear, it is thought that it may be due to the interaction between the mechanical and neurophysiological characteristics of the muscle's contractile components (Goodwin & Jeffreys, 2016; Potach & Chu, 2016).

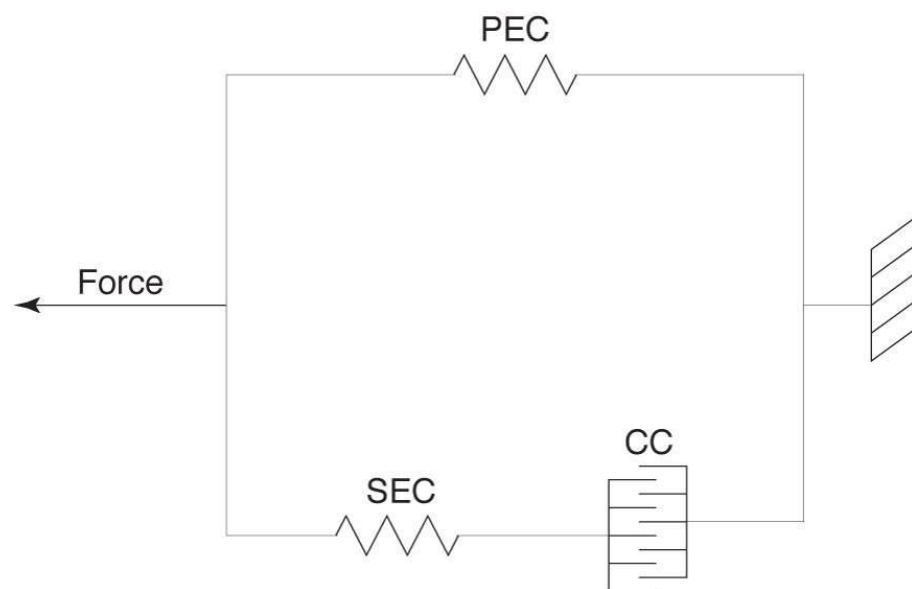


Figure 2.3 Hill's (1938) three component mechanical model of skeletal muscle.

The SSC is a muscle-tendon unit (MTU) phenomenon which refers to the rapid eccentric to concentric contraction of skeletal muscle whereby greater force and power outputs are achieved in comparison to that which would occur from a concentric-only contraction (Flanagan & Comyns, 2008; Goodwin & Jeffreys, 2016; Komi, 2003). Hill's (1938) three component mechanical model (Figure 2.3) illustrates the relationship between the elastic components of the MTU and the contractile components. The contractile component (actin, myosin, and cross-bridges) produces an active force and is the predominant source of muscular force exertion during concentric contractions (Goodwin & Jeffreys, 2016;

Potach & Chu, 2016). The series elastic component (SEC) is comprised of the tendon, aponeurosis and cross-bridges (Cormie et al., 2011a; Goodwin & Jeffreys, 2016; Potach & Chu, 2016). The parallel elastic component (PEC) is composed of epimysium, perimysium, endomysium and sarcolemma which exert a passive force with unstimulated muscle stretch (Potach & Chu, 2016).

During the eccentric phase, where the MTU is stretched, the SEC acts as a spring and absorbs energy (Flanagan & Comyns, 2008; Potach & Chu, 2016). This energy is temporarily stored and released if the muscle begins a concentric action immediately following the eccentric action which enables greater force and power outputs as the energy is reused (Bobbert, Gerritsen, Litjens, & Van Soest, 1996; Cormie et al., 2011a; Potach & Chu, 2016). However, it has been reported that a delay of one second in the transition between the eccentric and concentric phase, known as the amortisation phase, can lead to dissipation of more than 50% of the stored elastic energy as heat (Flanagan & Comyns, 2008; Potach & Chu, 2016; Wilson, Murphy, & Pryor, 1994). Therefore, it is imperative that the amortisation phase is short to ensure that the stored elastic energy is reutilised (Flanagan & Comyns, 2008). SSC actions can be classified as either fast, where contraction time is <0.25 seconds with small angular displacements at the ankles, knees and hip joints, or slow, where contraction time is >0.25 seconds with larger angular displacements (Flanagan & Comyns, 2008; Goodwin & Jeffreys, 2016; Markovic & Mikulic, 2010; Schmidtbleicher, 1992). Slower SSC actions include countermovement jumps (CMJ) and squat jumps, whereas fast SSC actions include drop jumps (DJ) and bounding (Flanagan & Comyns, 2008; Slimani, Chamari, Miarka, Del Vecchio, & Chéour, 2016). As such, strength and conditioning coaches must carefully design their training programmes to ensure that the chosen exercises incorporate appropriate SSC actions specific to the demands of the athlete's sport.

Another underpinning mechanism of the SSC is the stretch reflex (Figure 2.4) which is an involuntary response to rapid changes in muscle length (Cormie et al., 2011a; Goodwin & Jeffreys, 2016; Potach & Chu, 2016). This reflexive component of the SSC is predominantly composed of muscle spindle activity (Potach & Chu, 2016). Muscle spindles are mechanoreceptors located in intrafusal fibres and are innervated by γ -motor neurons (Lephart, Pincivero, Giraldo, & Fu, 1997; Riemann & Lephart, 2002). The lengthening of the MTU during the eccentric phase of SSC activities causes a mechanical deformation of the muscle spindles which activates the stretch reflex of α -motor neurons (Cormie et al., 2011a; Schmidt & Lee, 2005). Since muscle spindles are sensitive to the rate of change in muscle length, a reflexive muscle action occurs to protect the MTU as the rapid eccentric action could cause damage to the complex (Flanagan & Comyns, 2008; Potach & Chu, 2016). Consequently, there is a change in force-velocity characteristics of the muscle's contractile component (potentiation) resulting in enhanced force production during the concentric muscle action (Enoka, 1994; Flanagan & Comyns, 2008; Potach & Chu, 2016).

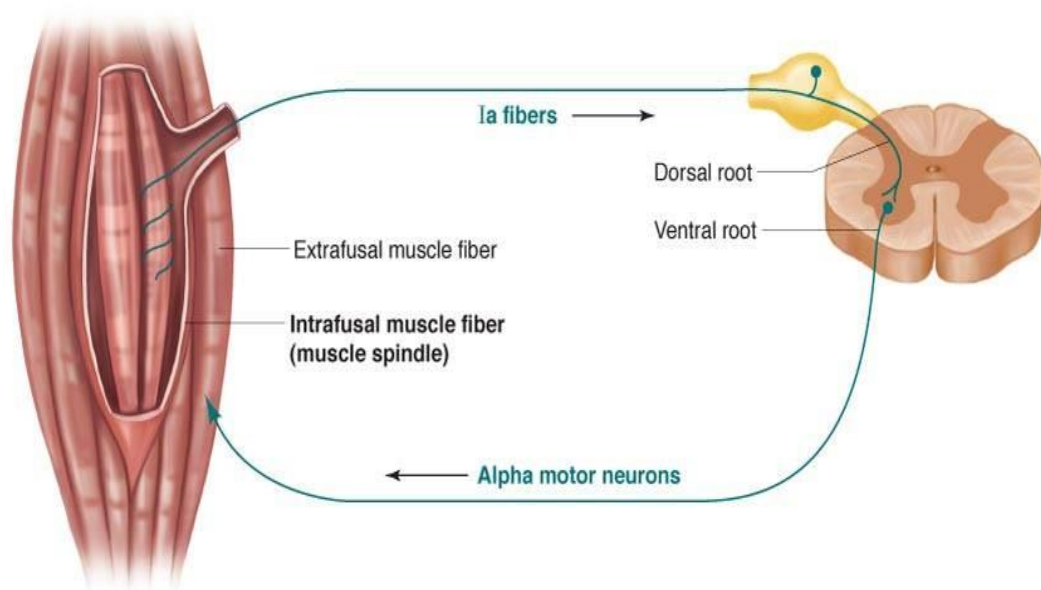


Figure 2.4 The stretch reflex (Potach & Chu, 2016).

Muscle spindle activity is inhibited by the golgi tendon organ (GTO) which is a proprioceptor located in extrafusal muscle fibres and is innervated by α -motor neurons (Enoka, 2008; Riemann & Lephart, 2002). The GTO responds to changes in muscle tension and acts as a protective mechanism to prevent damage to the MTU during activities which produce large contractile forces (Flanagan & Comyns, 2008; Goodwin & Jeffreys, 2016). There is an increase in afferent activity when contractile forces are large enough to cause damage to the MTU which facilitates heightened levels of excitability in motor neurons innervating antagonist muscles while simultaneously inhibiting motor neurons innervating agonist muscles (Flanagan & Comyns, 2008; Lephart et al., 1997; Riemann & Lephart, 2002). Consequently, the GTO acts as an inhibitor of force production during periods of high muscle tension (Flanagan & Comyns, 2008; Goodwin & Jeffreys, 2016). However, plyometric training can induce a downregulation of GTO activity in the agonist muscle therefore enabling the toleration of high contractile forces with reduced inhibition of force production (Goodwin & Jeffreys, 2016).

It is thought that peak force production is augmented 45-55 milliseconds following the rapid muscle stretch due to the latency of increased muscle activation (30-40 milliseconds) and electromechanical delay (15 milliseconds) (Goodwin & Jeffreys, 2016; Komi, 2003). Therefore, sport specific SSC actions which are shorter than this time-frame are unlikely to benefit from the stretch reflex (Goodwin & Jeffreys, 2016). However, most sporting SSC actions typically last 100-300 milliseconds and are preceded by pre-tensioning of the muscle (Brown, 2007; Goodwin & Jeffreys, 2016; Komi, 2003; Taber et al., 2016; Walshe, Wilson, & Ettema, 1998). The pre-tensioning of the muscle refers to a pre-emptive phase of activation where the muscle spindles are activated and sensitised prior to ground contact and the key phase of force production (Goodwin &

Jeffreys, 2016; Komi, 2003). This, in turn, enables the elastic component of the MTU to store and release the potential energy more effectively since intense muscular activation can increase the number of active cross-bridges (Komi, 2003). Furthermore, the displacement of muscle fibres during SSC actions is minimal therefore, based on the length-tension relationship, sarcomeres are able to operate nearer their optimal length (Cormie et al., 2011a). Although the shortening velocity of the MTU during SSC actions is high, muscle L_f shortening velocity is relatively slow; consequently, based on the force-velocity curve, it is possible for muscle fascicles to produce large forces (Cormie et al., 2011a; Fukashiro, Hay, & Nagano, 2006).

Finally, the stretch response of the MTU upon receiving the load during SSC actions is dependent on the magnitude and rate of loading (Goodwin & Jeffreys, 2016). It has been suggested that increased MTU stiffness enables a more rapid and efficient return of the stored elastic strain energy from the stretch response (Goodwin & Jeffreys, 2016; Markovic & Mikulic, 2010; Wilson & Lichtwark, 2011). This is because an increase in MTU stiffness reduces the time required to stretch the SEC which affects the electromechanical delay and RFD (Bojsen-Møller, Magnusson, Rasmussen, Kjaer, & Aagaard, 2005; Folland & Williams, 2007). However, there is also evidence which suggest that a more compliant MTU may be more advantageous in the storage and release of elastic strain energy during SSC actions (Kubo et al., 2007; Stafilidis & Arampatzis, 2007; Wilson, Wood, & Elliott, 1991). A plausible explanation for this is that different MTUs operate optimally at different levels of stiffness (Fouré, Nordez, Guede, & Cornu, 2009; Markovic & Mikulic, 2010).

Collectively, it appears that both mechanical and neural properties of the MTU contribute to increased force production during the concentric phase of SSC actions however, the extent to which each mechanism contributes to this remains unclear (Potach & Chu,

2016). Nevertheless, a comprehensive understanding of the SSC is paramount for strength and conditioning practitioners, especially in rugby league, since training programmes can be designed to take advantage of the SSC, optimising force and power production. Moreover, the SSC exercises incorporated into strength and conditioning programmes must be sport specific.

2.3 Muscle Architecture

The ability to generate maximum power outputs is dictated by the contractile capacity of the muscles involved with the specific athletic movement (Cormie et al., 2011a). The contractile capacity of a muscle is dependent upon a number of morphological features including architectural features (Cormie et al., 2011a). Muscle architecture refers to the organisation of muscle fibres within a muscle relative to the axis of force production (Lieber & Fridén, 2000). Common aspects of muscle architecture which are investigated include MT, P_{ang} and L_f (Lieber & Fridén, 2000). The shortening velocity of skeletal muscle is influenced by biochemical factors such as, adenosine triphosphatase activity (Abe, Kumagai, & Brechue, 2000). However, research has demonstrated that muscle architecture can modulate such biochemical effects (Abe et al., 2000).

2.3.1 Muscle Thickness

Morphological adaptations of skeletal muscle to resistance training are thought to be associated with improvements athletic performance (Blazevich, 2006; Blazevich, Gill, & Zhou, 2007; Earp et al., 2010). Increases in MT, which is indicative of muscle CSA, have been observed in response to resistance training and are highly correlated with force generation capabilities (Cormie et al., 2011a; Earp et al., 2010; Seynnes, de Boer, & Narici, 2007). The maximal force produced by a muscle fibre is directly proportional to its CSA, regardless of the muscle fibre type (Cormie et al., 2011a). Since peak power output (PPO) is influenced by maximal force production, a muscle with a greater CSA

can generate increased power output (MacIntosh & Holash, 2000; Malisoux, Francaux, Nielens, & Theisen, 2006; Widrick, Stelzer, Shoepe, & Garner, 2002).

Scientific research has demonstrated that increases in CSA and maximal force production typically enhance PPO (MacIntosh & Holash, 2000; Malisoux et al., 2006; Widrick et al., 2002; Wilson, Newton, Murphy, & Humphries, 1993). This research typically involved relatively untrained participants therefore any increases in CSA may have been due to less experienced individuals having a greater reserve for adaptation (Bompa & Buzzichelli, 2015; Fleck, 1999). In contrast, increases in CSA following a heavy resistance exercise training programme are likely to be less and take longer to manifest in more experienced individuals (Cormie et al., 2011a; Sale, 1988). The magnitude of muscular hypertrophy is dependent upon a number of training variables including, type of exercise, intensity, volume and frequency (Wernbom, Augustsson, & Thomeé, 2007). Scientific evidence suggests that heavy load resistance exercise is typically utilised to mediate a hypertrophic response whereas lighter, more explosive loads exploited during power training do not elicit this response (Komi, Suominen, Heikkinen, Karlsson, & Tesch, 1982; Potteiger et al., 1999; Wernbom et al., 2007). However, research has reported increases in type I and type II muscle fibre CSA when plyometric training has been implemented (Malisoux et al., 2006; Potteiger et al., 1999). It is important to note that the participants of these studies had no experience in a structured plyometric training programme. As such, further research is required to elucidate the effects of different training modalities on MT.

2.3.2 Pennation Angle

Muscle fibre P_{ang} is defined as the angle between the muscle fascicles and the inner aponeurosis which provides information regarding the orientation of muscle fibres in relation to connective tissue (Folland & Williams, 2007; Tillin & Bishop, 2009). P_{ang} is

important in relation to athletic performance as it affects the force-velocity relationship and consequently power output (Cormie et al., 2011a; Earp et al., 2010; Folland & Williams, 2007; Reardon et al., 2014). An increase in P_{ang} is associated with an increase in force production as this allows a greater number of sarcomeres to be arranged in parallel and increases the packing of muscle fibres within a given anatomical CSA (Cormie et al., 2011a; Earp et al., 2010; Folland & Williams, 2007; Fukunaga et al., 2001; Reardon et al., 2014). This enables a greater amount of contractile tissue to attach to a given area of tendon or aponeurosis (Kawakami, Abe, Kuno, & Fukunaga, 1995). It is theorised that an increased P_{ang} enables muscle fibres to work closer to their optimum length as they have to shorten less for a given tendon displacement due to the rotation of pennate muscle fibres during contraction (Blazevich, Gill, Bronks, & Newton, 2003; Cormie et al., 2011a). In addition, the shortening velocity of a muscle fibre decreases due to the displacement of the muscle fibre during contraction; according to the force-velocity relationship, force production will increase (Blazevich, 2006; Cormie et al., 2011a).

Since increased P_{ang} are associated with slow contraction velocities, this may negatively impact the shortening velocity of muscle fibres and subsequently power output (Cormie et al., 2011a). Although there is an increase in the packing of muscle fibres within a given anatomical CSA, there is less force from each muscle fibre transmitted and utilised by the tendon due to the increased oblique angle of pull (Blazevich, 2006; Folland & Williams, 2007; Ikegawa et al., 2008). The resultant force of all of the muscle fibres transmitted to the tendon during contraction is reduced by a factor of $\cos\theta$ (Blazevich, 2006; Folland & Williams, 2007; Tillin & Bishop, 2009). A smaller P_{ang} has a greater mechanical advantage in relation to force transmission from the muscle to the tendon (Folland & Williams, 2007; Tillin & Bishop, 2009). Therefore, the effect of P_{ang} on force production

and power output is a trade-off between mechanical advantage and packing of muscle fascicles (Folland & Williams, 2007).

Research has demonstrated that P_{ang} increases in response to heavy resistance training (Blazevich, Cannavan, Coleman, & Horne, 2007; Duclay, Martin, Duclay, Cometti, & Pousson, 2009; Seynnes et al., 2007). Furthermore, increases in P_{ang} have also been accompanied by increases in CSA and maximum force production (Aagaard et al., 2001; Alegre, Jiménez, Gonzalo-Orden, Martín-Acero, & Aguado, 2006) subsequently increasing PPO (Andersen & Aagaard, 2000; Andersen et al., 2005). Although an increase in P_{ang} does not necessarily result in hypertrophy, this evidence suggests that hypertrophy involves an increase in P_{ang} (Folland & Williams, 2007). However, other longitudinal training intervention studies have reported little or no change in P_{ang} as a result of heavy resistance training (Blazevich, Gill, Deans, & Zhou, 2007; Blazevich & Giorgi, 2001; Rutherford & Jones, 1992). Collectively, these findings demonstrate that the effects of heavy strength training on P_{ang} are not well understood. Furthermore, it is unknown if other training modalities can impact P_{ang} . Therefore, further research is required to elucidate the effects of different training modalities on P_{ang} .

2.3.3 Fascicle Length

In humans, muscle L_f has been shown to be indicative of muscle fibre length (Cormie et al., 2011a). Although the shortening velocity of a sarcomere varies between muscle fibre types, the shortening velocity of a muscle fibre is proportional to its length assuming that muscle activation levels are constant (Cormie et al., 2011a; MacIntosh & Holash, 2000). Consequently, a greater muscle L_f is associated with the ability to produce force over large length ranges and increased shortening velocities due to a larger number of sarcomeres in series simultaneously contracting (Blazevich, 2006; Earp et al., 2010).

Furthermore, the shortening velocity of each sarcomere in a muscle fibre is slower for a given whole-fibre shortening velocity; according to the force-velocity relationship, sarcomere force would not decrease as quickly in relation to the increase in fibre shortening velocities (Blazevich, 2006). Therefore, longer muscle L_f are able to generate greater forces at higher shortening velocities (Blazevich, 2006). Since power output is determined by the ability to produce force at high velocities, longer fibre lengths contribute to the generation of greater power outputs (Cormie et al., 2011a; MacIntosh & Holash, 2000). This is substantiated by correlational research which has reported significant relationships between muscle L_f of the VL and GM and 100-metre sprint times (Abe, Fukashiro, Harada, & Kawamoto, 2001; Kumagai et al., 2000). In addition, muscle L_f has been shown to be greater in top 100-metre sprint runners in comparison to long distance runners (Abe et al., 2000) and lesser-trained sprinters (Kumagai et al., 2000). Therefore, it is conceivable that muscle L_f alters force-length characteristics of a muscle fibre and consequently the muscle of which it is a constituent (Willems & Huijing, 1994).

The adaptation of muscle L_f in response to training is not well understood. However, the limited research has reported increases in L_f in response to heavy load resistance exercise (Blazevich, Cannavan, et al., 2007; Reeves, Maganaris, & Narici, 2004; Seynnes et al., 2007) as well as light load resistance exercise (Alegre et al., 2006) and individuals who ceased strength training and performed jump and sprint training only (Blazevich et al., 2003). In contrast, other research implementing heavy load resistance training programmes have demonstrated no effect on muscle L_f in the upper (Kawakami et al., 1995) or lower body (Blazevich, Gill, Deans, et al., 2007; Rutherford & Jones, 1992). Although some of these adaptations were coupled with improvements in performance, the extent to which muscle L_f affects maximum shortening velocity, force production and power output remains unclear. Strength training is typically associated with increases in

P_{ang} and decreases in muscle L_f , whereas individuals who perform speed training appear to have increased muscle L_f and decreased P_{ang} . Therefore, it is possible that morphological adaptations to training are velocity-specific (Blazevich et al., 2003). Consequently, further research is required to investigate the effects of heavy load resistance training combined with high contraction velocities (e.g. plyometric training) in order to elucidate the most effective training modality for the growth of muscle fibres and the enhancement of athletic performance.

2.4 Mechanisms of PAP

The underlying mechanisms of PAP are not clear at present however, it is thought that it could be due to increased phosphorylation of the myosin RLC heightening the sensitivity of actin and myosin to Ca^{2+} availability, increased excitability of α -motor neurons, and short-term decreases in muscle fibre P_{ang} (Docherty et al., 2004; Tillin & Bishop, 2009; Wilson et al., 2013). It is thought that the most plausible explanation for the potentiated state of a muscle following maximal, or near maximal, stimulation is the phosphorylation of myosin RLC (Baudry & Duchateau, 2007; Docherty et al., 2004; Hodgson et al., 2005). However, there is evidence which suggests that the PAP response could be due to increased neural activity; this may occur through the recruitment of higher order motor units, a decrease in presynaptic inhibition, or increased α -motor neuron excitability (Docherty et al., 2004; Güllich & Schmidbleicher, 1996; Hodgson et al., 2005). In addition, research examining the phosphorylation of myosin RLCs and post-tetanic potentiation (potentiation response due to an involuntary contraction) concluded the PAP response may be a result of interactions between neural and muscular mechanisms (Tubman, MacIntosh, & Maki, 1996). Finally, there is research which suggests that short-term decreases in muscle fibre P_{ang} may also be an influential factor in contributing to PAP (Mahlfeld et al., 2004; Reardon et al., 2014) however, research investigating this

mechanism is limited. The ability to understand these mechanisms and how specific muscle groups respond to near maximal voluntary contractions may be of benefit in eliciting an enhanced PAP response. As such, this is of importance for strength and conditioning practitioners aiming to improve the force and power production of their athletes.

2.4.1 Phosphorylation of Myosin Regulatory Light Chains

The interaction between actin and myosin filaments plays a vital role in the production of force (Szczesna, 2003). Research has demonstrated that there is a strong correlation between acute increases in myosin RLC phosphorylation and increases in twitch force in response to tetanic stimulation of specific efferent neural fibres in animals (Grange, Vandenboom, & Houston, 1993; Manning & Stull, 1982; Moore & Stull, 1984; Szczesna et al., 2002). However, there are few studies which have replicated a similar response in human skeletal muscle (Stuart, Lingley, Grange, & Houston, 1988; Tillin & Bishop, 2009; Vandervoort, Quinlan, & McComas, 1983). Nevertheless, the evidence suggests that changes in the excitation-contraction coupling process may be an important factor in eliciting a PAP response.

Near maximal voluntary contractions are thought to potentiate subsequent muscular contractions due to increased phosphorylation of myosin RLCs (Hodgson et al., 2005; Sale, 2002; Tillin & Bishop, 2009). This occurs through the activation of myosin light chain kinase, an enzyme which catalyses the phosphorylation of myosin RLCs, when Ca^{2+} is released from the sarcoplasmic reticulum via ryanodine receptors during muscular contraction and binds to the calcium regulatory protein calmodulin (Grange et al., 1993; Hodgson et al., 2005; Jones et al., 2013; Szczesna, 2003; Szczesna et al., 2002; Vandenboom, Grange, & Houston, 1995). This is theorised to potentiate subsequent muscular contractions due to a structural alteration as the myosin head moves away from

the filament surface therefore, making it is easier for the actin filament to interact with the myosin head and increasing the rate of actin-myosin cross-bridging (Hodgson et al., 2005; Jones et al., 2013; Szczesna, 2003; Tillin & Bishop, 2009). Phosphorylation of myosin RLCs also renders the actin-myosin complex more sensitive to Ca^{2+} released from the sarcoplasmic reticulum; consequently, phosphorylation of the myosin RLCs exerts its greatest effect in circumstances where Ca^{2+} concentrations are relatively low, as evidenced during low frequency tetanic contractions (Baudry, Klass, & Duchateau, 2008; Hodgson et al., 2005; Sale, 2002; Tillin & Bishop, 2009). The increased number of cross-bridges and rate of cross-bridge cycling enhances the explosive capability of the muscle during subsequent contractions in this potentiated state (Bevan et al., 2010; Docherty et al., 2004; Hodgson et al., 2005; Szczesna, 2003; Szczesna et al., 2002; Tillin & Bishop, 2009).

More specifically, Stuart et al. (1988) reported an association between increased phosphate content of RLC and twitch potentiation proceeding a 10 second isometric voluntary contraction of the knee extensors. Smith and Fry (2007) reported that individuals who expressed elevated phosphorylation of myosin RLCs improved voluntary muscular performance post-CA, whereas those with decreased phosphorylation levels of myosin RLCs responded negatively to a voluntary CA. It is thought that methodological techniques and differences in fibre type distribution is responsible for the inconsistencies observed in human studies in comparison to animals (Tillin & Bishop, 2009). Collectively, the research suggests that an underpinning mechanism of PAP may be due to changes in the excitation-coupling process however, more research is required in human populations to clarify this assumption. It is possible that the phosphorylation of myosin RLC is not the only contributing mechanism to the PAP response (Docherty et

al., 2004; Hodgson et al., 2005; Stuart et al., 1988; Tillin & Bishop, 2009; Tubman et al., 1996).

2.4.2 Increased Recruitment of Higher Order Motor Units

An increase in the recruitment of higher order (Type II) motor units is another proposed mechanism which underpins the PAP response (Docherty et al., 2004; Hodgson et al., 2005; Tillin & Bishop, 2009). Typically, research has assessed this theory by measuring the amplitude of the Hoffman-reflex (H-reflex) in humans using EMG (Folland, Wakamatsu, & Fimland, 2008; Güllich & Schmidtbleicher, 1996; Trimble & Harp, 1998). The H-reflex is a result of an afferent neural volley in response to the submaximal stimulation of type Ia afferent muscle nerves and indicates the number and magnitude of motor units recruited (Folland et al., 2008; Hodgson et al., 2005; Tillin & Bishop, 2009). It is theorised that an increase in the H-reflex is a result of elevated transmission efficiency between Ia afferent terminals and post-synaptic membranes of α -motor neurons of homologous muscle (Hodgson et al., 2005). Therefore, this may represent a decrease in presynaptic inhibition and an increase in α -motor neuron excitability (Hodgson et al., 2005; Tillin & Bishop, 2009). As a result, there is an increase in action potential propagation from type Ia neural fibre terminals across synaptic junctions at the spinal cord (Hodgson et al., 2005; Tillin & Bishop, 2009). According to Henneman's size principle, the recruitment of motor units by type Ia afferent nerves follows a hierarchical pattern from smallest to largest diameter (Henneman & Olson, 1965; Hodgson et al., 2005; Tillin & Bishop, 2009; Zehr, 2002). It is assumed that, in accordance with the size principle, an increase in H-reflex amplitude following a voluntary CA may be indicative of activation of larger, high-threshold, fast motor units (Hodgson et al., 2005). In addition, the ability to recruit high-threshold motor units, and have them discharge at a high frequency, is regarded as a key factor in force production (Güllich & Schmidtbleicher,

1996; Hodgson et al., 2005). As such, it is assumed that the activation of higher-order motor units during a voluntary CA may be responsible for the increase in force production during subsequent contraction of skeletal muscle (Güllich & Schmidtbleicher, 1996; Hodgson et al., 2005). This potentiated state can last for several minutes (Güllich & Schmidtbleicher, 1996; Tillin & Bishop, 2009).

The theory that PAP is a result of the recruitment of higher-order motor units during a voluntary CA is attributed to the initial work of Güllich and Schmidtbleicher (1996), who examined the H-reflex amplitude before and after a 5 second isometric maximal voluntary contraction of the plantar-flexors. The results indicated a significant decrease in H-reflex amplitude immediately following the CA; however, H-reflex amplitude was significantly potentiated 4-13 minutes post-CA. In addition, a significant Pearson correlation coefficient ($r = 0.90$) between the time course changes of H-reflex amplitude and explosive isometric force production was observed. Furthermore, Trimble and Harp (1998) reported an increased H-reflex amplitude in response to a voluntary CA, 3-10 minutes following 8 sets of 10 repetitions of dynamic maximal voluntary contractions of the triceps surae muscles. Similarly, Folland et al. (2008) demonstrated an increased H-reflex amplitude following a 10 second isometric maximal voluntary contraction in the quadriceps femoris muscle group 5-11 minutes post-CA.

However, these results may have been influenced by inherent methodological constraints associated with H-reflex measurements (Hamada, Sale, MacDougall, & Tarnopolsky, 2000; Hodgson et al., 2005; Tillin & Bishop, 2009). For example the amplitude of the H-reflex was not normalised to the muscle compound action potential amplitude (M-wave). Consequently, an increase in EMG amplitude can be attributed to the stimulation of the muscle fibre membrane's $\text{Na}^+\text{-K}^+$ pump activity (Hamada, Sale, MacDougall, & Tarnopolsky, 2003; C. K. Thomas, Johansson, & Bigland-Ritchie, 2006). As such, the

normalisation of EMG amplitude to the M-wave is important since it nullifies the effect of peripheral changes in membrane excitability, enabling central drive to be more reliably quantified (Arabadzhev, Dimitrov, Dimitrova, & Dimitrov, 2010; Lepers, Maffiuletti, Rochette, Brugniaux, & Millet, 2002). In addition, the H-reflex appeared to be evoked under resting muscle conditions which may not reflect changes in neuromuscular function and performance during actual muscle contraction (Aagaard, Simonsen, Andersen, Magnusson, & Dyhre-Poulsen, 2002b; Voigt, Chelli, & Frigo, 1998).

Although research suggests that the recruitment of higher-order motor units may be a contributing mechanism to PAP, Duchateau, Semmler, and Enoka (2006) state that the upper limit of motor unit recruitment is approximately 85% of maximal force in most muscles. Therefore, the increased recruitment of higher-order motor units as a contributing mechanism to PAP following a maximal voluntary CA may be minimal. Taking this into consideration alongside the methodological constraints associated with H-reflex measurements, the effect of a maximal voluntary CA on motor unit recruitment during subsequent voluntary contractions remains to be determined.

It has been previously demonstrated that an increase in surface EMG amplitude is synonymous with enhanced levels of motor unit recruitment (Farina, Fosci, & Merletti, 2002). The use of surface EMG is advantageous as it enables neural activation to be assessed in a non-invasive manner during explosive plyometric exercise within applied PAP studies. As such, Hough, Ross and Howatson (2009) reported an increase in surface EMG amplitude in human skeletal muscle during a concentric-only vertical jump where dynamic stretching was utilised as a PAP inducing stimulus. However, research which has utilised heavy load CAs as a PAP stimulus have reported no improvement in surface EMG amplitude during the subsequent plyometric activity (Ebben, Jensen, & Blackard, 2000; Fukutani et al., 2014; Jones & Lees, 2003). There is a limited amount of research

which has used surface EMG to investigate motor unit activity during the plyometric exercise following a heavy load PAP stimulus. Therefore, studies which assess the voluntary PAP response on a neural level in an applied setting are required.

2.4.3 Changes in Pennation Angle

Although the phosphorylation of myosin RLCs and increased recruitment of higher order motor units are well documented, the underpinning mechanism of the voluntary PAP response is yet to be elucidated. There is evidence, albeit very limited, to suggest that acute changes in muscle architecture may contribute to the voluntary PAP response (Tillin & Bishop, 2009). Research has demonstrated that the potentiated state of a muscle may be due to an improvement in the coupling of muscle fibres to the tendon (Fukunaga, Ichinose, Ito, Kawakami, & Fukashiro, 1997; Ishikawa, Finni, & Komi, 2003). Consequently, a near maximal voluntary contraction may induce alterations to the muscle-tendon interface (Mahlfeld et al., 2004). More specifically, muscle P_{ang} appears to affect force transmission from the muscle fibres to the tendons therefore affecting power output (Folland et al., 2008; Fukunaga et al., 1997; Tillin & Bishop, 2009). For example, larger P_{ang} are thought to be associated with increased force generating capabilities however, the force per CSA has been reported to decrease (Earp et al., 2010; Ikegawa et al., 2008). In contrast, a smaller P_{ang} is synonymous with greater shortening velocities and increased rate of force transmission in the muscles (Kumagai et al., 2000).

Although limited, acute studies investigating the effects of a CA on muscle P_{ang} have demonstrated short-term decreases in this muscle architecture variable. Mahlfeld et al. (2004) used ultrasound to assess P_{ang} of the VL before and after a 3 second isometric maximal voluntary contraction. Immediately post-CA, there was no change in P_{ang} ; however, there was a significant decrease in P_{ang} 3-6 minutes post-CA. Similarly, Reardon et al. (2014) reported acute decreases in VL muscle P_{ang} at 8 and 20 minutes following

three different squat protocols however, there was no significant PAP response was observed.

These studies are not without limitations as the authors acknowledges methodological factors which may have influenced the results. As such, the time points at which P_{ang} was measured may have been too short to draw any conclusions with respect to this architectural potentiation phenomenon (Mahlfeld et al., 2004). Furthermore, Reardon et al. (2014) instructed each participant to lay supine on an examination table for 15 minutes prior to ultrasound examination. Following the squat protocols, more ultrasound images were recorded at 8 and 20 minutes in the same position. It is likely that the movement from a standing position to a supine position resulted in fluid shift which may have skewed the ultrasound data and also affected jump performance (Berg, Tedner, & Tesch, 1993). Additionally, research has reported that voluntary CAs are likely to increase compliance of muscle tendons which may inhibit enhanced force transmission of skeletal muscle as a result of decreased P_{ang} (Kubo, Kanehisa, Kawakami, & Fukunaga, 2001).

It has been suggested that acute changes in muscle architecture changes may be more important as a stimulus for the onset of the remodelling process as opposed to a voluntary PAP mechanism (Mahlfeld et al., 2004). It is plausible that chronic adaptations to muscle architecture could be an influential factor of the voluntary PAP response. There is currently very little research which has investigated the longitudinal effects of complex training on muscle architecture (Stasinaki et al., 2015) and the subsequent effect of this on the voluntary PAP response. Therefore, the muscle architecture adaptations as a result of complex training require investigation to determine if favourable adaptations can be induced.

2.5 Balance between PAP and Fatigue

Scientific research has demonstrated that it is possible for PAP and fatigue to coexist therefore, the enhancement of muscular performance following the completion of a near maximal CA appears to be dependent on the net balance between and fatigue (Docherty et al., 2004; MacIntosh & Rassier, 2002; Rassier & MacIntosh, 2000). The force and power production capability of skeletal muscle may decrease if fatigue predominates PAP, increase if PAP predominates fatigue, or remain unchanged if levels of PAP and fatigue are similar; the PAP-fatigue model (Figure 2.5) illustrates the theoretical relationship between these two parameters (Sale, 2002). Whilst fatigue predominates in the early stages of recovery following the CA, negating the PAP effect, it is generally accepted that fatigue dissipates at a greater rate than PAP; consequently, muscular performance is enhanced at the time point where the muscle has partially recovered from fatigue but is still in a potentiated state (Docherty et al., 2004; Hodgson et al., 2005; Tillin & Bishop, 2009). However, if the recovery is too long then the PAP response may also decay and no enhancement in performance will be observed (Hodgson et al., 2005; Sale, 2002; Tillin & Bishop, 2009).

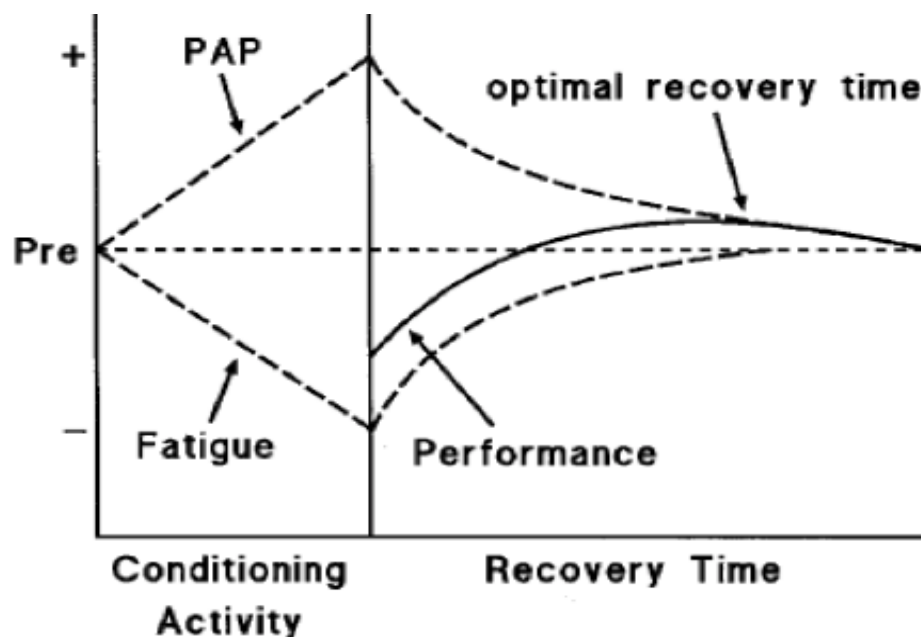


Figure 2.5 The theoretical relationship between PAP and fatigue (Sale, 2002).

The mechanisms of fatigue are not fully understood however, they are likely to be due to a combination of central (e.g. neural inhibition) and peripheral (e.g. accumulation of hydrogen ions (H^+) and inorganic phosphates) factors (Allen, Lamb, & Westerblad, 2008; Kent-Braun, 1999; MacIntosh, 2003). Given that there are several processes which take place during muscle activation, failure at any point in the sequence could cause fatigue (Rassier & MacIntosh, 2000). Nevertheless, it is likely that fatigue associated with a near maximal CA could be due to the accumulation of H^+ and inorganic phosphates leading to impairments in the release of Ca^{2+} from the sarcoplasmic reticulum (MacIntosh, 2010; Rassier & MacIntosh, 2000). This could result in reduced peak myoplasmic Ca^{2+} concentrations and myofibrillar Ca^{2+} sensitivity therefore inhibiting the force and power production capability of skeletal muscle even in the presence of PAP (Allen et al., 2008; Hamada et al., 2003; Vandervoort et al., 1983). Therefore, it is crucial for the effects of fatigue to be minimised to take advantage of the voluntary PAP response. This could be achieved by enhancing resistance to fatigue via appropriate training modalities (e.g. resistance training) which are associated with increased buffering capacity and resistance to skeletal muscle damage (Kendrick et al., 2008; McHugh, Connolly, Eston, & Gleim, 1999; Sale, 2002; Skulachev, 2000). This may explain why strength level and training status influence the voluntary PAP response.

More recently, it has been suggested that there may actually be two opportunities for the voluntary PAP response to manifest (Figure 2.6) (Jones et al., 2013; Tillin & Bishop, 2009). Empirical evidence has reported that the magnitude and recovery interval of the voluntary PAP response can be influenced by loading volume and intensity of the CA (Sale, 2002; Wilson et al., 2013). When the loading volume of the CA is lower, less fatigue is induced enabling PAP to be realised at an earlier recovery interval (Window 1 in Figure 2.6) (French, Kraemer, & Cooke, 2003; Gourgoulis et al., 2003). However, the

PAP response may not be elicited if the loading volume is too low to stimulate the underpinning mechanisms of the response (Tillin & Bishop, 2009). In contrast, when the loading volume of the CA is greater, fatigue predominates PAP; therefore, a longer recovery interval is required before explosive performance is acutely augmented (Window 2 in Figure 2.6) (Chatzopoulos et al., 2007; Güllich & Schmidtbleicher, 1996; Kilduff et al., 2007). In addition, the PAP response may be negated by fatigue during the recovery window (Hodgson et al., 2005; Rassier & MacIntosh, 2000; Tillin & Bishop, 2009). Research also suggests that CAs of more moderate intensities (60-85% 1RM) may be more beneficial than those of higher intensities (>85% 1RM) (Sale, 2002; Wilson et al., 2013). The equivocal findings in acute PAP studies are likely to be due a combination of factors including, the characteristics of the CA and of the individual (Figure 2.7) (Carter & Greenwood, 2014; Kilduff et al., 2008; Robbins, 2005; Seitz, de Villarreal, et al., 2014; Tillin & Bishop, 2009). Given that it may be possible to elicit PAP at an earlier recovery interval, methods of reducing fatigue and maximising the voluntary PAP response require investigation.

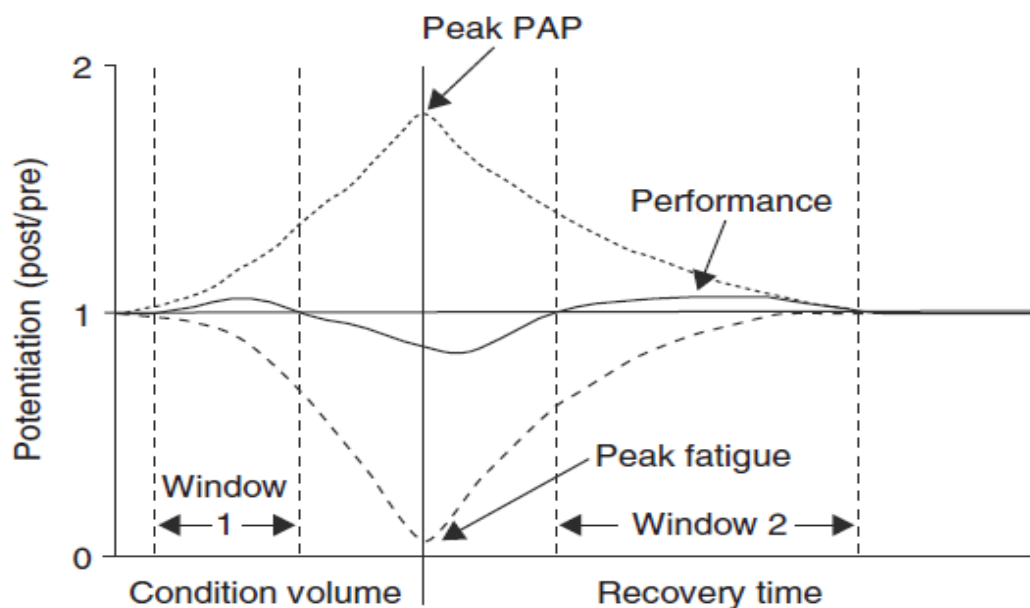


Figure 2.6 The hypothetical relationship between PAP and fatigue (Tillin & Bishop, 2009).

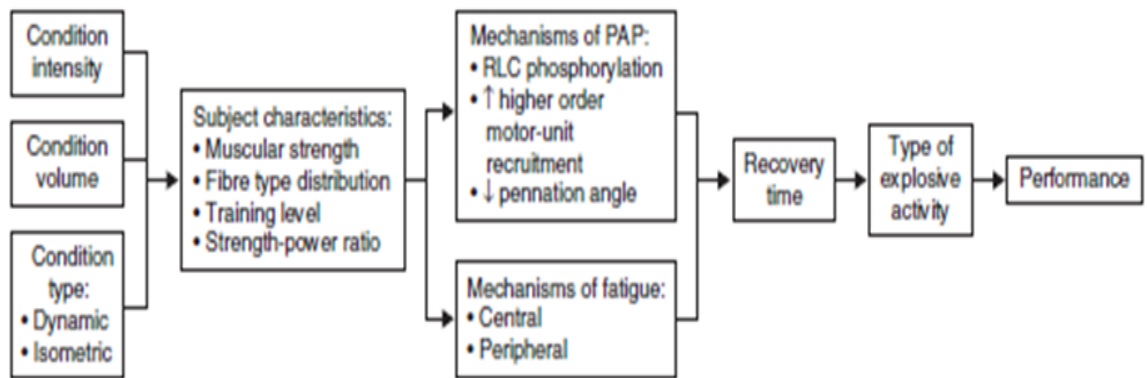


Figure 2.7 The multiple factors influencing the performance of an explosive activity following the completion of a voluntary CA (Tillin & Bishop, 2009).

2.6 Modulating Factors of Post-Activation Potentiation

Scientific research has investigated the effects of voluntary CAs on the PAP response in both the upper and lower extremities (Appendix A). For example, numerous acute studies have been conducted to examine the effects of near maximal voluntary contractions on subsequent muscular performance during explosive sporting activities such as, jumping (Jones & Lees, 2003; Kilduff et al., 2008; Ruben et al., 2010), throwing (Baker, 2001a, 2009; Esformes et al., 2011) and sprinting (Comyns et al., 2010; Seitz, Trajano, et al., 2014; Wyland et al., 2015). Although the relative contributions of the underpinning mechanisms of PAP remain unclear, there is a growing body of scientific evidence to suggest that force and power production of skeletal muscle is temporarily augmented following a voluntary CA (Bevan et al., 2010; Crewther et al., 2011; Kilduff et al., 2007, 2008; Seitz, de Villarreal, et al., 2014). However, conflicting empirical evidence has reported no change or decreases in subsequent explosive activities (Andrews et al., 2011; Comyns et al., 2006; Jensen & Ebben, 2003; Jones & Lees, 2003; McCann & Flanagan, 2010). Collectively, this evidence demonstrates that no conclusions can be drawn as to whether PAP can be reliably elicited through voluntary CAs. Furthermore, the results of these studies have been equivocal due to the fact that a number of variables must be

considered when utilising complex training such as: the recovery interval between the CA and subsequent plyometric action, exercise selection, the load of the CA, the volume of the CA and the training status of the individual (Carter & Greenwood, 2014; Docherty et al., 2004; Robbins, 2005; Tillin & Bishop, 2009). Therefore, future research should determine the modulating factors which influence the voluntary PAP response in order to develop clear training programmes which strength and conditioning coaches can implement within their practice.

2.6.1 Intra-Complex Recovery Interval

As previously discussed, an increase in muscular performance is dependent upon the balance between the co-existence of fatigue and PAP following a voluntary CA (Rassier & MacIntosh, 2000). According to the PAP-fatigue model, fatigue dissipates at a greater rate than PAP; therefore, force and power production are enhanced when the working muscles have partially recovered from fatigue but are still in a potentiated state (Docherty et al., 2004; Tillin & Bishop, 2009). As such, there is a window of opportunity to acutely augment performance when an appropriate intra-complex recovery interval (ICRI), the recovery period between the CA and subsequent plyometric activity, is applied. This model is consistent with previously discussed research investigating the underpinning mechanisms of PAP as significant changes in H-reflex response and P_{ang} were only observed following a recovery interval (Folland et al., 2008; Güllich & Schmidtbleicher, 1996; Mahlfeld et al., 2004; Trimble & Harp, 1998). The duration of PAP manifestation is currently unclear however, it has been suggested that it is likely that the PAP response dissipates within 30 minutes of completing a CA (Rixon, Lamont, & Bembien, 2007; Wilson et al., 2013).

Interpretation of the optimal ICRI required to elicit PAP is difficult as research has investigated recovery intervals ranging from 10 seconds (Jensen & Ebben, 2003) up to

24 minutes (Kilduff et al., 2008). Empirical evidence has indicated that the optimal ICRI may lie between 0.3 and 18.5 minutes (Kilduff et al., 2008; Seitz, de Villarreal, et al., 2014; Seitz & Haff, 2015b). To date, the limited number of PAP studies which have examined the optimal ICRI have produced varying and conflicting results. For example, it has been reported that a short ICRI of 4-5 minutes (Crewther et al., 2011; Esformes et al., 2010; Mitchell & Sale, 2011), moderate ICRI of 8-12 minutes (Crewther et al., 2011; Kilduff et al., 2007, 2008; Seitz, de Villarreal, et al., 2014), and long ICRI of 18.5 minutes (Chiu et al., 2003) elicit a PAP response. Although the research is inconclusive with respect to the optimal ICRI required to maximise subsequent performance, it is generally accepted that a 4-12 minute recovery interval should be applied when attempting to elicit a voluntary PAP response in the lower body (Bevan et al., 2010; Crewther et al., 2011; Kilduff et al., 2007, 2008; Seitz, de Villarreal, et al., 2014). However, what does appear conclusive is that immediately (10-30 seconds) after the CA, there is a decrease in subsequent performance due to fatigue being greater than the PAP response (Crewther et al., 2011; Jensen & Ebben, 2003; Jones & Lees, 2003; Kilduff et al., 2007, 2008; Seitz, de Villarreal, et al., 2014).

A meta-analysis by Gouvêa, Fernandes, César, Silva and Gomes (2013) suggests that an ICRI of 8-12 minutes is optimal when eliciting PAP in the lower body. Contrastingly, a meta-analysis by Seitz and Haff (2015b) propose a shorter ICRI of 5-7 minutes. Consistent with both of these findings is a meta-analysis by Wilson et al. (2013) which suggests that shorter ICRIs of 3-7 minutes and moderate ICRIs of 7-10 minutes maximise the PAP response. Interestingly, trained athletes with at least 1 year of resistance training experience expressed PAP following more moderate ICRIs of 7-10 minutes, whereas experienced athletes who had 3 or more year's resistance training experience expressed PAP at shorter ICRIs of 3-7 minutes. This appears to be consistent with acute PAP

research studies which also suggest that training status and strength levels influence the PAP response (Jo, Judelson, Brown, Coburn, & Dabbs, 2010; Kilduff et al., 2007, 2008; Seitz, de Villarreal, et al., 2014). Furthermore, Wilson et al. (2013) suggest that moderately loaded CAs of 60-85% of 1RM are better able to elicit PAP in comparison to heavy loads of >85% of 1RM.

Collectively, these findings substantiate the PAP-fatigue model which suggests that there are two windows of opportunity to elicit PAP. It is theorised that a lower intensity CA evokes a PAP response almost immediately after the CA (window 1); this is due to PAP rising more sharply than fatigue (French et al., 2003; Gourgoulis et al., 2003). However, a higher intensity CA initially induces a greater fatigue response than PAP which negatively affects muscular performance. Therefore, an appropriate ICRI (window 2) is required in order for fatigue to dissipate and PAP to be realised, consequently muscular performance is temporarily enhanced (Chatzopoulos et al., 2007; Güllich & Schmidtbleicher, 1996; Kilduff et al., 2007). The findings within scientific research investigating the optimal ICRI required to elicit PAP appear to be equivocal due to methodological inconsistencies such as, training status and magnitude of the CA. As such, various training variables must be considered in order to effectively elicit a PAP response and subsequently enhance muscular performance.

2.6.2 Optimal Load

It typically thought that PAP is induced by traditional heavy load CAs, such as the BS exercise, which are greater than 85% of 1RM (Bevan et al., 2010; Kilduff et al., 2007, 2008; Seitz, de Villarreal, et al., 2014). Despite the resistive load of the CA appearing to be an influential factor in eliciting PAP there is limited scientific research which has specifically examined the effects of different CA loads on the PAP response. Comyns, Harrison, Hennessy and Jensen (2007) investigated the effects of different BS loads on

the PAP response on 12 elite rugby players. The participants performed three repetitions of one of the specified resistive loads of 65%, 80% or 93% of 1RM. Following a 4 minute ICRI, three single-legged sledge DJs were completed from a height of 0.3m; a sledge frame with rails inclined at 30°, a sliding chair and a force platform were used to assess SSC performance. This was considered to be one complex pair; a total of three complex pairs were completed, with a 6 minute recovery interval between complex pairs, to cater for the three resistive loads. Each participant performed all three conditions during a single visit and the order of the resistive loads were randomised. The results indicated that although all resistive loads significantly reduced ground contact time (GCT), lifting at 93% of 1RM also resulted in improved leg stiffness (K_{leg}) during the single-legged sledge DJ. This suggests that using heavier loads may result in greater fast SSC performance. However, a possible limitation of this study is that one set of BS at a specified resistive load may have impacted upon the performance of the next complex pair. Therefore, future studies of a similar design should consider conducting each resistive load on a different testing day.

These results are substantiated by Moir, Mergy, Witmer and Davis, 2011) who investigated the acute effects of a high-load BS protocol in comparison to a high volume BS protocol on the PAP response in 11 female NCAA division II volleyball players. The participants either performed three repetitions at 90% of 1RM or twelve repetitions at 37% of 1RM followed by 10 CMJs every 2 minutes. The experimental sessions were conducted on different days. The results demonstrated no increase in jump height for either condition however, there was a significant improvement in MTU stiffness during the CMJ 4-20 minutes following the high-load condition. The improvement in MTU stiffness in these studies could be due to increased neural activation as a result of the CA; it is plausible that this increased neural activation contributed to the observed increase in

stiffness (Comyns et al., 2007). The observed increases in K_{leg} may be due to alterations to the MTU (Mahlfeld et al., 2004) affecting the way in which it behaves during explosive plyometric actions and resulting in fast SSC being performed more rapidly (Comyns et al., 2007).

Moreover, Fukutani et al. (2014) examined the PAP response due to a single set of 3 repetitions of moderately loaded (75% of 1RM) BS in comparison to heavy loaded (90% of 1RM) BS in 8 Olympic weightlifters. The results revealed a significant improvement in CMJ height following both conditions however, the heavy load induced significantly greater improvements in comparison to the moderate load. Therefore, it appears that the PAP response is more likely to be elicited using heavier loads as these findings are in agreement with previous research which has utilised heavy loads (>85%) to induce a PAP response (Crewther et al., 2011; Gourgoulis et al., 2003; Kilduff et al., 2007, 2008; Mitchell & Sale, 2011; Seitz, de Villarreal, et al., 2014; Weber et al., 2008; Young, Jenner, & Griffiths, 1998). However, results remain equivocal as other studies which have investigated the use of heavy load CAs on PAP have demonstrated no improvements or decreases in performance measure (Comyns et al., 2006; Jensen & Ebben, 2003; Jones & Lees, 2003; McCann & Flanagan, 2010; Till & Cooke, 2009). It is typically thought that this may be due to stronger athletes with more experience of resistance training being better able to express PAP in comparison to their weaker and less experienced counterparts (Jo et al., 2010; Kilduff et al., 2007, 2008; Seitz, de Villarreal, et al., 2014; Wilson et al., 2013). In general, studies which have used less experienced individuals have demonstrated no significant PAP response whereas a significant PAP response has been observed in studies using more experienced individuals; however, this is not always the case, highlighting that numerous training variables must be considering when attempting to elicit a PAP response.

There is limited research which has investigated the effects of lighter or moderate loads on the PAP response in the lower body. For example, Smilios, Pilianidis, Sotiropoulos, Antonakis and Tokmakidis (2005) utilised 3 sets of 5 repetitions of loaded jump squats at 30% and 60% 1RM where CMJs were used as a performance measure 1 minute after each set (3 minutes recovery between complex sets) and at 5 and 10 minutes following the completion of all sets. The results indicated a PAP response following sets 1 and 2 for the 30% 1RM condition and after sets 2 and 3 for the 60% 1RM condition in comparison to baseline. Similarly, Clark, Bryant and Reaburn, (2006) investigated the effect of a single set of 6 repetitions of loaded CMJs (40kg) on the subsequent performance of 4 sets of 6 repetitions of loaded CMJ (20kg). A 4 minute recovery interval was employed between sets. The results revealed a significant improvement in displacement following set 3, and improved PPO after sets 2 and 3. However, a limitation of these studies is that the use of multiple sets may have influenced the PAP response. Moreover, results reported by McBride et al. (2005) indicated that a single set of 3 repetitions of BS at 90% of 1RM expressed a significant improvement in 40-metre sprint performance 4 minutes post-CA in comparison to a single set of 3 repetitions of loaded CMJs at 30% of 1RM. Evidently, further research is required to provide a greater understanding of the effects of lighter and moderate loads on the PAP response in the lower body as the limited evidence has demonstrated equivocal findings.

2.6.2.1 Accommodating resistance

Traditional heavy load resistance exercises, such as BS, typically involve high force production and slow contraction velocities (Baker & Newton, 2005, 2009; Newton, 2011). The mechanics involved in such lifts, due to the body's lever systems and the length-tension relationship of skeletal muscle, creates a biomechanically disadvantageous position; this is commonly referred to as the "sticking point" and inhibits power

production (Anderson et al., 2008; Edman, 2003; Nijem et al., 2016; Wyland et al., 2015). For example, during the BS the end range of the eccentric phase will act as a sticking point, whereas the end range of the concentric phase enables optimal force production for a short period of time (Mina et al., 2014; Nijem et al., 2016). However, the latter stages of the concentric phase also induce slow contraction velocities as the bar decelerates towards the top of the lift (Baker & Newton, 2009; Shoepe, Ramirez, & Almstedt, 2010). Consequently, heavy load resistance exercise trains the neuromuscular system to decelerate towards the end of the range of motion (ROM) which is, generally, not specific to sporting activities (Baker & Newton, 2009).

Accommodating resistance is theorised to modify the force-velocity curve during resistance exercise by adding a percentage of the total resistance through latex bands or chains (Baker, 2008). This enables additional resistance to be applied as the barbell continues through the ROM during the concentric phase of a lift (Baker & Newton, 2009; Wyland et al., 2015). Consequently, the effects of sticking points are reduced which results in increased acceleration and velocity during the concentric phase of the lift; this enables greater power outputs to be achieved (Anderson et al., 2008; Baker & Newton, 2009; Nijem et al., 2016; Wallace, Winchester, & McGuigan, 2006; Wyland et al., 2015). According to Schmidbleicher (1992) near maximal contractions performed at high velocities induce the greatest neural adaptations. As such, the utilisation of accommodating resistance may be an optimal method of evoking a PAP response as the length-tension relationship is accounted for (Edman, 2003; Nijem et al., 2016; Wyland et al., 2015). This reduction in sticking points may enhance type IIb muscle fibre recruitment and elicit optimal adaptations (Wyland et al., 2015). Moreover, the increased acceleration and contraction velocities throughout the full ROM may translate more specifically to the subsequent plyometric or SSC actions (Crewther et al., 2011; Crum, Kawamori, Stone,

& Haff, 2012) since the rapid production of force throughout the full ROM is a necessity in most sports (Baker, 2008; Wyland et al., 2015). In addition, it has been suggested that the use of accommodating resistance reduces joint stress throughout the ROM (McCurdy, Langford, Jenkerson, & Doscher, 2008; Nijem et al., 2016) and therefore, could be a safer and more suitable resistance training method for all levels of athletes in comparison to traditional heavy load resistance exercises.

Interestingly, there is evidence to suggest that it may be possible to evoke a PAP response by utilising a moderate load combined with accommodating resistance, equating to a heavy load (Baker, 2008; Wyland et al., 2015). Baker (2008) examined the effects of 4 sets of 2 repetitions of paused box squats combined with accommodating resistance ($68 + 6-19.6\%$ 1RM) in the form of elastic bands. Loaded (80kg) jump squats were used as a performance measure 75-90 seconds after each box squat (3 minutes recovery between complex sets). The results demonstrated a PAP response in sets 2, 3 and 4 in comparison to set 1 (baseline) and therefore suggest that a PAP response may be realised 90 seconds post-CA. However, the author recognised that the limitations of this study were low subject numbers and the lack of a control (CON) group. As evidenced by Smilios et al. (2005) it is possible to evoke a PAP response using loaded squat jumps. Therefore, it is possible that the loaded squat jumps, used as a performance measure of the paused box squats combined with accommodating resistance, influenced the PAP response throughout the study. Furthermore, Wyland et al. (2015) investigated the effects of a single set of BS combined with accommodating resistance ($55 + 30\%$ 1RM) on sprint performance and reported significant improvements after 4 minutes. Although the evidence is limited, it appears that PAP can be realised 1.5-4 minutes post-CA when accommodating resistance is implemented. Since the ICRI is shorter than that of traditional heavy load resistance exercises, moderately loaded resistance exercises

combined with accommodating resistance may be a more suitable PAP stimulus in a practical setting, where the time available to strength and conditioning coaches to work with athletes is often limited.

These results may be explained due to the accommodating resistance inducing a preparatory muscle stiffness during the CA where there is an increase in motor unit activation at the top of the lift however, at the bottom of the lift where the load is decreased, the motor units are still activated therefore resulting in a surplus of neural activation subsequently evoking a PAP response (Baker, 2008). Furthermore, due to the bands actively pulling the loads downwards with greater force than the effect of gravity during the eccentric phase of the CA, the muscles may be better able to utilise the stored elastic strain energy during the concentric phase as result of the reduced effects of “sticking points” (Wyland et al., 2015). Finally, anecdotal evidence suggests that accommodating resistance training increases the speed of the eccentric phase of the lift therefore inducing a greater stretch reflex (Simmons, 2007). This attempts to override the GTO reflex, consequently contributing to greater force production during the concentric phase and is referred to as “overspeed eccentrics” (Simmons, 2007; Stevenson, Warpeha, Dietz, Giveans, & Erdman, 2010). Collectively, this evidence suggests that the combination of a moderate load and accommodating resistance may be an effective method of eliciting PAP. However, more research is required to elucidate these findings.

2.6.3 Influence of Strength Level and Training Status

As previously mentioned, numerous studies suggest that an individual’s strength level and training status may be modulating factors in eliciting a PAP response (Jo et al., 2010; Kilduff et al., 2007, 2008; Ruben et al., 2010; Seitz, de Villarreal, et al., 2014; Seitz & Haff, 2015b; Wilson et al., 2013). For example, Kilduff et al. (2008) reported a significant correlation between strength levels and the magnitude of the PAP response. Moreover, a

significant correlation between relative BS strength and the magnitude of the PAP response has been demonstrated in vertical (Seitz, de Villarreal, et al., 2014) and horizontal (Ruben et al., 2010) jump tests. More specifically, it was reported that individuals who were able to squat ≥ 2 times body mass may be able to express a greater degree of PAP in comparison to individuals who squat < 2 times body mass (Ruben et al., 2010; Seitz, de Villarreal, et al., 2014). Seitz, de Villarreal, et al. (2014) reported that stronger individuals expressed the greatest PAP response 6 minutes post-CA, whereas weaker individuals peaked at 9 minutes. Furthermore, a correlation was found between strength level and the PAP response in a study investigating the effect of BS and power cleans on 20-metre sprint performance (Seitz, Trajano, et al., 2014). In addition, it also appears that individuals with prior resistance training experience express a greater PAP response in comparison to those with little or no experience (Jo et al., 2010; Seitz & Haff, 2015b; Wilson et al., 2013). This finding makes sense as individuals who are inexperienced or less experienced are more likely to exhibit lower strength levels in comparison to more experienced individuals hence, a lower PAP response is likely to be observed. Collectively, empirical evidence suggests that the magnitude of the PAP response following a CA is dependent upon the strength level of an individual.

Although the exact reason for stronger individuals being better able to express PAP remains unclear, a plausible explanation is that stronger individuals may have a greater percentage of type II fibres (Aagaard & Andersen, 1998; Maughan, Watson, & Weir, 1983). Therefore a greater PAP response is more likely to be elicited due to a greater phosphorylation of the MLC (Moore & Stull, 1984), which is a proposed underpinning mechanism of PAP. Furthermore, type II fibres exhibit the greatest neural excitation following heavy resistance exercise therefore suggesting that the ability to elicit PAP is increased as a result of resistance training (Hamada et al., 2000; Jo et al., 2010; Sale,

2002). It has also been suggested that stronger individuals may develop fatigue resistance to heavier CAs (Chiu et al., 2003; Hamada et al., 2000; Jo et al., 2010), which may affect the balance between PAP and fatigue, enabling PAP to predominate at an earlier stage. In addition, stronger individuals are also reported to possess a greater muscle CSA, muscle fibre P_{ang} and L_f (Cormie et al., 2010c). As such, it is conceivable that any PAP response as a result of a voluntary CA may be associated with these muscle architectural characteristics. However, the relationship between an individual's muscle architecture and the PAP response is yet to be examined. It remains unclear whether the strength level of an individual causes PAP in response to a voluntary CA or if the relationship is only correlational. Each of these variables must be considered in order to determine why stronger individuals appear to exhibit a greater magnitude of PAP.

2.6.4 Exercise Selection

Scientific research has typically exploited heavy load BS as the CA when attempting to elicit a PAP response (Crewther et al., 2011; Jones & Lees, 2003; Kilduff et al., 2008; Seitz, de Villarreal, et al., 2014). Other CAs which have been utilised to elicit PAP in the lower body include, front squats (Yetter & Moir, 2008), BS of varying depth (Crum et al., 2012; Esformes & Bampouras, 2013; Gourgoulis et al., 2003; Mangus et al., 2006), box squats (Baker, 2008) conventional deadlift (Till & Cooke, 2009), dynamic contractions (McBride et al., 2005; Smilios et al., 2005), plyometric exercises (Esformes et al., 2010; Turner, Bellhouse, Kilduff, & Russell, 2015), and derivatives of Olympic lifts (Andrews et al., 2011; McCann & Flanagan, 2010; Seitz, Trajano, et al., 2014).

When employing traditional heavy load BS as a CA, it appears that squat depth is an important factor to consider (Seitz & Haff, 2015b). It is theorised that the use of half-squats or quarter-squats is likely to reduce levels of acute fatigue in comparison to full squats due to less time spent under tension (Seitz & Haff, 2015b; Tran, Docherty, &

Behm, 2006) therefore increasing the likelihood a PAP response. For example, Gourgoulis et al. (2003) examined the effects 5 sets of 2 repetitions of half-squats at intensities of 20, 40, 60, 80 and 90% of 1RM on CMJ performance in 20 active males. The results indicated that there was a significant increase in jump height immediately following 5 sets of the CA and that stronger individuals expressed the greatest improvement in comparison to weaker individuals. However, conflicting findings in a study by Crum et al. (2012) reported no significant improvement in CMJ performance at ICRI of 0.5, 3, 5, 10 and 15 minutes following moderately loaded (50-65%) quarter-squats. Although the study recruited males who could quarter-squat at least 2.4 times body weight, the CA may not have evoked PAP due to the moderate loads utilised. Similarly, Mangus et al. (2006) demonstrated no significant improvement in CMJ performance following heavy load (90% of 1RM) quarter-squats or half-squats in weightlifters with at least 1-year experience. However, an ICRI of 3 minutes was utilised which may not have been long enough for PAP to predominate fatigue. Contrastingly, Esformes and Bampouras (2013) investigated the effects of 3RM parallel-squats and quarter-squats on CMJ performance 5 minutes post-CA in semi-professional rugby union players. The results revealed significant improvements in both conditions however, the parallel-squat condition was significantly greater than the quarter-squat condition.

Although research has attempted to reduce the amount of eccentric work by reducing the length of time spent under tension using squats of varying depth, this undoubtedly reduces the amount of work during the concentric phase. Crum et al. (2012) suggests that the lack of any substantial eccentric muscle action during the CA may have reduced the PAP response; it is likely that CAs which contain an eccentric phase result in an increased activation of type Ia neural fibres due to an increase in muscle spindle activity (Taylor, Butler, & Gandevia, 2000). If there is a lack of muscle stimulation during the eccentric

phase, then it is more than likely that there is a lack of muscle activity during the concentric phase to evoke a PAP response. As such, it appears that the full ROM throughout the concentric phase of the BS may be imperative in eliciting PAP. Therefore, future research should investigate methods of reducing the amount of time spent under tension during the eccentric phase, since this may reduce fatigue (Tran et al., 2006), as well as maximising the amount of concentric work.

Alternative CAs which have been exploited in an attempt to elicit a PAP response include dynamic and plyometric actions. As previously discussed, the use of dynamic CAs (a lighter load combined with an explosive action) such as, loaded CMJs, have provided equivocal findings (Clark et al., 2006; McBride et al., 2005; Smilios et al., 2005). In addition, research has also investigated the PAP response as a result of plyometric CAs. Esformes et al. (2010) examined the effects of 3 sets of a 3RM BS protocol in comparison to a plyometric protocol on the PAP response in athletes who had 2 years resistance training experience. The results demonstrated a significantly improved jump height in sets 1 and 3 of the BS condition in comparison to set 1 of the plyometric condition, and in set 1 of the BS condition in comparison to set 3 of the CON condition. Furthermore, de Villarreal, González-Badillo and Izquierdo (2007) investigated the effects of different warm-up strategies on the PAP response and reported significant improvements in jump performance 5 minutes following loaded CMJs, heavy load BS, and a sport-specific warm-up. In particular, no significant difference was identified between the BS and plyometric conditions. Similarly, Turner et al. (2015) reported improved sprint performance 4-8 minutes following a weighted and non-weighted plyometric CA which consisted of 3 sets of 10 repetitions of alternate leg bounding. In contrast, Till and Cooke (2009) did not observe any improvements in CMJ performance or sprint performance at ICRIs of 4-9 minutes following a single set of 5 tuck jumps. Although research is limited,

it appears that plyometric CAs may be a suitable method of inducing PAP. An explanation for this is that plyometric exercises are associated with the recruitment of type II motor units (Desmedt & Godaux, 1977) which is an underpinning mechanism of PAP on a central level (Güllich & Schmidtbleicher, 1996). Furthermore, in relation to the PAP-fatigue model, a plyometric CA may produce less fatigue, due to reduced time under tension, in comparison to a traditional heavy load CA therefore enabling a PAP response to be realised at an earlier ICRI (Seitz & Haff, 2015b).

It has been suggested that the variability among the complex training research studies may be due to the lack of specificity between the CA and subsequent explosive activity (Crewther et al., 2011; Tillin & Bishop, 2009; Winwood, Posthumus, Cronin, & Keogh, 2016). The subsequent plyometric action involves a high-velocity, eccentric to concentric muscle contraction (Turner et al., 2015). In contrast, the BS facilitates the production of large forces at low velocities (Haff et al., 2001). Whilst there is evidence to support more explosive, lighter and moderately loaded CAs as an appropriate PAP stimulus, it has also been suggested that lighter CAs are not sufficient enough to induce fatigue, without which PAP is unlikely to occur (Whelan, O'Regan, & Harrison, 2014). Therefore, it would appear that high-force and high-velocity contractions are an optimal PAP stimulus. Previous research has investigated effects of Olympic style lifts, which involve high-force and high-velocity production, on the PAP response (Andrews et al., 2011; McCann & Flanagan, 2010; Seitz, Trajano, et al., 2014). Seitz, Trajano, et al. (2014) compared the effects of 1 set of 3 repetitions of BS and power cleans at 90% of 1RM on 20 metre sprint performance in 13 elite junior rugby league players. The results revealed a significant improvement in sprint performance 7 minutes following both conditions. However, the power clean condition expressed significantly greater sprint times, velocities and average accelerations in comparison to the BS condition. In contrast, McCann and Flanagan

(2010) reported no differences between the effects of a single set of 5RM BS and hang cleans on CMJ performance. Similarly, Andrews et al. (2011) examined the effects of 3 sets of 3 repetitions of BS at 75% of 1RM and hang cleans at 60% of 1RM on subsequent CMJ performance 3 minutes post-CA. The results revealed no significant improvements in jump performance for either condition however, the hang clean condition was superior in maintaining the consistency of jump performance. An explanation for these conflicting findings may be the inconsistencies of the load utilised and the ICRIIs not being long enough to allow PAP to manifest. In addition, it is possible that the technical difficulty of the Olympic style lifts introduce more variability in technique and ability to benefit from the voluntary PAP response.

Collectively, there is evidence to suggest that Olympic style lifts may be able to evoke a PAP response due to the generation of high-forces at high-velocities (Seitz, Trajano, et al., 2014). However, the results of these studies are equivocal and more research is required to further understand the effects of high-force and high-velocity contractions on the voluntary PAP response. Additionally, the technical demands of the Olympic style lifts may be a limiting factor of this type of CA and contribute towards these findings. Therefore, future research should investigate the effects of CAs with different force-velocity profiles and of lower technical difficulty.

2.6.4.1 Hex-Bar Deadlift

Although heavy load BS are typically used as a CA to evoke a PAP response, it appears that the magnitude of eccentric work and amount of time spent under tension induces high levels of acute fatigue (Seitz & Haff, 2015b; Tran et al., 2006). Furthermore, the lumbar spine is the only connecting column between the upper and lower body, therefore all forces must be transferred via the lumbar spine to the lower extremity (Alexander, 1985). However, when large forces are placed on the back, there is an increased risk of injury

(Lander, Bates, & Devita, 1986). Injuries occurring during the BS are primarily due to inexperience or poor technique (Kritz, Cronin, & Hume, 2009; Russell & Phillips, 1989). As such, individuals must ensure that their lumbar spine remains stable and straight during the BS otherwise compressive and shear forces on the lumbar spine increase the risk of injury (Kritz et al., 2009).

Due to the technical demands and injury risk of the BS, a safer alternative exercise to induce PAP may be the HBD. According to Escamilla, Francisco, Kayes, Speer and Moorman (2002) deadlift and BS exercises are biomechanically similar in nature. The HBD is a variation of the conventional straight bar deadlift which allows an individual to stand in the centre of the bar, therefore the load distribution enables the individual's centre of gravity to be more in line with that of the load (Gentry, Pratt, & Caterisano, 1987). The HBD has been reported to reduce the amount of stress on the lumbar spine, hip and ankle when compared to the conventional deadlift; this may enable a greater load to be lifted consequently increasing neural activation (Bompa & Buzzichelli, 2015; Stewart & Stewart-Menteth, 2008; Swinton, Stewart, Agouris, Keogh, & Lloyd, 2011). In addition, the HBD has been shown to induce greater peak velocities in comparison to the conventional deadlift (Swinton et al., 2011).

The HBD may be an advantageous voluntary PAP stimulus in comparison to the BS since it may enable minimal eccentric loading if the bar is released at the top of the lift. Consequently, time under tension and neuromuscular fatigue may be reduced (Tran et al., 2006). Interestingly, Till and Cooke (2009) investigated the effects of a single set of 5 repetitions of the conventional straight bar deadlift exercise at a load equivalent to 5RM in 12 full-time professional academy footballers. Although the study demonstrated no significant improvements in sprint or vertical jump performance, there were small but non-significant improvements. However, the authors acknowledge that PAP may not

have been evident due to the ICRIs utilised and due to vertical jump testing being conducted immediately after sprint testing. Furthermore, it can only be assumed that both the concentric and eccentric phases were performed in this study as the deadlift technique is not specified. Based on the results of this study, future research utilising the deadlift as a PAP stimulus is warranted.

Previous research has investigated varying BS depths to reduce the magnitude of eccentric loading (Crum et al., 2012; Esformes & Bampouras, 2013; Gourgoulis et al., 2003; Mangus et al., 2006) and paused box squats to induce a concentric-only contraction (Baker, 2008) in an attempt to enhance the PAP response. However, there is still an eccentric portion to these exercises which is likely to induce fatigue. Therefore, it is conceivable that the HBD is advantageous in eliciting PAP as the lifting technique may enable individuals to focus on performing concentric work while minimising the eccentric load if the bar is released at the top of the lift. Consequently, there may be less neuromuscular fatigue induced due to less time spent under tension (Tran et al., 2006). Furthermore, the increased load may enhance the PAP response due to greater neural activation (Bompa & Buzzichelli, 2015; Swinton et al., 2011). Finally, due to the HBD being a less technically demanding and safer exercise (Gentry et al., 1987; Stewart & Stewart-Menteth, 2008), this may be an advantageous PAP stimulus for less experienced individuals. Consequently, future research should be conducted to determine if the HBD can be used as an alternative CA to evoke PAP.

2.6.5 Volume – Number of Sets

The results of acute studies examining the PAP response due to a voluntary CA often assume that chronic neuromuscular adaptations would occur if complex training was utilised within a training programme. Moreover, these studies generally investigate the effects a single set of a CA on the PAP response. However, the application of PAP to

complex training for long-term neuromuscular adaptations typically involves multiple sets of complex pairs (Carter & Greenwood, 2014; Chu, 1996; Docherty et al., 2004; Jones et al., 2013). Naclerio et al. (2015) investigated the effects of differing CA volumes on the ICRI required to elicit a PAP response in 11 college athletes who had at least 2 years' experience within structured resistance training programmes. The participants completed three experimental conditions of BS at 80% of 1RM: low volume (1 repetition), moderate volume (3 repetitions) and high volume (2 sets of 3 repetitions). CMJ performance was assessed before and at 7 different time points (15 seconds and 1, 2, 3, 5, 8, and 12 minutes) after each condition. The results revealed no significant improvements at any of the ICRI following any condition however, the low volume condition expressed significantly lower CMJ performance at 3 minutes in comparison with the high volume condition and at 5 minutes in comparison to the moderate volume condition. The authors conclude that moderate and high volume CAs are a more effective PAP stimulus in comparison to low volume CAs. Although no relationship between the volume of the CA and the optimal ICRI required to elicit PAP was evident, there was a high degree of inter-individual variability observed therefore, complex training variables should be individualised to achieve a PAP response and not generalised.

Interestingly, recent meta-analyses have demonstrated that multiple sets of a CA produce a greater PAP response in comparison to single sets (Seitz & Haff, 2015b; Wilson et al., 2013). Furthermore, it appears that the training status and strength level of the individual mediates the PAP response induced by different volumes of the CA. More specifically, Wilson et al. (2013) state that weaker individuals demonstrate a greater decline in muscular power following multiple sets of a CA in comparison to single sets, whereas stronger individuals express an enhanced PAP response when performing multiple sets in comparison to single sets. In contrast, Seitz and Haff (2015b) suggest that stronger

individuals exhibit a greater PAP response following a single set of a CA in comparison to multiple sets, whereas weaker individuals appear to benefit more from multiple sets. However, this finding was likely to be influenced due to the larger number of single set PAP studies in comparison to multiple set research designs. Long-term resistance training is associated with increases in fatigue resistance due to an enhanced buffering capacity and a greater resistance to skeletal muscle damage (Kendrick et al., 2008; McHugh et al., 1999; Skulachev, 2000). Theoretically, a multiple set CA will evoke a greater fatigue response, consequently reducing the ability of weaker individuals to express a PAP response. In contrast, it is likely that stronger and more experienced individuals exhibit a greater PAP response during multiple set CAs due to the ability to recover from fatigue at a greater rate therefore enabling an increased magnitude of PAP to be induced. Evidently, future research with respect to the influence of strength level on the PAP response following single and multiple sets is required. Although volume appears to be a modulating factor of the PAP response, it is also important to consider the influence of both volume and intensity when investigating the ability to evoke a voluntary PAP response.

2.7 Chronic Effects of Complex Training

It is important to note that for the purpose of this thesis complex training is defined as alternating heavy and light loads on a set for set basis. There is scientific research which has investigated the longitudinal effects of different forms of combination training, such as contrast training (Juárez, González-Ravé, & Navarro, 2009; Santos & Janeira, 2008; Talpey, Young, & Saunders, 2016) and compound training (Mihalik, Libby, Battaglini, & McMurray, 2008). As such, only research which adheres to the definition of complex training will be discussed for the purpose of this thesis.

Although the acute effects of voluntary PAP have been proven to be an effective method of enhancing subsequent explosive performance when training variables are carefully considered, a common goal for strength and conditioning practitioners is to implement training programmes which enable sport-specific chronic adaptations to occur (Tredrea, 2017). Furthermore, Carter and Greenwood (2014) state that carryover strength is an important consideration when designing and implementing resistance training programmes. Carryover strength is defined as “the degree of strength improvement achieved during exercise that is reflected in improved performance in another activity” (Hoffman & Faigenbaum, 2007). Therefore, it is imperative that the carryover effects of complex training are investigated so that comprehensive training recommendations can be made in relation to the efficacy of complex training and the longitudinal adaptations over several microcycles and mesocycles. The limited research examining chronic performance adaptations to complex training has provided equivocal results; it is speculated that there may be no real difference between complex training and more traditional methods (MacDonald et al., 2012, 2013; Stasinaki et al., 2015), whereas other studies advocate that complex training is an effective training modality (Alves et al., 2010; Walker et al., 2010). It is probable that these findings are largely due to methodological inconsistencies.

MacDonald et al. (2012) compared the effects of complex training, resistance training and plyometric training on measures of strength and anthropometrics. The study recruited 30 recreationally trained college-aged males who completed 2 sessions per week for 6 weeks. Although the training groups were not equal in terms of volume and intensity, the protocols were kept as similar as possible. Briefly, 3 sets of 3-6 repetitions of resistance exercises (45-90% of 1RM) and plyometric exercises were utilised; the complex training group were allowed an ICRI of 3 minutes. The study demonstrated that each training

group significantly improved 1RM BS, Romanian deadlift (RDL) and standing calf-raise however, there were no significant differences observed between the groups. Similarly, body mass and girth measurements of the participants' quadriceps and triceps surae increased but no differences were identified between the groups. Furthermore, MacDonald et al. (2013) published a secondary study using the data from the previously mentioned study (MacDonald et al., 2012). This examined the effects of complex training, resistance training and plyometric training on CMJ height, peak force and peak power. The results demonstrated no significant differences between the groups however, there were significant improvements in peak force for the complex training group and the plyometric training group. Additionally, there was an increase in peak power for the plyometric training group. The authors concluded that complex training produced similar results to resistance training or plyometric training alone. Moreover, complex training was deemed a viable training modality as no detriments to performance were observed. It should be noted that these studies (MacDonald et al., 2012, 2013) employed a 30 second ICRI during the first mesocycle and a 3 minute ICRI during the second mesocycle which may not have been an adequate time frame to allow PAP to predominate fatigue, especially in a sample population of recreationally trained males. As evidenced by the PAP-fatigue model, there may be two windows of opportunity for PAP depending on the intensity of the CA. The intensity of the CAs in these studies ranged from 45-90% of 1RM and therefore the CA may not have induced a PAP response in some instances. Finally, the authors advocate that future research should consider investigating complex training in more athletic populations.

Similarly, Walker et al. (2010) investigated the effects of an 11-week complex training intervention in 10 recreationally active males who had not undertaken regular training prior to the study. The protocol involved 3-5 sets of 3 repetitions of heavy resistance

exercise (80% of 1RM) coupled with lighter, more explosive exercises following an ICRI of 3 minutes. The results revealed significant improvements in 1RM scores, squat jump height, isometric force and RFD. However, it is important to note that no CON group or conventional training group was included within this study. Although the findings of this study illustrate that complex training may be an efficient training modality, more research is required to understand the extent to which complex training can chronically enhance strength and power in well-trained, stronger individuals.

Alves et al. (2010) examined the effectiveness of complex training of differing frequencies during a six week pre-season in 23 male footballers (aged 17.4 ± 0.6 years) who play in the Portuguese elite championship. The participants were split into two experimental groups who either trained once or twice a week. The training programme consisted of 3 stations comprising of 1 set of heavy resistance exercise (80-90% of 1RM), 1 set of plyometric exercise and 1 set of a sport-specific exercise. The variables under examination were vertical jump height, 5 and 15-metre sprint, and the 5-0-5 agility test. The results revealed significantly improved sprint times and vertical jump heights in both groups, but no improvements in agility. Furthermore, there were no differences between the groups. Although the guidelines for PAP were adhered to with respect to exercise intensity, only single sets were utilised and no precise details regarding the ICRIs were given other than performed in 'continuation'. The footballers were of an appropriate training status however, they were of maturation age which may have influenced the results.

More recent research by Stasinaki et al. (2015) compared a 6-week complex training intervention to a compound training (strength and power training on different days) protocol in 25 moderately trained students who had not performed any systematic resistance training during the previous year. The participants completed 3 training

sessions per week where the volume and intensities were consistent between groups. More specifically, the study examined CMJ height, backward overhead throw, 1RM leg press, box squat and bench press as well as muscle architecture measures of MT, P_{ang} and L_f of the VL and GM. In addition, muscle biopsies were used to assess the muscle fibre CSA and fibre type composition of the VL and GM. The results revealed significant improvements in CMJ and throwing performance for the compound training group only. Bench press, leg press and Smith machine box squat increased following both training protocols. VL MT and P_{ang} , and GM P_{ang} were increased following both training programmes. However, GM L_f decreased following the complex training intervention. Finally, muscle fibre CSA increased only after the complex training protocol, whilst fibre type composition was affected by neither intervention. It is concluded that compound training may be a more effective training strategy in comparison to complex training. Although the exercise intensity and volumes utilised adhered to the recommendations within PAP literature, an ICRI of 3 minutes was implemented which may not have been an appropriate recovery interval to elicit PAP in the sample population.

Collectively, research suggests that complex training is just as effective as more conventional training methods. There are a number of limitations evident within chronic complex training studies. The research has typically involved younger or less experienced individuals which may have influenced the results as the maturation process causes an increase in androgenic hormones, such as testosterone, and enhances body mass and strength (Fleck & Kraemer, 2005). Furthermore, less experienced individuals have a greater reserve for adaptation, meaning that any form of resistance training is likely to induce positive adaptations (Bompa & Buzzichelli, 2015; Tredrea, 2017). It is likely that these adaptations are neurological in nature as the first adaptations as a result of resistance training are at the neural level (Fleck & Kraemer, 2004; Sale, 2003) however, it is unclear

whether hypertrophic adaptations also manifest (Tredrea, 2017). In addition, the ICRIs and intensity of the selected exercises utilised within the research are not consistent with the recommendations made in acute PAP studies. Heavy load BS are predominantly employed as a voluntary PAP stimulus which may not be optimal for eliciting PAP in the sample populations under examination. Therefore, future studies should appropriately design complex training interventions by implementing the training variables in accordance with academic literature and should consider alternative CAs within the training intervention.

Chapter 3: The effect of exercise selection and training status on post-activation
potentiation in rugby league players.

3.1 Introduction

Complex training is an effective, time efficient training modality for enhancing strength and power which alternates heavy resistance exercise, with an explosive plyometric exercise which is biomechanically similar (Docherty et al., 2004; Weber et al., 2008). This enables both extremes of the force-velocity curve to be trained in one session. Consequently, strength and conditioning coaches can address two training variables in one session.

Complex training is underpinned by PAP which theoretically enhances force and power output following a near maximal voluntary contraction, or CA (Gourgoulis et al., 2003; Hodgson et al., 2005; Tillin & Bishop, 2009). The CA also induces fatigue which may inhibit the effects of PAP (Tillin & Bishop, 2009). PAP and fatigue can coexist, however fatigue dissipates at a greater rate, therefore performance can be enhanced when the working muscles have partially recovered but are still potentiated (Docherty et al., 2004; Tillin & Bishop, 2009). Currently, the underlying mechanisms of PAP are unclear, however it is thought that they could include neural and muscular interactions, and muscle architectural changes (Docherty et al., 2004; Reardon et al., 2014; Talpey, Young, & Saunders, 2014; Tillin & Bishop, 2009). Suggested mechanisms include, phosphorylation of myosin RLC, recruitment of higher order motor units, and changes in muscle P_{ang} (Docherty et al., 2004; Reardon et al., 2014; Talpey et al., 2014; Tillin & Bishop, 2009). Scientific research which has investigated the acute effects of complex training on lower body power has provided equivocal results, as some studies have reported enhancements in performance (Chiu et al., 2003; Crewther et al., 2011; Esformes & Bampouras, 2013; Kilduff et al., 2007, 2008; Seitz, de Villarreal, et al., 2014; Seitz, Trajano, et al., 2014), whilst other studies have reported no changes or decreases in performance (Andrews et

al., 2011; Comyns et al., 2006; Duthie et al., 2002; Esformes et al., 2010; Jensen & Ebben, 2003; Jones & Lees, 2003; McCann & Flanagan, 2010).

Interpretation of the optimal ICRI, the recovery period between the CA and the plyometric exercise, is difficult as previous studies have suggested that this rest period may lie between 0.3 and 18.5 minutes (Kilduff et al., 2008; Seitz, de Villarreal, et al., 2014; Seitz & Haff, 2015b). The optimal ICRI and magnitude of the PAP response appears to be dependent on factors including the type of CA and the training status of the individual (Hodgson et al., 2005; Ruben et al., 2010; Seitz, de Villarreal, et al., 2014; Tillin & Bishop, 2009). It is thought that well trained individuals express a greater degree of PAP due to greater type II muscle fibre content and a shorter time course of fatigue following the CA (Seitz, de Villarreal, et al., 2014; Tillin & Bishop, 2009). Academic research typically utilises heavy load BS as the CA when employing complex training for the lower body and the PAP response is measured by vertical jumping (Crewther et al., 2011; Gourgoulis et al., 2003; Jones & Lees, 2003; Kilduff et al., 2008). Other CAs which have been investigated include front squats (Yetter & Moir, 2008), squats with varying depth (Crum et al., 2012; Esformes & Bampouras, 2013; Gourgoulis et al., 2003; Mangus et al., 2006), dynamic contractions (Smilios et al., 2005), plyometric exercises (Andrews et al., 2011; Turner et al., 2015), and Olympic style lifts (Andrews et al., 2011; McCann & Flanagan, 2010; Seitz, Trajano, et al., 2014).

It has been suggested that optimal neural adaptations are induced by near maximal concentric only contractions performed as fast as possible (Schmidtbleicher, 1992). In this regard the conventional straight bar deadlift may be a useful alternative CA, with the technique allowing participants to focus on performing concentric work, with minimal eccentric loading if the bar is released at the top of the lift (Swinton et al., 2011; Till &

Cooke, 2009). This may reduce neuromuscular fatigue by decreasing the amount of time under tension (Tran et al., 2006). The HBD is a variation of the conventional deadlift that has been reported to reduce the amount of stress on the lumbar spine, hip, and ankle, which may allow a greater load to be lifted and increase muscle activation (Bompa & Buzzichelli, 2015; Swinton et al., 2011). Additionally, HBD has been shown to induce significantly greater peak velocities in comparison to the straight bar deadlift (Swinton et al., 2011).

The purpose of this study was to determine if HBD reduced the optimal ICRI in comparison to BS. It was hypothesised that HBD would enhance the PAP response due to less time spent under tension and consequently lower fatigue. Currently no studies have considered the HBD as a CA. A secondary aim of this study was to determine any differences in the PAP response between stronger and weaker athletes. It was hypothesised that stronger athletes would express a greater degree of PAP.

3.2 Methods

3.2.1 Experimental Approach to the Problem

The present study employed a repeated measures design. Participants completed two familiarisation sessions and two experimental sessions to investigate the effects of exercise selection and strength level on the temporal profile of PAP (Figure 3.1). During the experimental sessions, the participants performed maximal CMJs before and 2, 4, 6, 8, 10, 12, 14 and 16 minutes after 1 set of 3 repetitions at 93% of 1RM of either HBD or BS. As suggested by Schmidbleicher (1992) optimal neural adaptations are induced by near maximal concentric only contractions performed as fast as possible. Therefore, this load was chosen since it is the heaviest load which has demonstrated a PAP response (Comyns et al., 2007). The following dependent variables were compared between the

baseline and the post-CA CMJs: PPO, ground reaction force (GRF) at PPO, velocity at PPO, jump height, and mean EMG values of the VL, biceps femoris (BF), tibialis anterior (TA) and GM.

3.2.2 Subjects

Ten professional and ten amateur rugby league players were recruited for this study (Table 3.1). The professional players were recruited from a First Utility Super League academy, Kingstone Press Championship and League One clubs. Amateur players were recruited from a University level rugby league team who play in BUCS Premier North Division. Ten participants, of the twenty players recruited, also completed a CON trial where the CA was replaced with a 5 minute seated rest period. Participants were required to have a minimum of 6-months previous experience in a structured resistance training programme and were able to complete HBD, BS and CMJ exercises with correct technique under the supervision of a qualified strength and conditioning coach. Each participant provided written informed consent (Appendix B) to participate in the present study and completed a pre-exercise medical questionnaire (Appendix F). Participants were asked to refrain from engaging in any strenuous or unaccustomed exercise 48 hours prior to testing, avoid the intake of caffeine 6 hours prior to testing and avoid the intake of alcohol 12 hours prior to testing. The study received full institutional approval by the Department of Sport, Health and Exercise Science's Ethics Committee.

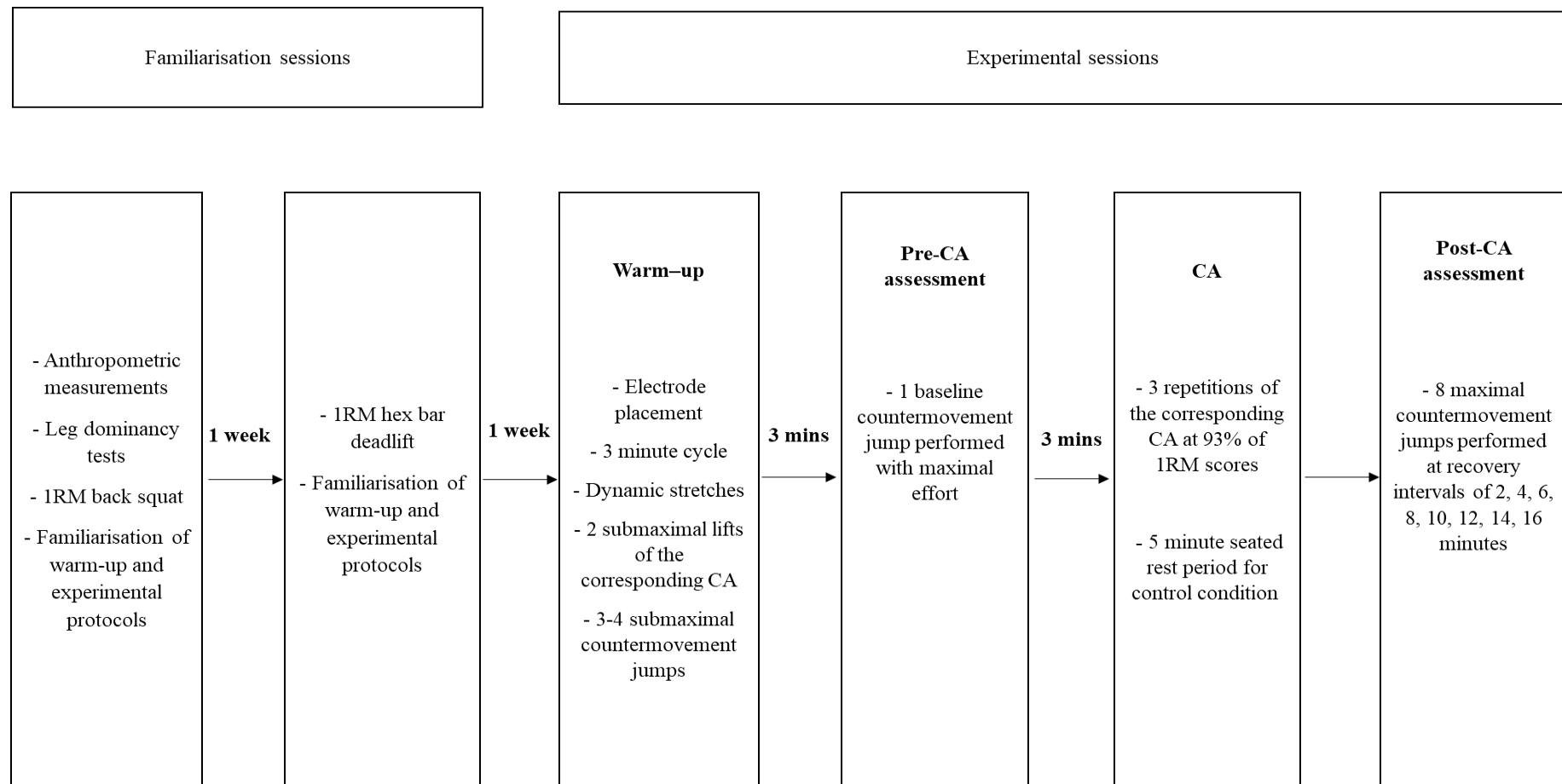


Figure 3.1 A schematic representation of the study design. 1RM = 1 repetition maximum; CA = conditioning activity

3.2.3 Familiarisation Sessions

The first familiarisation session involved anthropometric measurements, determination of 1RM BS scores, and familiarisation with the warm-up and experimental protocols. For the purpose of electrode placement, leg dominance was determined using the following three tests: the step up, balance recovery and ball kick test (Hass et al., 2005). The dominant leg was defined as the leg which was dominant in two out of the three tests. The participants also practised performing CMJs following demonstration and verbal instruction with the aim of optimising jump height. During the second familiarisation session, 1RM HBD scores were determined. The participants were reminded of the experimental protocols and given further CMJ practice.

Table 3.1 Anthropometric and physical characteristics of the participants (n = 20).

Variable	Stronger (n=10) Mean $\pm$ SD	Weaker (n=10) Mean $\pm$ SD	Control (n = 10) Mean $\pm$ SD
Age (years)	22.30 $\pm$ 2.91	19.10 $\pm$ 1.10	21.50 $\pm$ 2.59
Height (cm)	178.99 $\pm$ 6.52	183.75 $\pm$ 5.67	180.74 $\pm$ 8.51
Weight (kg)	85.89 $\pm$ 11.47	88.35 $\pm$ 11.93	85.47 $\pm$ 11.02
1RM Back Squat (kg)	149.50 $\pm$ 27.30	109.00 $\pm$ 15.69	126.25 $\pm$ 34.48
1RM Hex-Bar Deadlift (kg)	180.50 $\pm$ 22.42	154.00 $\pm$ 17.57	156.00 $\pm$ 27.16
Relative 1RM Back Squat (kg/kg)	1.75 $\pm$ 0.32	1.24 $\pm$ 0.14	1.49 $\pm$ 0.42
Relative 1RM Hex-Bar Deadlift (kg/kg)	2.11 $\pm$ 0.24	1.76 $\pm$ 0.28	1.84 $\pm$ 0.35

1RM = 1 repetition maximum

1RM testing: The participants underwent a standardised warm up which comprised of a 3 minute cycle on a Wattbike ergometer (Wattbike Ltd, Nottingham, United Kingdom) at a low intensity of 60 Watts (W), followed by a series of dynamic stretches with emphasis

placed on the musculature associated with the HBD and BS (Table 3.2). 1RM testing for the corresponding exercises was conducted following NSCA guidelines (Appendix G; Brown, 2007). The participants were subsequently split into two equal groups, a stronger and a weaker group, based on their relative 1RM BS scores (Table 3.3 and Table 3.4) as this has previously been suggested as a predictor of the voluntary PAP response (Ruben et al., 2010; Seitz, de Villarreal, et al., 2014).

Table 3.2 Standardised dynamic warm up for strength testing, experimental trials and control trials.

Exercise	Sets	Reps
Body weight squats	1	6
Mountain climbers	1	6 e/s
Thoracic rotations	1	6 e/s
Glute Bridge	1	6
Band pull aparts	1	6

e/s = each side

Table 3.3 Absolute 1RM loads lifted by the participants.

Participants	Hex-Bar Deadlift (kg) Mean $\pm$ SD	Back Squat (kg) Mean $\pm$ SD	p value
All (n =20)	167.25 $\pm$ 23.85	129.25 $\pm$ 30.02	< 0.001
Stronger (n =10)	180.50 $\pm$ 22.42	149.5 $\pm$ 27.30	< 0.001
Weaker (n = 10)	154.00 $\pm$ 17.57	109. 00 $\pm$ 15.69	0.146

1RM = 1 repetition maximum

Table 3.4 Relative 1RM loads lifted by the participants.

Participants	Relative 1RM Hex- Bar Deadlift (kg/kg)	Relative 1RM Back Squat (kg/kg)	p value
All (n =20)	1.94 ± 0.31	1.49 ± 0.35	< 0.001
Stronger (n =10)	2.11 ± 0.24	1.75 ± 0.32	< 0.001
Weaker (n = 10)	1.77 ± 0.28	1.24 ± 0.14	0.042

1RM = 1 repetition maximum

3.2.4 Experimental Sessions

A randomised, repeated measures, counterbalanced research design was utilised to examine the hypothesis. The participants underwent a standardised warm-up which consisted of a 3 minute cycle on a Wattbike ergometer at an intensity of 60 W, a series of dynamic stretches with emphasis placed on the musculature associated with the CMJ, HBD and BS, warm-up sets of the corresponding CA, and 3-4 submaximal repetitions of CMJs. A baseline CMJ was then performed before completing 3 repetitions of the CA at 93% 1RM. During the HBD, participants were instructed not resist the eccentric phase of the movement by dropping the bar following a successful lift to, ensure the movement was predominantly concentric. CMJs were performed at recovery intervals of 2, 4, 6, 8, 10, 12, 14 and 16 minutes following the CA. During the second experimental session the CA was changed. Additionally, of the twenty recruited participants, ten were required to complete a CON trial which involved the same experimental procedures to determine if any observed effect was due to the CA and not a result of a warm-up effect or fatigue effect from subsequent CMJs. The CON trial consisted of four stronger and six weaker level athletes. The experimental sessions were separated by one week and were conducted at the same time of day to control for circadian variations (Atkinson & Reilly, 1996).

3.2.5 Measurements

CMJ: To ensure that only the lower limbs were contributing to the development of power, the CMJ was performed with arms akimbo. A quick countermovement was performed, with instructions to then flex the knees to approximately 90° , and then explode upwards with maximal effort. Participants were instructed to keep their legs straight throughout the jump and land in the same position as take-off. To minimise the risk of injury, they were instructed to cushion the landing by bending the knees as soon as the feet made contact with the ground.

Force Platform: A strain gauge force platform (AMTI, BP600900; dimensions 900x600mm, Watertown, Massachusetts, USA), which sampled at 1500Hz, was used for the collection of GRF data during the CMJ. The force platform was calibrated and checked before testing according to manufacturer guidelines.

Surface EMG: Surface EMG of the VL, BF, TA and GM of the participants' dominant leg was recorded during each CMJ using a wireless Noraxon EMG system with 16 bit analogue to digital resolution (Telemetry 2400T, Noraxon, Scottsdale, Arizona, USA). The surface EMG was recorded at a sampling frequency of 1500Hz and was synchronised to the GRF data via Qualisys Track Manager Software (Qualisys Oqus 400, Gothenburg, Sweden). The muscles under examination were prepared prior to data collection to reduce skin resistance following Surface Electromyography for the Non-Invasive Assessment of Muscles (SENIAM) guidelines (Appendix H; Freriks, 1999).

3.2.6 Data Analysis

All data were analysed using MATLAB (MATLAB, version R2014b, MathWorks, Inc., Natick, MA). The vertical component of the GRF was unfiltered because no noise was

evident in the signal. This allowed accurate extraction of the dependent variables whilst controlling the effects of different filtering techniques (Hori et al., 2009).

PPO: The participants' mass was calculated by taking an average of the GRF data 2 seconds prior to the start of the CMJ. Equations (1) and (2) were used to calculate PPO:

$$1) A_{inst.} (m \cdot s^{-2}) = [GRF_{inst.} (N) / m (kg)] - g (9.81 m \cdot s^{-2})$$

where $A_{inst.}$ is instantaneous acceleration, $GRF_{inst.}$ is instantaneous ground reaction force, m is the mass of the participant, and g is the acceleration due to gravity.

$$2) P_{inst.} (W) = GRF_{inst.} (N) \times V_{inst.} (m \cdot s^{-1})$$

where $P_{inst.}$ is instantaneous power, and $V_{inst.}$ is instantaneous velocity which was calculated by integration of instantaneous acceleration using the Simpson's rule. The start of the CMJ was determined as the instant where the instantaneous GRF was reduced by 10% of the participant's body weight. Integration started from the start of the jump and finished at the point of landing, where the intervals were equal to the band width (Figure 3.2). PPO was determined by obtaining the greatest value for instantaneous power.

GRF and Velocity at PPO: GRF at PPO and velocity at PPO were determined by identifying the time point at which PPO occurred and finding the corresponding GRF and velocity values.

Jump Height: The height of each CMJ was determined using the flight-time method, equation (3) (Linthorne, 2001):

$$3) JH (m) = [g (9.81 m \cdot s^{-2}) \times FT^2 (s)] / 8$$

where JH is jump height, and FT is flight time which was calculated by finding the difference in time between take-off and landing. Take-off was determined as the instant where the force data was less than 5N and landing was defined as the instant at which the force was greater than 5N.

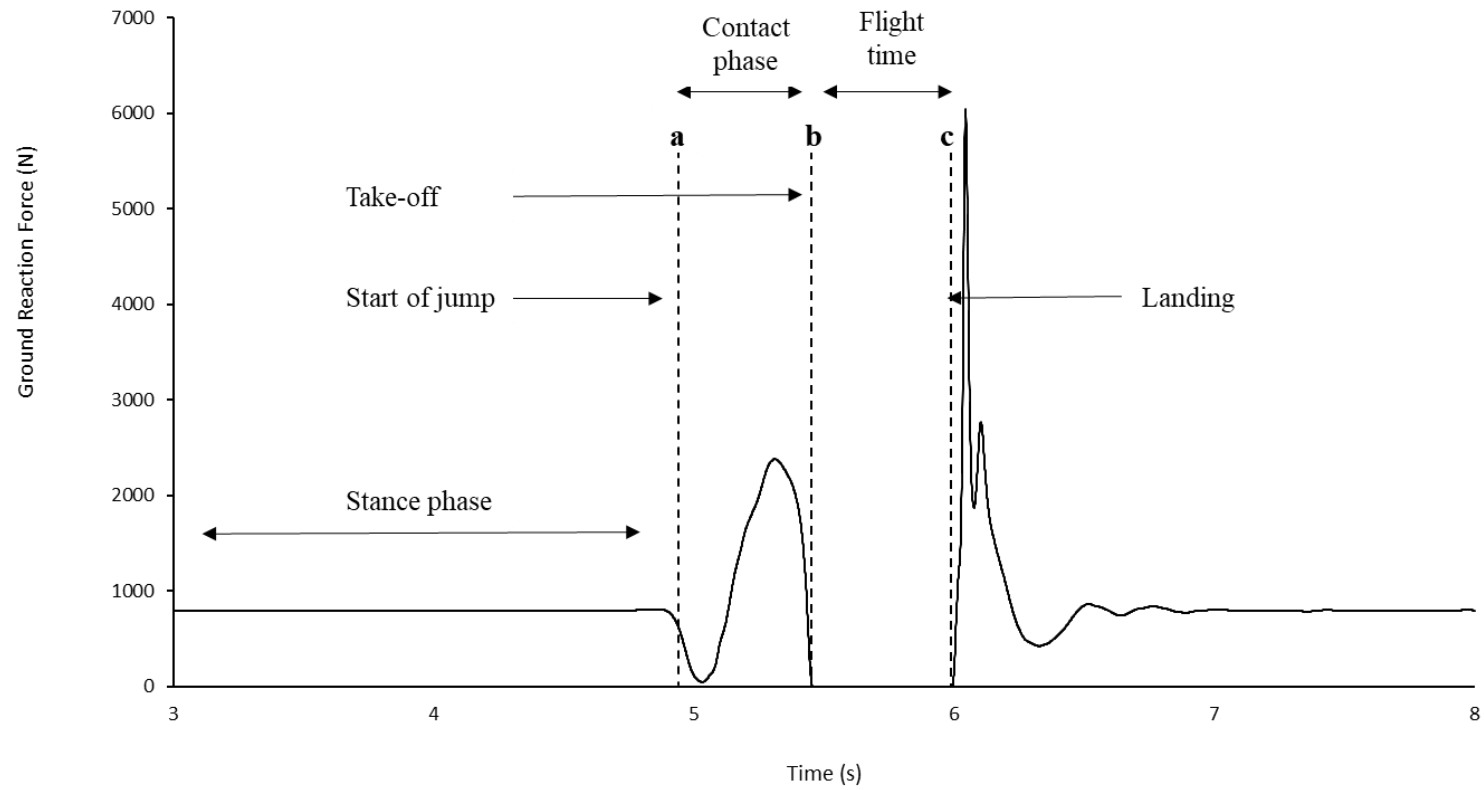


Figure 3.2 The vertical force trace from a participant performing a countermovement jump. *Note:* point 'a' represents the start of the jump; point 'b' represents take-off; point 'c' represents landing

Muscle Activity: The EMG data were used to derive the mean muscle activity from the start of the jump to take-off for the VL, BF, TA and GM. The raw EMG data were first band-pass filtered (10-450Hz) using a digital 2nd order zero-lag Butterworth filter. The EMG data were then full wave rectified and run through a digital 2nd order zero-lag Butterworth low pass filter with a 6Hz cut off frequency, to create a linear envelope. At the chosen ICRI, the EMG activity of the muscles under examination were normalised to the EMG values during the baseline CMJ of the corresponding experimental session and expressed as a percentage of the movement.

Intra-class correlation coefficients (ICC) were calculated by correlating the baseline jumps from the first experimental session to the second experimental session. The ICC for PPO, force at PPO, velocity at PPO, and jump height were 0.964, 0.964, 0.724, and 0.884, respectively. The ICC for the mean muscle activity of the VL, BF, TA, and GM were 0.735, 0.57, 0.775, and 0.914, respectively.

To ensure that the comparisons between the strength levels of the participants were relative, each variable was expressed as a percentage of potentiation using equation (4) (Chiu et al., 2003):

$$4) \% = [(Potentiated\ Variable / Un-potentiated\ Variable) \times 100] - 100$$

where a potentiation percentage of 0% highlights no potentiation, greater than 0% highlights a potentiation effect, and less than 0% highlights a potentiation depression.

3.2.7 Statistical Analyses

All statistical procedures were conducted using SPSS 22 (SPSS Inc., Chicago, IL). Following tests of normal distribution, statistical analysis was conducted using a 2 x 2 x 9 (strength level x exercise x jump repetition) factorial analysis of variance (ANOVA) with repeated measures on jump repetition to analyse pre-CA and post-CA changes. Any

significant interaction effects were further analysed using pairwise comparisons with Sidak corrections to correct for type I errors. Additionally, a separate repeated measures one-way ANOVA was used to analyse the data from the CON trial to determine whether any observed effects were due to the CA or if there was a warm-up effect or fatigue effect from subsequent CMJs. This analyses was conducted separately since the single CON trial consisted of ten participants from the recruited twenty. As such, there was an unequal number of trials between the CON and the main experimental conditions. Significance was set at $p \leq 0.05$.

3.3 Results

3.3.1 Peak Power Output

There was a significant interaction effect (time x exercise) for PAP during the CMJs ($p = 0.006$). Follow up pairwise comparisons revealed that HBD significantly improved PPO in comparison to baseline by 6.43% at 2 minutes ($p < 0.001$, confidence interval [CI] = 2.83 to 10.03%), by 5.01% at 4 minutes ($p = 0.01$, CI = 0.70 to 9.32%), and by 6.14% at 6 minutes ($p = 0.002$, CI = 1.50 to 10.79%), however, there were no significant ($p > 0.05$) improvements for BS. The HBD expressed greater improvements than BS by 4.97% at 2 minutes ($p = 0.002$, CI = 1.98 to 7.96%), 5.41% at 6 minutes ($p = 0.007$, CI = 1.56 to 9.27%), 4.79% at 10 minutes ($p = 0.012$, CI = 1.10 to 8.48%), 4.02% at 12 minutes ($p = 0.021$, CI = 0.65 to 7.38%), 3.89% at 14 minutes ($p = 0.019$, CI = 0.68 to 7.10%), and 5.71% at 16 minutes ($p = 0.003$, CI = 2.03 to 9.39%) (Figure 3.3 A). There were no significant ($p > 0.05$) differences between stronger and weaker players. The CON condition (Figure 3.3 B) demonstrated a significant decrease in PPO by -5.47% at 16 minutes ($p = 0.016$, CI = -10.09 to -0.85%).

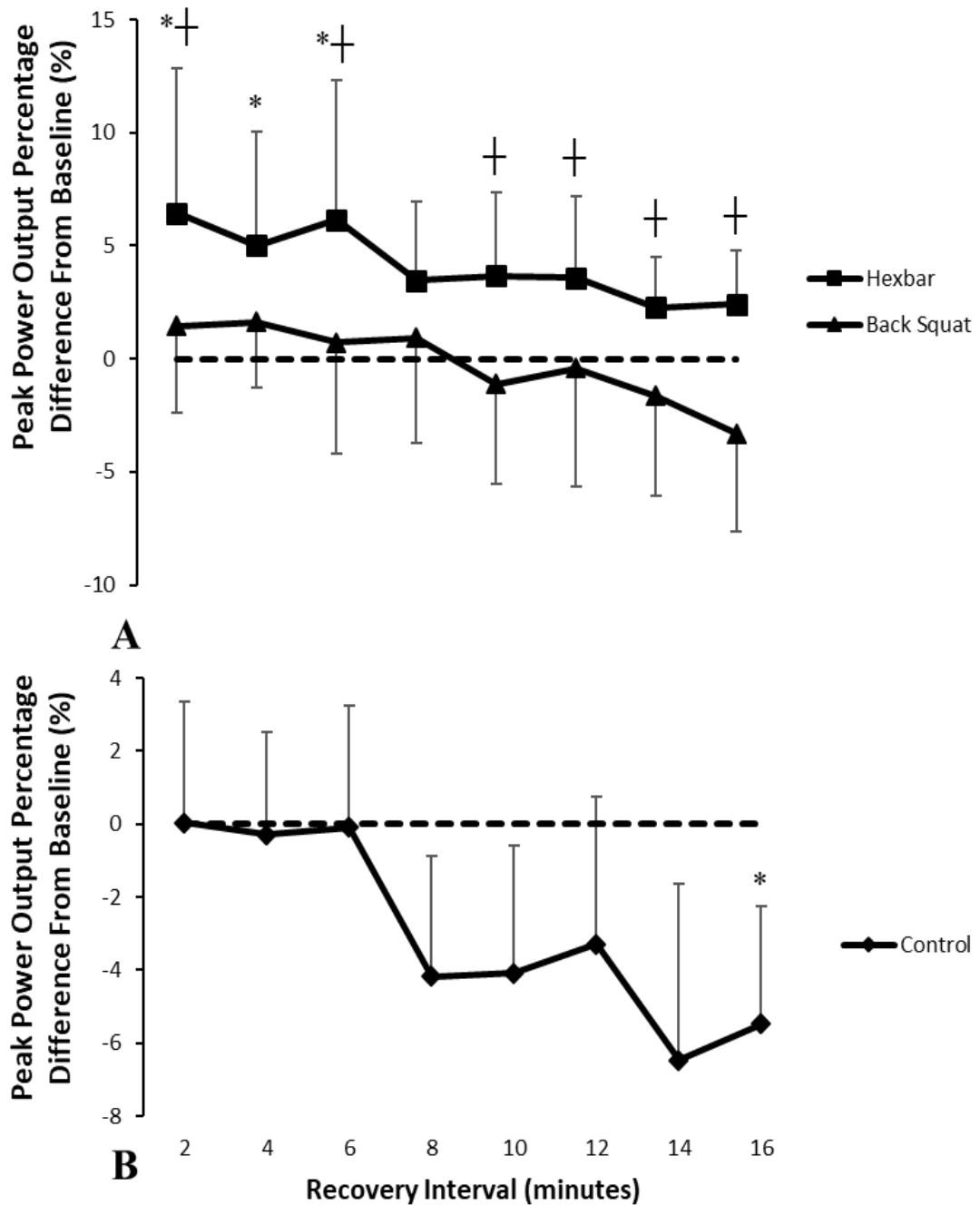


Figure 3.3 A) PPO PAP response during the series of CMJs for the hex-bar deadlift and back squat exercises. B) Time course for the control trial. All results are expressed as a percentage of baseline. *significantly different from baseline ($p \leq 0.05$). †hex-bar condition significantly different to back squat condition.

3.3.2 Ground Reaction Force at Peak Power Output

For GRF at PPO, there were no significant ($p > 0.05$) interaction effects, however there was a significant main effect ($p = 0.022$). Regardless of group or CA, follow up pairwise comparisons revealed a significant improvement in comparison to baseline by 2.49% at 4 minutes ($p = 0.014$, CI = 0.30 to 4.69%) (Figure 3.4).

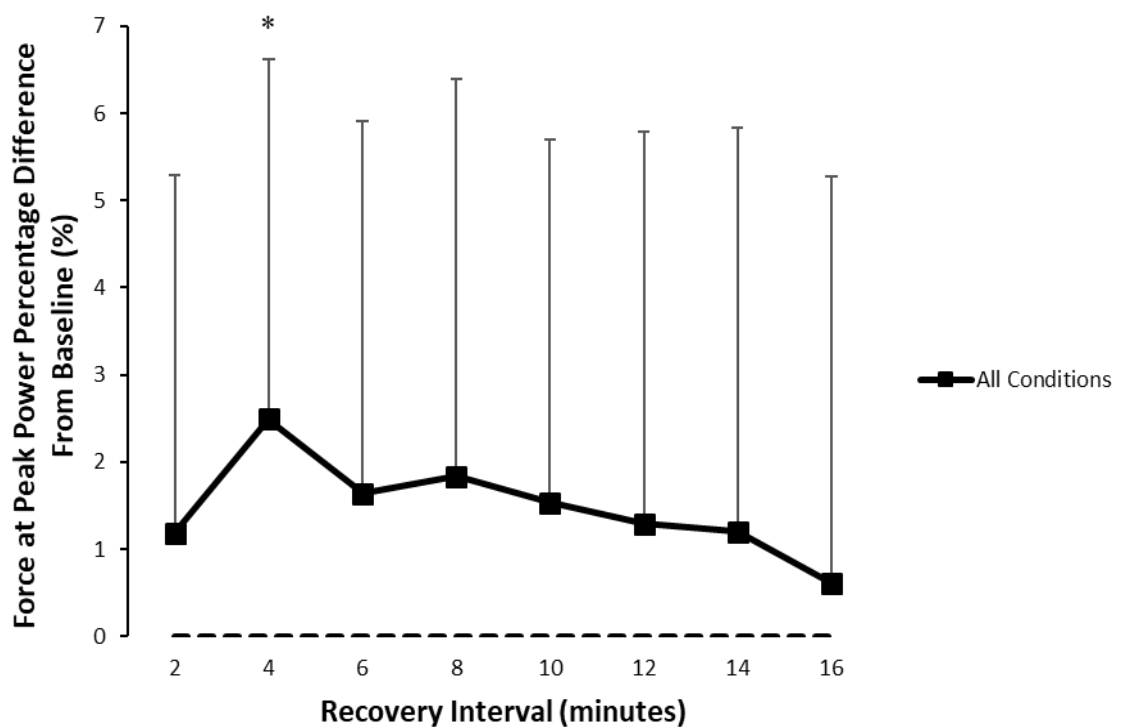


Figure 3.4 Force at PPO PAP response during the series of CMJs for both exercises and stronger and weaker athletes. All results are expressed as a percentage of baseline. *significantly different from baseline ($p \leq 0.05$).

3.3.3 Velocity at Peak Power Output

For velocity at PPO, there were no significant ($p > 0.05$) interaction effects, however there was a significant main effect ($p < 0.001$). Regardless of group or CA, follow up pairwise comparisons revealed a significant decrease in comparison to baseline by -3.26% at 16 minutes ($p = 0.004$, CI = -5.86 to -0.65%) (Figure 3.5 A). The CON condition also

expressed a significant decrease in velocity at PPO by -5.30% at 14 minutes ($p = 0.05$, CI = -10.59 to -0.01%) (Figure 3.5 B). There were no significant ($p > 0.05$) differences between the exercise conditions (Figure 3.5 C).

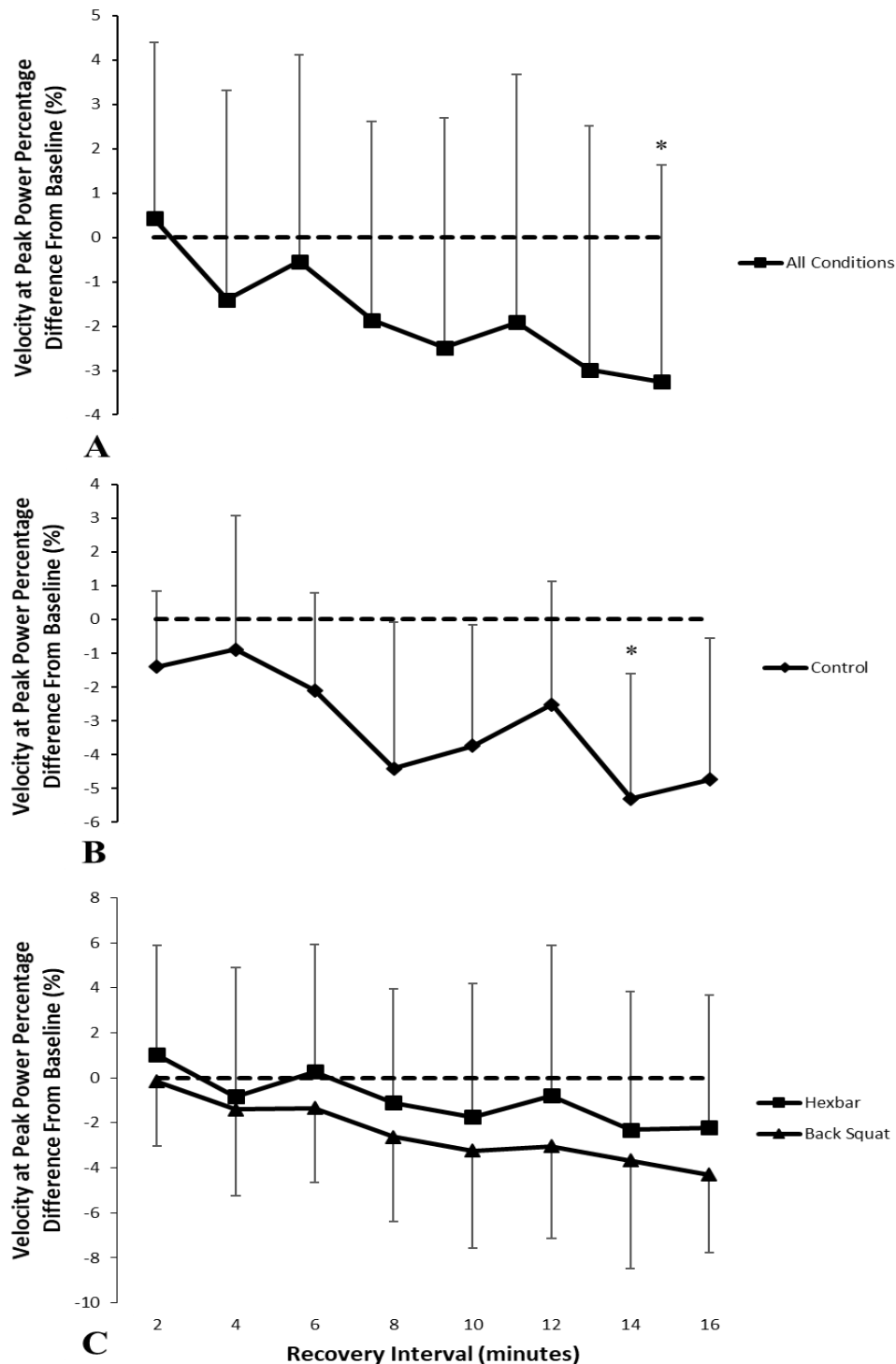


Figure 3.5 A) Velocity at PPO PAP response during the series of CMJs for both exercises and stronger and weaker athletes. B) Time course for the control trial. All results are expressed as a percentage of baseline. C) Time course for the hex bar deadlift and back squat exercises. *significantly different from baseline ($p \leq 0.05$).

Table 3.5 Mean $\pm$ SD jump height for all post-CA jumps. Values expressed as a percentage difference from the baseline jump.

	Jump Height					
	Overall	Hex-Bar Deadlift	Back-Squat	Stronger	Weaker	Control
2 minutes	0.84 $\pm$ 6.67	2.57 $\pm$ 7.20	-0.88 $\pm$ 5.77	1.17 $\pm$ 4.92	0.52 $\pm$ 8.18	-2.63 $\pm$ 5.56
4 minutes	-1.67 $\pm$ 8.26	-1.71 $\pm$ 10.34	-1.62 $\pm$ 5.76	-0.74 $\pm$ 6.69	-2.60 $\pm$ 9.68	-2.85 $\pm$ 5.01
6 minutes	0.80 $\pm$ 9.08	2.46 $\pm$ 9.65	-0.85 $\pm$ 8.38	1.60 $\pm$ 8.77	0.01 $\pm$ 9.53	-2.37 $\pm$ 5.69
8 minutes	-1.34 $\pm$ 8.55	0.04 $\pm$ 9.95	-2.73 $\pm$ 6.85	-0.86 $\pm$ 7.44	-0.86 $\pm$ 7.44	-8.42 $\pm$ 6.40
10 minutes	-2.48 $\pm$ 8.55	-1.34 $\pm$ 10.14	-3.63 $\pm$ 6.66	-1.32 $\pm$ 7.39	-3.65 $\pm$ 9.62	-8.39 $\pm$ 5.07
12 minutes	-2.65 $\pm$ 8.99	-1.46 $\pm$ 10.8	-3.84 $\pm$ 6.8	-3.00 $\pm$ 8.76	-2.30 $\pm$ 9.42	-8.33 $\pm$ 7.75
14 minutes	-4.45 $\pm$ 8.53	-3.80 $\pm$ 9.06	-5.09 $\pm$ 8.14	-4.26 $\pm$ 7.08	-4.64 $\pm$ 9.95	-10.96 $\pm$ 7.71
16 minutes	-4.69 $\pm$ 9.07	-1.98 $\pm$ 10.89	-7.40 $\pm$ 5.89	-4.28 $\pm$ 8.04	-5.10 $\pm$ 10.19	-8.77 $\pm$ 6.42

CA = conditioning activity

3.3.4 Jump Height

For jump height, there were no significant interaction effects ($p > 0.05$) and there was no significant main effect ($p > 0.05$) (Table 3.5).

3.3.5 Muscle Activity

For mean muscle activity of the VL, BF, TA and GM, there were no significant interaction effects ($p > 0.05$) and there were no significant main effects ($p > 0.05$). There was a high degree of variability expressed within the data. For all conditions the EMG data ranged from $2.72 \pm 20.29\%$ to $-0.91 \pm 17.46\%$, $6.58 \pm 20.08\%$ to $-2.65 \pm 22.22\%$, $3.00 \pm 24.77\%$ to $-5.20 \pm 22.64\%$, and $9.98 \pm 20.95\%$ to $3.72 \pm 17.68\%$ for the VL, BF, TA and GM, respectively.

3.4 Discussion

When investigating the optimal ICRI of the PAP response, previous studies have used recovery intervals ranging from 0.3-24 minutes for the BS exercise (Crewther et al., 2011; Jensen & Ebben, 2003; Jones & Lees, 2003; Kilduff et al., 2008; Seitz, de Villarreal, et al., 2014). It is thought that the optimal ICRI for the BS is 4-12 minutes for well-trained individuals (Crewther et al., 2011; Kilduff et al., 2007, 2008; Seitz & Haff, 2015b). The PAP response following the HBD significantly improved PPO at 2, 4 and 6 minutes post-CA for both stronger and weaker rugby league players. This finding suggests that HBD is a suitable CA for inducing PAP.

Optimal adaptations to the nervous system are induced by near maximal concentric only contractions performed as fast as possible (Schmidtbleicher, 1992). The HBD was performed as a concentric only contraction as participants were instructed not to resist the eccentric phase of the movement. This lifting technique may have reduced the effects of neuromuscular fatigue due to a reduction in time under tension and a reduced eccentric

load (Tran et al., 2006), therefore enabling a greater magnitude of PAP to be elicited at a greater rate.

Although no study has ever used HBD as a CA, other studies have attempted to reduce the volume of eccentric work by examining the effects of partial BS on jump performance. Crum et al. (2012) reported no significant improvement in CMJ performance following moderately loaded (50-65%) quarter-squats in males who could perform the CA at a load ≥ 2.4 times body weight. However, the moderately loaded CAs may not have been sufficient enough to evoke a PAP response. Similarly, Mangus et al. (2006) demonstrated no significant improvement in CMJ performance following heavy load (90% of 1RM) quarter-squats or half-squats in weightlifters with at least 1-year experience. Although the eccentric phase of the lift is reduced during quarter-squats and half-squats, potentially reducing fatigue, the concentric phase is also reduced which may reduce the potentiating effect. In contrast, Esformes and Bampouras (2013) investigated the effect of 3RM parallel squats and 3RM quarter squats on jump performance. Although both conditions significantly improved performance, the parallel squat condition demonstrated a greater improvement. This may have been due to the fact that professional athletes with greater strength levels were recruited and the longer concentric phase induced by the parallel squat condition. Collectively, these results suggest that the full ROM throughout the concentric phase of the lift is paramount in eliciting PAP. The HBD exercise may be advantageous as the lifting technique allows the eccentric phase to be reduced and the concentric phase to be maximised. This may explain why HBD appears to elicit a greater magnitude of PAP in weaker athletes as well as stronger athletes in the present study.

Velocity at PPO for both exercises decreased over time however, HBD appeared to express greater velocities than BS during the PAP time course (Figure 3.5 C). HBD may

have enhanced the contraction velocity, making the CA more specific to the plyometric action (Crum et al., 2012; Ruben et al., 2010). Swinton et al. (2011) found that HBD reduced peak moments at the lumbar spine, hip, and ankle therefore more evenly distributed the load across the joints of the body. Interestingly, there was an increased peak moment at the knee despite the magnitude of the moment arm being reduced, therefore indicating that muscular effort was enhanced due to the distribution of the load. It is possible that the mechanics of HBD alters the force-velocity curve of the movement, subsequently enhancing the contraction velocity. This may allow greater forces to be generated at greater velocities during key phases of the lift, which may explain the enhanced PAP response.

Previous research has investigated the effects of differing contraction velocities during the CA, by utilising Olympic style lifts. Andrews et al. (2011) and Seitz, Trajano, et al. (2014) found that Olympic style lifts were superior in evoking PAP in comparison to conventional methods, highlighting that the ability to produce high forces at high velocities may influence the PAP response. Conversely, McCann and Flanagan (2010) reported no differences between the PAP response of BS and hang clean on CMJ performance. Perhaps, the technical demands of the Olympic style lifts are also a contributing factor to the ambiguous findings. Additionally, the optimal ICRI for Olympic style lifts is reported at 7-10 minutes post-CA (Seitz & Haff, 2015b; Seitz, Trajano, et al., 2014), further emphasising the advantages of HBD demonstrated in this study.

The present study found no significant improvements in CMJ performance following BS, which is in agreement with previous research (Comyns et al., 2006; Jensen & Ebben, 2003; McCann & Flanagan, 2010). However, it is important to note that the ICRIs were

relatively short in these studies (10 seconds to 6 minutes) and may not have been adequate for PAP to occur. These results are substantiated by Jones and Lees (2003) who reported no improvement in CMJ performance at 3, 10 or 20 minutes post-CA. However, the authors recognise that there was a small sample size ($n = 8$) and that the trends in the data were not significant as a result. Contrastingly, Kilduff et al. (2008) reported significant increases in CMJ performance 8 minutes following heavy load BS with professional rugby union players. Crewther et al. (2011) also found significant improvements in CMJ performance after a single set of 3RM BS at ICRIIs of 4, 8, and 12 minutes in professional rugby union players. Collectively, research indicates that BS decreases performance with shorter ICRIIs but may be an appropriate CA for well-trained athletes (Crewther et al., 2011; Jensen & Ebben, 2003; Kilduff et al., 2007, 2008; Seitz, de Villarreal, et al., 2014).

It has previously been reported that the ability to BS 1.5 x body mass is an influential factor in the PAP response and is typically used as a cut-off to determine between stronger and weaker athletes (Chiu et al., 2003; Jo et al., 2010; Ruben et al., 2010; Seitz, de Villarreal, et al., 2014). The ten strongest individuals, with respect to relative 1RM, were assigned to the 'stronger' group. However, 90% of participants assigned to the 'stronger' group were able to BS 1.5 x body mass. To avoid unequal sample sizes between the groups, ten participants were assigned to each group. Although it is unlikely that this would have affected the between-group analyses, it is important to note group assignment as a limitation of this study.

In the present study, there were no significant differences between stronger and weaker players in any of the dependent variables. This finding conflicts with previous research which has suggested that training status is a modulating factor in eliciting PAP (Hodgson et al., 2005; Ruben et al., 2010; Seitz, de Villarreal, et al., 2014). Kilduff et al. (2007)

found a significant correlation between strength levels and the magnitude of the PAP effect. Seitz, de Villarreal et al. (2014) reported that individuals able to squat $\geq 2 \times$ body mass expressed a significantly greater PAP response than individuals who squatted $< 2 \times$ body mass. In the present study, the relative 1RM BS scores for stronger and weaker players were 1.75 ± 0.32 and 1.24 ± 0.14 , respectively. Whereas, the relative 1RM HBD scores were 2.11 ± 0.24 and 1.76 ± 0.28 for stronger and weaker players, respectively. This may further explain why HBD induced a greater PAP response since weaker players were able to lift a greater relative load.

Due to HBD being a less technically demanding exercise, it was possible for a greater absolute load to be lifted, which is likely to have heightened the PAP response. A possible explanation for this enhanced response is that it may have elevated the phosphorylation of myosin RLC (Talpey et al., 2014; Tillin & Bishop, 2009). The increased load may have caused a greater increase in sarcoplasmic Ca^{2+} , therefore activating more myosin light chain kinase. Consequently, the amount of adenosine triphosphate (ATP) available at the actin-myosin complex may have increased therefore, increasing the rate of actin-myosin cross-bridging.

Another underpinning mechanism of PAP is enhanced neural excitability within type II muscle fibres (Hodgson et al., 2005; Seitz, de Villarreal, et al., 2014). In the present study muscle fibre type was not assessed however, neural activation was assessed using surface EMG. Few studies have examined the effects of PAP with EMG analysis. This study highlighted a large amount of variability within the EMG data, with no significant changes in muscle activation and no clear trends when interpreting the mean differences of the data. Therefore, no conclusions can be drawn from the EMG data of this study about the underlying mechanisms of PAP. This is in agreement with Jones and Lees

(2003) who reported no significant differences in EMG data and high variability within the data. Ebben et al. (2000) also reported no significant improvements in EMG variables during upper body complex training. Collectively, this evidence suggests that it is less likely that the underpinning mechanism of PAP is due to the recruitment of higher order motor units (Young et al., 1998). However, given the high level of variability reported within the EMG data of scientific research, further studies are required to elucidate the contribution of the neural system to the voluntary PAP response.

Some studies of similar design have failed to include a CON condition (McCann & Flanagan, 2010; Seitz, de Villarreal, et al., 2014). The CON condition in the present study highlighted no potentiating effects due to the warm up protocol or due to earlier CMJs in the time course inducing a PAP response on later CMJs. It is likely that the PAP response was due to the CAs as previous studies have demonstrated this using a CON condition (Jensen & Ebben, 2003; Kilduff et al., 2008; Seitz, Trajano, et al., 2014). However, there appeared to be fatiguing effects due to the CMJs. Andrews et al. (2011) and Weber et al. (2008) reported significant decreases in jump performance during the CON conditions of their experimental protocols. Additionally, Jones and Lees (2003) reported no significant decrease during their CON trials however, when interpreting the data it is clear that there was a mean decrease in jump performance over time. Therefore, future research should carefully consider the post-CA recovery intervals to ensure there is no fatiguing effects due to the CMJs.

In conclusion, the results of this study suggest that the optimal ICRI for HBD is 2-6 minutes, which is earlier than the 4-12 minutes proposed by previous research for the BS. It is likely that the concentric only contraction induced by the HBD enhances the PAP response and reduces neuromuscular fatigue as less time is spent under tension. Complex

training appears to be a suitable training modality for both stronger and weaker rugby league players when HBD is used as a CA. Future research should investigate the effects of CAs with different force-velocity profiles and the impact this has on subsequent plyometric performance as contraction velocity could be an influential factor in eliciting PAP. Further research is required to understand the underpinning neuromuscular mechanisms of PAP. Lastly, future studies should carefully consider the post-CA ICRI, or reduce the number of post-CA ICRI, as too many post-CA measures may induce additional fatigue.

3.5 Practical Applications

Based on the findings of the current study, strength and conditioning coaches should carefully consider exercise selection when implementing complex training to enhance lower body power. Although training status has been highlighted as an important factor in eliciting PAP response, it appears that the absolute load which is lifted may also influence PAP. HBD is an effective potentiating stimulus as it is a safer, less technically demanding exercise which enables a greater load to be lifted. The results of this study suggest that an ICRI of 2-6 minutes is optimal for HBD and it appears to be a suitable CA for stronger and weaker athletes. When designing complex training programmes strength and conditioning specialists should consider the training status of the individuals, the most appropriate CA, and the recovery interval between the CA and subsequent plyometric exercise to optimise performance.

Chapter 4: The effect of accommodating resistance on the post-activation potentiation response in rugby league players.

4.1 Introduction

PAP is a phenomenon which refers to the acute augmentation of force and power production following a near-maximal voluntary contraction of skeletal muscle (Docherty et al., 2004; Jensen & Ebben, 2003; Wyland et al., 2015). This enhancement in force and power production is thought to be due to increased phosphorylation of myosin RLCs heightening the sensitivity of actin and myosin to Ca^{2+} availability, increased excitability of α -motor neurons, and short-term decreases in muscle fibre P_{ang} (Docherty et al., 2004; Tillin & Bishop, 2009; Wilson et al., 2013). The relative contributions of these mechanisms to PAP remain unclear however, there is a growing body of scientific research to suggest that muscular power is temporarily augmented following heavy load conditioning activities (CA) of $>85\%$ 1 RM (Bevan et al., 2010; Crewther et al., 2011; Kilduff et al., 2007, 2008; Scott, Ditroilo, & Marshall, 2017; Seitz, de Villarreal, et al., 2014). Similarly, there is empirical evidence which has demonstrated little or no potentiation effects (Andrews et al., 2011; Comyns et al., 2006; Jensen & Ebben, 2003; Jones & Lees, 2003; McCann & Flanagan, 2010).

A common issue with PAP is the ICRI required between the CA and plyometric activity, which can limit its practical application. Traditional heavy load CAs, such as BS, typically report optimal ICRI of 4-12 minutes (Bevan et al., 2010; Crewther et al., 2011; Kilduff et al., 2007, 2008; Scott et al., 2017; Seitz, de Villarreal, et al., 2014). This is due to heavy load CAs simultaneously inducing fatigue which inhibits the PAP response (Tillin & Bishop, 2009). However, fatigue dissipates at a greater rate and there is an opportunity to augment performance when the working muscles have partially recovered but are still potentiated (Docherty et al., 2004; Tillin & Bishop, 2009). Although PAP is typically thought to be elicited by heavy load resistance CAs, there is evidence to suggest that PAP may be evoked by more moderate loads of 60-85% 1RM (Baker & Newton,

2005; Smilios et al., 2005; Wilson et al., 2013). Therefore, it is plausible that a moderate resistance load combined with accommodating resistance, equating to a heavy resistance load, could be a more practical training strategy to elicit PAP. Previous research has utilised moderate loaded BS combined with accommodating resistance and reported a PAP response 90 seconds (Baker, 2008) and 4 minutes (Wyland et al., 2015) post-CA.

Accommodating resistance is theorised to modify the force-velocity curve during resistance exercise by adding a percentage of the total resistance through latex bands or chains (Baker & Newton, 2009). This means that as the barbell continues through the ROM during the concentric phase, additional resistance will be applied (Baker & Newton, 2009; Wyland et al., 2015). Consequently, the effects of biomechanically disadvantageous positions, known as “sticking points”, are reduced; this results in increased acceleration and velocity during the concentric phase of the lift which enables greater power outputs to be achieved (Nijem et al., 2016; Wyland et al., 2015).

Schmidtbleicher (1992) suggests that near maximal contractions performed at high velocities induce the greatest neural adaptations. Therefore, the use of accommodating resistance may be an optimal method of eliciting PAP as the length-tension relationship of skeletal muscle is accounted for (Nijem et al., 2016; Wyland et al., 2015). The reduction in sticking points may enhance type IIb muscle fibre recruitment and elicit optimal adaptations (Wyland et al., 2015). Furthermore, the enhanced acceleration and contraction velocities throughout the full ROM may translate more specifically to plyometric or SSC actions (Crewther et al., 2011; Crum et al., 2012) since the rapid production of force throughout the full ROM is a necessity in most sports (Baker, 2008; Wyland et al., 2015).

Anecdotal evidence suggests that accommodating resistance training increases the speed of the eccentric phase of the lift therefore inducing a greater stretch reflex (Simmons, 2007). This attempts to override the GTO, consequently contributing to greater force production during the concentric phase and is referred to as “overspeed eccentrics” (Simmons, 2007). It has been suggested that the use of accommodating resistance reduces joint stress throughout the ROM (Nijem et al., 2016) and therefore, could be a safer and more suitable resistance training method for all levels of athletes in comparison to traditional heavy load resistance exercises.

The length of time required to achieve a PAP response may make it difficult for strength and conditioning practitioners to implement complex training in real-world training scenarios, where time is often very limited. Empirical evidence suggests that a voluntary PAP response can be elicited at shorter ICRI of 0.3-4 minutes following the completion of lighter, more explosive CAs (Seitz & Haff, 2015b). Specifically, Turner et al. (2015) demonstrated PAP responses at 4-8 minutes following the use of a weighted plyometric action as a CA, which involves a fast eccentric to concentric action. The lifting technique of the HBD exercise combined with accommodating resistance may evoke an overspeed eccentric phase and increase contraction velocity during the concentric phase, whilst facilitating a near maximal voluntary contraction. It is plausible that this may enhance the specificity of the CA to the plyometric action (Crewther et al., 2011; Crum et al., 2012) and subsequently induce a PAP response in a shorter period of time which would fit more effectively into real-world training scenarios. In contrast, the technique of the BS exercise combined with accommodating resistance may well increase contraction velocity during the concentric phase, however it encourages a slower eccentric phase since the greater technical difficulty requires increased control during the descent; this may reduce the

specificity between the CA and plyometric activity (Crewther et al., 2011; Crum et al., 2012).

To date there is very little academic literature which has investigated the effects of accommodating resistance on the PAP response (Baker, 2008; Wyland et al., 2015). Therefore, the purpose of this study was to determine whether PAP could be elicited at a shorter, more practical ICRI after a single set of either HBD or BS with the addition of accommodating resistance. It was hypothesised that PAP would be induced following both exercises in comparison to a CON condition. Furthermore, it was hypothesised that the HBD would elicit a greater PAP response due to the technique of the lift inducing a greater velocity during the eccentric phase, thus enhancing the specificity between the CA and plyometric action (Baker & Newton, 2009; Crewther et al., 2011; Crum et al., 2012).

4.2 Methods

4.2.1 Experimental Approach to the Problem

This study used a repeated measures, counterbalanced research design with random treatment order. The participants completed two familiarisation sessions, two experimental sessions, and a CON trial to examine the impact of the HBD and BS exercises combined with accommodating resistance on CMJ performance. During the experimental sessions, the participants performed maximal CMJs before and 30, 90, and 180 seconds after 1 set of 3 repetitions of either HBD or BS. Both CAs were performed at 70% 1RM, with the addition of elastic band resistance, which varied from 0-23% 1RM across the ROM, with maximum band tension achieved at end range. Each participant also completed a CON trial with no CA. The following dependent variables were

compared between the baseline and the post-CA CMJs: PPO, GRF at PPO, velocity at PPO, jump height, and mean EMG values of the VL, BF, TA and GM.

4.2.2 Subjects

Twenty rugby league players ($n = 20$) were recruited from a University level rugby league team who play in the BUCS Premier North Division (age: 22.35 ± 2.68 years; height: 182.23 ± 6.00 cm; weight: 94.79 ± 12.79 kg). Inclusion criteria required participants to have at least 6-months prior experience in a structured resistance training program and to be able to perform HBD, BS and CMJ exercises with correct technique under the supervision of a qualified strength and conditioning coach. The study received full institutional approval from the University's Sport, Health and Exercise Science Ethics Committee. Prior to any experimental procedures, the participants gave their voluntary written informed consent (Appendix C) and completed a pre-exercise medical questionnaire (Appendix F). Participants were asked to refrain from engaging in any strenuous or unaccustomed exercise 48 hours prior to testing, to avoid the intake of caffeine 6 hours prior to testing and avoid the intake of alcohol 12 hours prior to testing.

4.2.3 Procedures

Prior to any experimental trials, the participants attended two familiarisation sessions which were separated by one week. During these sessions the anthropometric measurements of height (The Leicester Height Measure, Seca, Birmingham, UK) and body mass (Seca digital scales, Birmingham, UK) were recorded. Leg dominance was also determined, for the purpose of electrode placement, using three tests: the step up, balance recovery and ball kick test (Hass et al., 2005). Leg dominance was defined as the leg which was dominant in two of the three tests.

The additional resistance from the elastic bands for the corresponding CAs were measured using Seca weighing scales (Seca digital scales, Birmingham, UK) which were previously calibrated following the manufacturer guidelines. Similar to previous research (Baker, 2008; Wallace et al., 2006) the participants stood on the scales with the bar and the mass was recorded. The bands (Pullum Sports, Leighton Buzzard, Bedfordshire) were then attached to the bar and the participants stood at the end of range for each lift and the mass was recorded. Band tension was defined as the difference between these two measures. This process was repeated with bands of various tension until the additional resistance reached up to 23% 1RM at end range for the corresponding CA.

Prior to the completion of the 1RM tests, the participants underwent a standardised warm-up consisting of a three minute cycle on a Wattbike ergometer (Wattbike Ltd, Nottingham, United Kingdom) at a low intensity of 60 W, a series of dynamic stretches (Table 4.1) which specifically focussed on the musculature associated with HBD, BS and CMJ, and warm-up sets of the corresponding CA. The procedures for measuring muscular strength adhered to the guidelines recommended by the NSCA (Appendix G; Brown, 2007). Briefly, this involved progressively increasing the load on the bar until the participants could only perform one successful repetition with correct technique (Table 4.2).

Following demonstrations and verbal instructions, the participants practised performing CMJs with correct technique and the aim of optimising jump height. The participants were instructed to jump with their hands on their hips throughout the CMJ to ensure that it was only the lower body contributing to the production of force and power. Instruction was given to perform the eccentric phase of the jump by flexing the knees to a self-selected depth of approximately 90° knee flexion (Hori et al., 2009) and exploding

upwards as forcefully and as quickly as possible to minimise the amortisation phase. The participants were instructed to keep their legs straight during the flight phase of the CMJ and to land in the same position as take-off. To reduce the risk of injury, instruction was given to cushion the landing by bending the knees as soon as the feet made contact with the ground. The use of CMJs to measure the PAP response is well documented in empirical research (Comyns et al., 2006; Crewther et al., 2011; Jensen & Ebben, 2003; Jones & Lees, 2003; Kilduff et al., 2007, 2008; Scott et al., 2017).

Table 4.1 Standardised dynamic warm up for strength testing, experimental trials and control trials.

Exercise	Sets	Reps
Body weight squats	1	6
Mountain climbers	1	6 e/s
Thoracic rotations	1	6 e/s
Glute Bridge	1	6
Band pull aparts	1	6

e/s = each side

Table 4.2 Comparison of the absolute and relative 1RM loads lifted.

Strength Measure	Hex-Bar Deadlift (Mean ± SD)	Back Squat (Mean ± SD)	p value
1RM Absolute Load (kg)	167.00 ± 33.98	133.75 ± 28.19	< 0.001
1RM Relative Load (kg/kg)	1.78 ± 0.41	1.42 ± 0.30	< 0.001

1RM = 1 repetition maximum

To control for circadian rhythm, the experimental sessions were separated by one week and were conducted at the same time of day (Atkinson & Reilly, 1996). Prior to the warm-up and data collection, the muscles under EMG examination were prepared following SENIAM guidelines (Appendix H; Freriks, 1999) to reduce skin resistance. This process involved measuring anatomical landmarks, shaving and minor abrasion of the site, and cleansing with an alcohol wipe. The surface EMG of the VL, BF, TA, and GM of each participant's dominant leg was recorded during each CMJ.

The participants then completed a standardised warm-up comprising of a three minute cycle on a Wattbike ergometer (Wattbike Ltd, Nottingham, United Kingdom) at an intensity of 60 W, a series of dynamic stretches (Table 4.1) with specific focus placed on the musculature associated with BS, HBD and CMJ, warm-up sets of the corresponding CA, and three to four submaximal repetitions of CMJs. Following a baseline CMJ, the participants completed three repetitions of the corresponding CA at $70 + 0-23\%$ 1RM from elastic band resistance throughout the full ROM. Subsequently, a single CMJ was performed with maximal effort at ICRI of 30, 90, and 180 seconds. The CON trial followed the same procedure however, the CA was replaced with a 5 minute seated rest period. This was to ensure that any PAP effects were due to the CAs and not the warm up protocol.

During the BS, the participants were instructed to control the eccentric phase of the lift, to avoid injury, and to lift as explosively as possible during the concentric phase. Similarly, during the HBD, the participants were instructed to lift as explosively as possible during the concentric phase, but also perform the eccentric phase of the lift as fast as possible. Additionally, the participants were instructed to minimise the

amortisation phase of the lift and avoid stopping or putting the bar on the floor between each repetition.

4.2.4 Measurements

Force Platform: To collect the GRF data during the CMJ, a strain gauge force platform (AMTI, BP600900; dimensions 900x600mm, Watertown, Massachusetts, USA) was used. The sampling frequency was set at 1500Hz. Prior to any experimental sessions, the force platform was calibrated according to manufacturer guidelines.

EMG: To collect the surface EMG data, a wireless Noraxon EMG system with 16 bit analogue to digital resolution (Telemetry 2400T, Noraxon, Scottsdale, Arizona, USA) was used. This was sampled at 1500Hz and was synchronised to the GRF data via Qualisys Track Manager Software (Qualisys Oqus 400, Gothenburg, Sweden).

4.2.5 Data Analysis

The GRF and EMG data were analysed using customised coding scripts in MATLAB (MATLAB, version R2014a, MathWorks, Inc., Natick, MA). The vertical component of the GRF data was left unfiltered as no noise was evident in the signal. Subsequently, the dependent variables could be calculated whilst controlling the effects of different filtering techniques (Hori et al., 2009).

PPO: The participants' mass was calculated by taking an average of the GRF data 2 seconds prior to the start of the CMJ. Equations (1) and (2) were used to calculate PPO:

$$1) \ A_{inst.} (m \cdot s^{-2}) = [GRF_{inst.} (N) / m (kg)] - g (9.81 m \cdot s^{-2})$$

where $A_{inst.}$ is instantaneous acceleration, $GRF_{inst.}$ is instantaneous ground reaction force, m is the mass of the participant, and g is the acceleration due to gravity.

$$2) \ P_{inst.} (W) = GRF_{inst.} (N) \times V_{inst.} (m \cdot s^{-1})$$

where $P_{inst.}$ is instantaneous power, and $V_{inst.}$ is instantaneous velocity which was calculated by integration of instantaneous acceleration using the Simpson's rule. The start of the CMJ was determined as the instant where the instantaneous GRF was reduced by 10% of the participant's body weight. Integration started from the start of the jump and finished at the point of landing, where the intervals were equal to the band width. PPO was determined by obtaining the greatest value for instantaneous power.

GRF and Velocity at PPO: GRF at PPO and velocity at PPO were determined by identifying the time point at which PPO occurred and finding the corresponding GRF and velocity values.

Jump Height: The height of each CMJ was determined using the flight-time method, equation (3) (Linthorne, 2001):

$$3) \text{ JH (m)} = [g (9.81 \text{ m}\cdot\text{s}^{-2}) \times \text{FT}^2 (\text{s})] / 8$$

where JH is jump height, and FT is flight time which was calculated by finding the difference in time between take-off and landing. Take-off was determined as the instant where the force data was less than 5N and landing was defined as the instant at which the force was greater than 5N.

EMG: The raw EMG data were first band-pass filtered (10-450Hz) using a digital 2nd order zero-lag Butterworth filter. The data were then full wave rectified and a linear envelope was created using a digital 2nd order zero-lag Butterworth low pass filter with a cut off frequency of 6Hz. It was then possible to quantify the muscle activity by taking the mean of the EMG data between the start of the jump to the point of take-off, for each muscle. At the chosen ICRI, the EMG activity of the muscles under examination were normalised to the EMG values during the baseline CMJ of the corresponding experimental session and expressed as a percentage of the movement.

To assess the relative change in performance between the participants following the CAs, each variable was expressed as a percentage of potentiation using equation (4) (Chiu et al., 2003):

$$4) \% = [(\text{Potentiated Variable} / \text{Un-potentiated Variable}) \times 100] - 100$$

where a potentiation percentage of 0% highlights no potentiation, greater than 0% highlights a potentiation effect, and less than 0% highlights a potentiation depression.

4.2.6 Statistical Analyses

Preliminary analysis was conducted to ensure normality and that the data met the assumptions of the statistical test. Statistical analysis was conducted using a 3 x 4 (condition x jump repetition) ANOVA with repeated measures on jump repetition to analyse pre-CA and post-CA changes. The peak relative changes in individual performance (baseline vs. maximum potentiation response) during the CAs were analysed using a 2-way ANOVA (condition x jump repetition) with repeated measures. Any significant interaction effects identified in the analyses were further analysed using pairwise comparisons with Sidak corrections to correct for type I errors. Significance was set at $p \leq 0.05$. All statistical procedures were conducted using SPSS 23 (SPSS Inc., Chicago, IL).

ICCs were calculated to measure the reliability of the experimental data. ICCs were calculated by correlating the absolute values of the variables from the baseline jumps of the experimental sessions. The average ICCs for PPO, GRF at PPO, velocity at PPO, and jump height were 0.932, 0.807, 0.845, and 0.897, respectively (Table 4.3). The average ICC for the mean muscle activity of the VL, BF, TA, and GM were 0.655, 0.715, 0.429, and 0.667, respectively. ICCs were interpreted as poor for values less than 0.5, moderate

for values between 0.5 and 0.75, good for values between 0.75 and 0.9, and excellent for values greater than 0.9 (Koo & Li, 2016).

Table 4.3 Average ICCs and ICCs between each condition for each variable.

Variables	HBD - BS	HBD - CON	BS – CON	Average	Interpretation
PPO	0.908	0.936	0.953	0.932	Excellent
GRF at PPO	0.817	0.825	0.779	0.807	Good
Velocity at PPO	0.844	0.785	0.907	0.845	Good
Jump Height	0.883	0.875	0.934	0.897	Good
Muscle activity of the VL	0.633	0.674	0.658	0.655	Moderate
Muscle activity of the BF	0.758	0.787	0.601	0.715	Moderate
Muscle activity of the TA	0.554	0.284	0.450	0.429	Poor
Muscle activity of the GM	0.799	0.519	0.684	0.667	Moderate

ICC = Intra-class correlation coefficient; HBD = Hex-bar deadlift; BS = Back-squat; CON = Control

4.3 Results – Group Responses

4.3.1 Peak Power Output

There was no significant ($p > 0.05$) interaction effect (time x exercise) for PAP during the CMJs at the specified ICRIIs. Furthermore, there was no significant ($p > 0.05$) main effect for time for any experimental conditions nor were there any significant ($p > 0.05$) differences between the HBD, BS or CON conditions (Figure 4.1A).

4.3.2 Ground Reaction Force at Peak Power

There was a significant ($p = 0.001$) interaction effect (time x exercise) during the PAP time course. Follow up pairwise comparisons revealed that HBD and BS were significantly different in comparison to the CON condition at 30 seconds by -6.62% ($p =$

0.001, CI = -11.02 to -2.23%) and -5.51% ($p = 0.009$, CI = -9.91 to -1.12%), respectively (Figure 4.2A). Furthermore, HBD displayed a significant difference in comparison to the baseline CMJ at 30 seconds by -4.33% ($p = 0.007$, CI = -7.77 to -0.89%) but not for BS. In addition, there was no significant ($p > 0.05$) PAP response for either exercise condition nor was there a significant ($p > 0.05$) difference between HBD and BS.

4.3.3 Velocity at Peak Power

There was a significant ($p = 0.008$) interaction effect (time x exercise) for PAP during the CMJs. Follow up pairwise comparisons revealed that both HBD and BS conditions were significantly greater at 30 seconds in comparison to the CON condition by 6.36% ($p = 0.001$, CI = 2.23 to 10.48%) and by 5.52% ($p = 0.007$, CI = 1.40 to 9.65%), respectively (Figure 4.3A). However, there was no significant ($p > 0.05$) main effect for time for either exercise condition nor was there a significant ($p > 0.05$) difference between HBD and BS.

4.3.4 Jump Height

There was a significant ($p = 0.035$) interaction effect (time x exercise) for PAP during the CMJs. Follow up pairwise comparisons revealed that both HBD and BS conditions were significantly greater at 30 seconds in comparison to the CON condition by 9.45% ($p = 0.003$, CI = 2.76 to 16.14%) and 8.98% ($p = 0.005$, CI = 2.30 to 15.67%), respectively (Figure 4.4A). However, there was no significant ($p > 0.05$) main effect for time for either exercise condition nor was there a significant ($p > 0.05$) difference between HBD and BS.

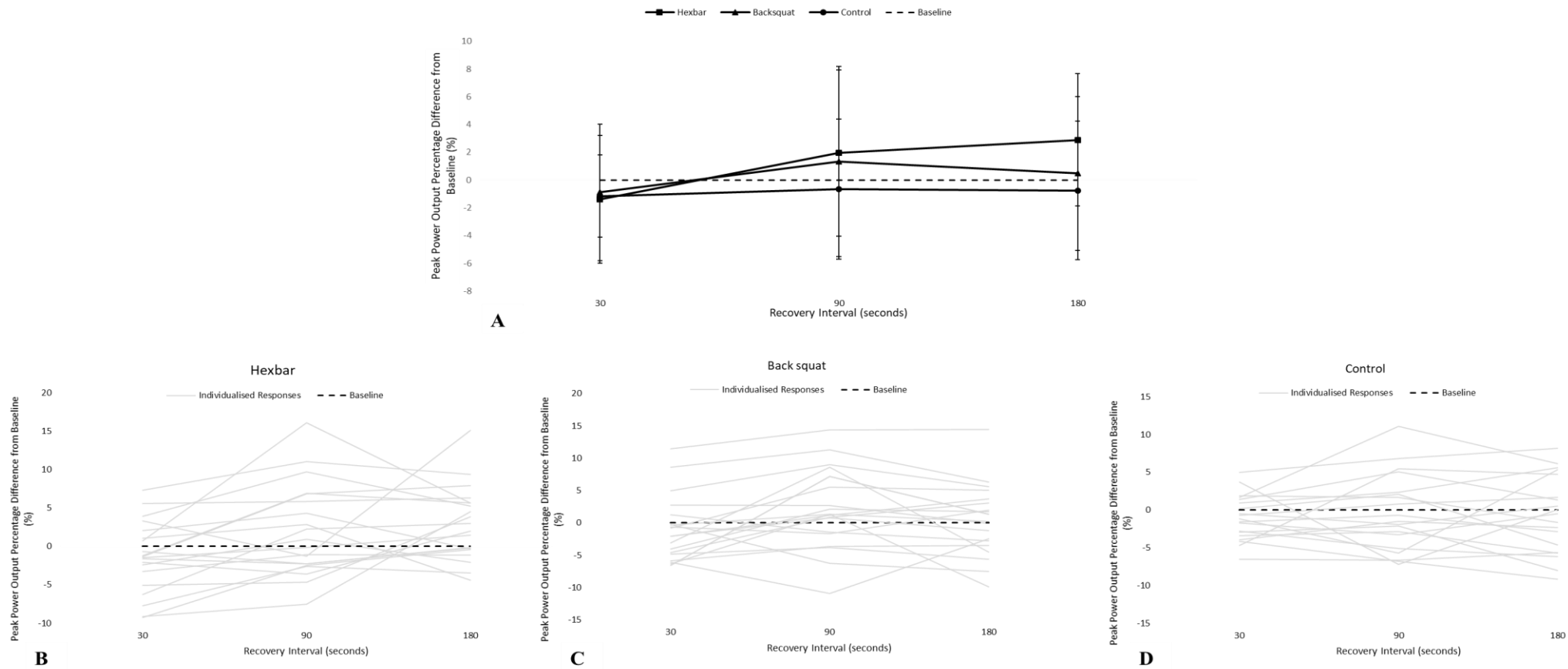


Figure 4.1 A) Mean $\pm$ SD PAP responses for PPO for each experimental condition. B) Individual PAP responses for PPO for the hexbar condition. C) Individual PAP responses for PPO for the back squat condition. D) Individual PAP responses for PPO for the control condition. All results are expressed as a percentage of baseline.

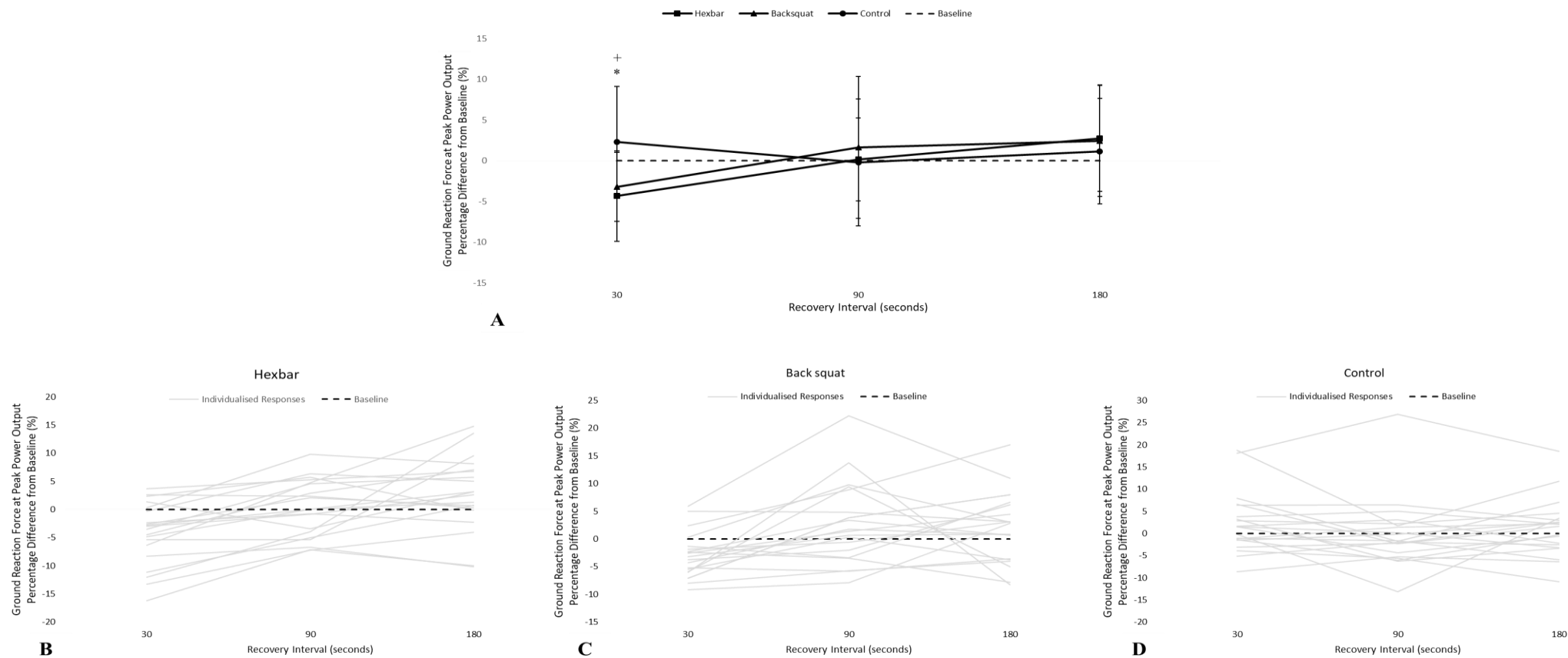


Figure 4.2 A) Mean $\pm$ SD PAP responses for GRF at PPO for each experimental condition. B) Individual PAP responses for GRF at PPO for the hexbar condition. C) Individual PAP responses for GRF at PPO for the back squat condition. D) Individual PAP responses for GRF at PPO for the control condition. All results are expressed as a percentage of baseline. *denotes a significant difference between the exercise conditions and the control condition ($p \leq 0.05$). +denotes a significant difference for the hexbar condition in comparison to baseline ($p \leq 0.05$).

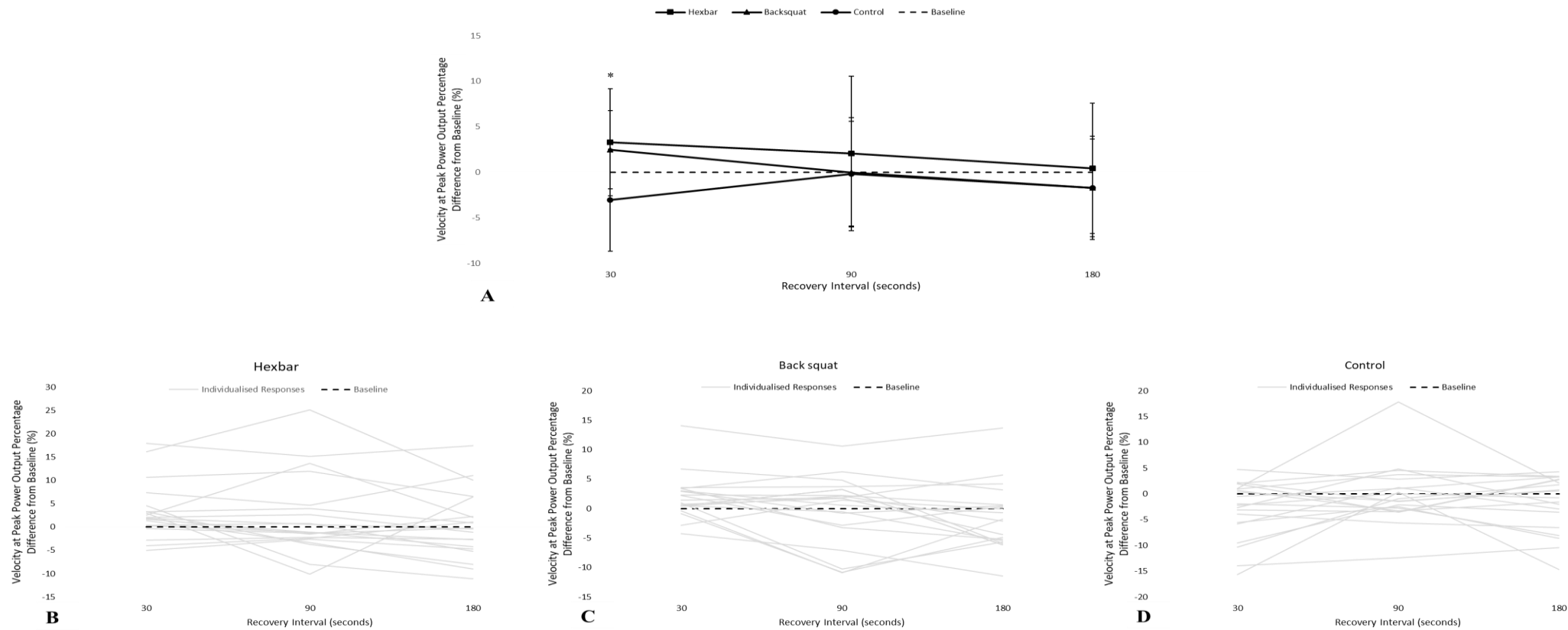


Figure 4.3 A) Mean $\pm$ SD PAP responses for velocity at PPO for each experimental condition. B) Individual PAP responses for velocity at PPO for the hexbar condition. C) Individual PAP responses for velocity at PPO for the back squat condition. D) Individual PAP responses for velocity at PPO for the control condition. All results are expressed as a percentage of baseline. *denotes a significant difference between the exercise conditions and the control condition ($p \leq 0.05$).

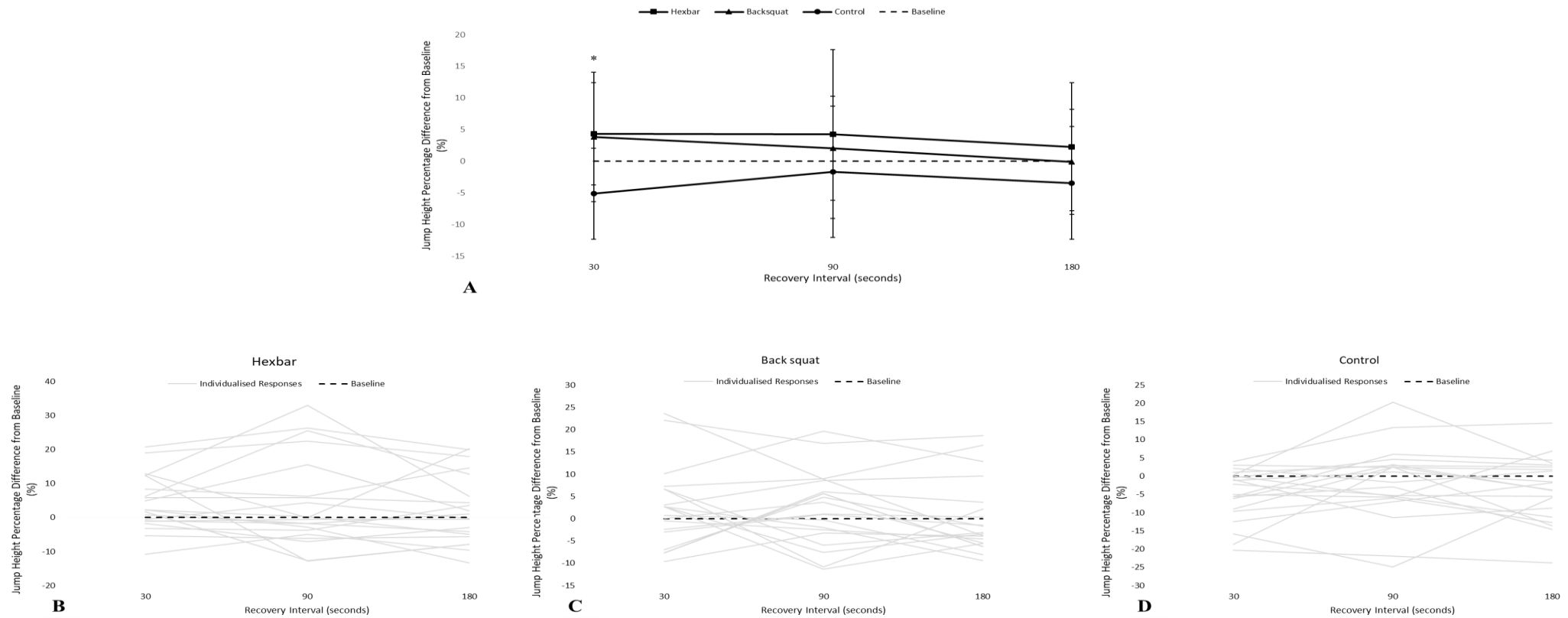


Figure 4.4 A) Mean $\pm$ SD PAP responses for jump height for each experimental condition. B) Individual PAP responses for jump height for the hexbar condition. C) Individual PAP responses for jump height for the back squat condition. D) Individual PAP responses for jump height for the control condition. All results are expressed as a percentage of baseline. *denotes a significant difference between the exercise conditions and the control condition ($p \leq 0.05$).

4.3.5 Muscle Activity

For mean muscle activity of the VL, BF, TA and GM, there were no significant ($p > 0.05$) interaction effects (time x condition). Furthermore, there were no significant ($p > 0.05$) main effects for either exercise condition nor were there any significant ($p > 0.05$) differences between any of the experimental conditions.

4.4 Results – Individualised Responses (Baseline vs. Maximum Potentiation Response)

4.4.1 Peak Power Output

There was no significant ($p > 0.05$) interaction effect (time x exercise) nor were there any significant ($p > 0.05$) differences between BS and HBD. However, there was a significant ($p < 0.001$) main effect for individualised ICRIs in comparison to baseline CMJs. Follow up pairwise comparisons revealed individualised improvements of 3.99% ($p < 0.001$, CI = 2.39 to 5.60%) in comparison to baseline CMJs for both exercise conditions (Table 4.4). The greatest number of participants expressed a PAP response for PPO at 180 seconds however, the magnitude of the PAP response was greatest at 90 seconds (Table 4.5).

4.4.2 Ground Reaction Force at Peak Power Output

There was no significant ($p > 0.05$) interaction effect (time x exercise) nor were there any significant ($p > 0.05$) differences between BS and HBD. There was, however, a significant main effect for individualised ICRIs in comparison to baseline CMJs. Follow up pairwise comparisons revealed individualised improvements of 4.87% ($p < 0.001$, CI = 2.82 to 6.91%) in comparison to baseline CMJs for both exercise conditions (Table 4.4). The greatest number of participants expressed a PAP response for GRF at PPO at 180 seconds; similarly, the magnitude of the PAP response was greatest at 180 seconds (Table 4.5).

Table 4.4 Mean $\pm$ SD of the percentage change in comparison to baseline for all variables across the different ICRIIs. Mean $\pm$ SD of the percentage change in comparison to baseline for all variables when the ICRIIs were individualised (baseline vs. maximum potentiation response).

Variables	30 seconds		90 seconds		180 seconds		Individualised ICRIIs
	Exercise conditions	Control condition	Exercise conditions	Control condition	Exercise conditions	Control condition	
PPO	-1.13 $\pm$ 4.70%	-1.15 $\pm$ 2.98%	3.16 $\pm$ 11.00%	-0.66 $\pm$ 5.03%	1.10 $\pm$ 9.23%	-0.76 $\pm$ 4.99%	3.99 $\pm$ 4.99% *
GRF at PPO	-3.77 $\pm$ 4.91% †	2.30 $\pm$ 6.86%	1.64 $\pm$ 6.36%	-0.20 $\pm$ 7.80%	1.68 $\pm$ 5.24%	1.19 $\pm$ 6.48%	4.87 $\pm$ 6.41% *
Velocity at PPO	2.88 $\pm$ 5.10% †	-3.06 $\pm$ 5.60%	0.90 $\pm$ 7.09%	-0.15 $\pm$ 5.77%	2.62 $\pm$ 6.59%	-1.71 $\pm$ 5.38%	4.30 $\pm$ 5.86% *
Jump Height	4.09 $\pm$ 9.10% †	-5.13 $\pm$ 7.19%	1.03 $\pm$ 7.34%	-1.67 $\pm$ 10.38%	-0.64 $\pm$ 6.46%	-3.44 $\pm$ 8.89%	8.45 $\pm$ 10.08% *
EMG VL	8.81 $\pm$ 32.93%	-1.10 $\pm$ 15.35%	9.33 $\pm$ 34.51%	-1.14 $\pm$ 15.55%	9.29 $\pm$ 37.80%	3.49 $\pm$ 15.60%	20.37 $\pm$ 34.48% *
EMG BF	8.40 $\pm$ 28.03%	7.94 $\pm$ 20.98%	9.37 $\pm$ 28.65%	0.26 $\pm$ 15.83%	4.47 $\pm$ 27.31%	4.03 $\pm$ 17.47%	22.67 $\pm$ 27.98% *
EMG TA	11.69 $\pm$ 38.85%	7.15 $\pm$ 23.83%	7.68 $\pm$ 29.30%	-1.12 $\pm$ 15.81%	2.60 $\pm$ 29.81%	2.33 $\pm$ 5.31%	21.96 $\pm$ 37.76% *
EMG GM	7.11 $\pm$ 20.19%	9.88 $\pm$ 35.34%	12.32 $\pm$ 18.56%	1.90 $\pm$ 34.84%	8.16 $\pm$ 21.74%	9.00 $\pm$ 40.12%	21.89 $\pm$ 19.65% *

*Denotes a significant ($p \leq 0.05$) difference in comparison to baseline; †denotes a significant difference in comparison to the control group.

Table 4.5. Number of participants that peaked at each ICRI and the number of participants that expressed no PAP response for the measured variables. Percentage differences for baseline vs. maximum potentiation response for the corresponding number of participants presented as mean $\pm$ SD.

Variables	30 seconds	90 seconds	180 seconds	Non-Responders
PPO	0	7 (7.58 $\pm$ 2.66%)	9 (2.94 $\pm$ 2.48%) [^]	4 (-1.58 $\pm$ 0.51%)
GRF at PPO	0	8 (4.32 $\pm$ 1.93%)	9 (6.65 $\pm$ 3.35%) [^]	3 (-2.75 $\pm$ 2.04%)
Velocity at PPO	10 (4.05 $\pm$ 3.41%) [^]	4 (5.33 $\pm$ 4.51%)	4 (2.35 $\pm$ 2.45%)	2 (-1.67 $\pm$ 0.56%)
Jump Height	7 (6.91 $\pm$ 5.03%) [^]	6 (11.17 $\pm$ 9.08%)	3 (8.00 $\pm$ 2.15%)	4 (-1.89 $\pm$ 1.79%)
EMG VL	3 (12.40 $\pm$ 10.32%)	6 (13.66 $\pm$ 12.39%)	8 (30.08 $\pm$ 32.96%) [^]	3 (-6.82 $\pm$ 0.57%)
EMG BF	5 (25.58 $\pm$ 24.10%)	6 (37.01 $\pm$ 23.48%) [^]	4 (17.48 $\pm$ 9.68%)	5 (-8.04 $\pm$ 7.07%)
EMG TA	7 (34.56 $\pm$ 23.38%) [^]	4 (30.91 $\pm$ 24.44%)	2 (43.99 $\pm$ 27.21%)	7 (-7.58 $\pm$ 6.26%)
EMG GM	5 (22.02 $\pm$ 13.93%)	6 (20.07 $\pm$ 14.21%)	7 (23.79 $\pm$ 13.12%) [^]	2 (-4.46 $\pm$ 3.11%)

[^]Denotes the ICRI at which the greatest number of participants expressed a peak PAP response

4.4.3 Velocity at Peak Power Output

There was no significant ($p > 0.05$) interaction effect (time x exercise) nor were there any significant ($p > 0.05$) differences between BS and HBD. However, there was a significant ($p < 0.001$) main effect for individualised ICRI in comparison to baseline CMJs. Follow up pairwise comparisons revealed individualised improvements of 4.30% ($p < 0.001$, CI = 2.43 to 6.17%) in comparison to baseline CMJs for both exercise conditions (Table 4.4). The greatest number of participants expressed a PAP response for velocity at PPO at 30 seconds however, the magnitude of the PAP response was greatest at 90 seconds (Table 4.5).

4.4.4 Jump Height

There was no significant ($p > 0.05$) interaction effect (time x exercise) nor were there any significant ($p > 0.05$) differences between BS and HBD. However, there was a significant ($p < 0.001$) main effect for individualised ICRI in comparison to baseline CMJs. Follow up pairwise comparisons revealed individualised improvements of 8.45% ($p < 0.001$, CI = 5.18 to 11.71%) in comparison to baseline CMJs for both exercise conditions (Table 4.4). The greatest number of participants expressed a PAP response for jump height at 30 seconds however, the magnitude of the PAP response was greatest at 90 seconds (Table 4.5).

4.4.5 Muscle Activity

It should be noted that there was a high degree of variability expressed within the data as the ICCs ranged from poor to moderate for the EMG activity of the assessed muscles therefore, these results should be interpreted with caution due to the risk of a type I error. There was no significant ($p > 0.05$) interaction effect (time x exercise) nor were there any significant ($p > 0.05$) differences between BS and HBD. However, there were significant

main effects for individualised ICRIs for VL ($p = 0.001$), BF ($p < 0.001$), TA ($p = 0.001$) and GM ($p < 0.001$) in comparison to baseline CMJs. Follow up pairwise comparisons revealed individualised improvements of 20.37% ($p = 0.001$, CI = 9.25 to 31.48%), 22.67% ($p < 0.001$, CI = 13.53 to 31.80%), 21.96% ($p = 0.001$, CI = 9.92 to 33.99%) and 21.89% ($p < 0.001$, CI = 9.25 to 31.48%) for VL, BF, TA and GM, respectively (Table 4.4). The greatest number of participants expressed increased muscle activity for the VL, BF, TA and GM at 180, 90, 30 and 180 seconds, respectively. The greatest increase in magnitude of muscle activity for the VL, BF, TA and GM was at ICRIs of 180, 90, 180, and 180 seconds, respectively (Table 4.5).

4.5 Discussion

This is the first study to have examined the effects of the PAP response on CMJ performance in rugby league players using HBD and BS exercises combined with accommodating resistance. This study observed no PAP responses when comparing the variables under investigation at the chosen ICRIs to baseline measures. However, when the ICRIs were individualised (baseline vs. maximum potentiation response) there is evidence to suggest that a single set of HBD and BS combined with accommodating resistance can acutely enhance CMJ performance.

Previous research (Baker, 2008) has examined the effects of four sets of two repetitions of paused box squats combined with accommodating resistance ($68 + 6-19.6\%$ 1RM) where loaded (80kg) jump squats were used as a performance measure 75-90 seconds after each box squat (3 minutes recovery between complex sets). The results demonstrated a PAP response in sets two, three and four in comparison to set one (baseline). However, the author recognised that the limitations of this study were low subject numbers and the lack of a CON condition. Furthermore, Wyland et al. (2015) investigated the effects of a

single set of BS combined with accommodating resistance (55 + 0-30% 1RM) on sprint performance and reported significant improvements after 4 minutes. This evidence suggests that the optimal ICRI lies between 1.5 and 4 minutes when inducing PAP using accommodating resistance, which is shorter than the conventional methods used for eliciting PAP (Kilduff et al., 2008; Seitz, de Villarreal, et al., 2014).

Although the present study demonstrated no significant improvements in any of the CMJ variables due to PAP at any of the ICRIs in comparison to baseline, there was a significant fatigue response observed for GRF at PPO immediately (30 seconds) following the HBD condition. Furthermore, both CAs were significantly less than the CON condition at 30 seconds. This is in agreement with previous research which has reported fatigue immediately (10-30 seconds) following CAs (Crewther et al., 2011; Jensen & Ebben, 2003; Kilduff et al., 2007, 2008; Seitz, de Villarreal, et al., 2014). This supports the notion that immediately after the CA, PAP is inhibited by fatigue.

There are a number of factors which must be considered when implementing complex training, including the ICRI and load (Tillin & Bishop, 2009; Wilson et al., 2013). There are currently no guidelines as to the optimal accommodating resistance load required to induce PAP. Based on the available scientific evidence, an accommodating resistance load of 15-30% has been recommended (Baker, 2008; Baker & Newton, 2009; Wyland et al., 2015). Anecdotal evidence has recommended a constant barbell load of 60% 1RM when utilising accommodating resistance (Simmons, 2007). Although PAP is typically thought to be elicited by heavy resistance loads of >85% 1RM (Crewther et al., 2011; Jones & Lees, 2003; Kilduff et al., 2008) there is also a strong evidence base to support the notion that PAP can be induced by lighter loads of 60-85% 1RM (Baker & Newton, 2005; Smilios et al., 2005; Wilson et al., 2013). According to Schmidbleicher (1992)

maximal concentric only contractions performed as quickly as possible induce optimal neural adaptations. Perhaps a lighter barbell load combined with a greater accommodating load would have induced a PAP response on a group level.

The results, unexpectedly, revealed that velocity at PPO and jump height for HBD and BS were significantly greater than the CON condition at 30 seconds, however there were no significant differences in comparison to baseline. Scientific evidence suggests that stronger individuals are more responsive to PAP stimuli due to greater type II muscle fibre content and quicker recovery from fatigue (Chiu et al., 2003; Seitz, de Villarreal, et al., 2014; Tillin & Bishop, 2009). Although these factors were not directly assessed, it is plausible that this result was due to the higher strength levels of some of the participants. Stronger individuals are also reported to possess a greater CSA, muscle fibre P_{ang} and L_f (Cormie et al., 2010c). Muscle fibre P_{ang} directly influences power output, as larger P_{ang} are associated with greater force generating capabilities, whereas smaller P_{ang} are synonymous with greater shortening velocities and an increased rate of force transmission in the muscles (Earp et al., 2010). Therefore, it is conceivable that an individual's muscle fibre P_{ang} may also be a contributing factor to PAP. Although the present study did not assess muscle architecture, muscle fibre P_{ang} warrants future investigation in PAP studies.

The present study did, however, assess neural activation using surface EMG. The results revealed no significant changes at any of the ICRIs in comparison to baseline for either CA. However, when the ICRIs were individualised (baseline vs. maximum potentiation response) the muscles under examination expressed significantly increased neural activity. Therefore, there is evidence to suggest that PAP is induced by the recruitment of higher order motor neurons due to increased motor neuron pool excitability (Docherty et al., 2004; Kilduff et al., 2007; Tillin & Bishop, 2009). However, these results must be

interpreted with caution as there was a high degree of variability present within the EMG data. As such, it is difficult to draw any conclusions regarding the underpinning mechanism of PAP from the EMG analysis. This is consistent with findings in previous research (Ebben et al., 2000; Jones & Lees, 2003; Scott et al., 2017).

Thomas, Toward, West, Howatson and Goodall (2015) utilised motor cortical and motor nerve stimulation to examine neuromuscular function following 3 sets of 3 repetitions of heavy load BS. No significant enhancements in these neuromuscular measurements were reported following an 8 minute ICRI however, there was evidence of muscle fatigue. Interestingly, there was a significant improvement in CMJ height which may have been indicative of enhanced force and power production. Although the authors identify various limitations within this study, perhaps research with more detailed methodologies which involve motor cortical stimulation are required to provide a more in-depth understanding of the mechanisms underpinning the voluntary PAP response. Evidently, further research is required to determine if the voluntary PAP response is facilitated by enhanced motor unit recruitment.

The present study aimed to kinetically alter the HBD and BS exercises by combining a moderate load CA with accommodating resistance to modify the force-velocity curve. Previous research has utilised Olympic style lifts to alter the force-velocity profile of the CA (Andrews et al., 2011; McCann & Flanagan, 2010; Seitz, Trajano, et al., 2014). Andrews et al. (2011) and Seitz, Trajano, et al. (2014) reported significantly greater PAP responses in Olympic style lifts in comparison to heavy load CAs, therefore the ability to produce high forces at high velocities may induce optimal PAP responses due to the specificity of the CA to the plyometric action (Crum et al., 2012). However, McCann and Flanagan (2010) reported no significant difference between hang cleans and heavy load BS as a CA in eliciting PAP and state that the ICRIs were “highly individualised”.

Although there was no significant PAP response at any of the ICRIs in comparison to baseline, the results of the present study highlighted significant improvements in CMJ performance when the ICRIs were individualised (baseline vs. maximum potentiation response) which is in agreement with previous research (Bevan et al., 2010; Chiu et al., 2003; Comyns et al., 2006; Crewther et al., 2011; McCann & Flanagan, 2010). A possible explanation for this individualised response is the elevation of the phosphorylation of myosin RLC (Docherty et al., 2004; Kilduff et al., 2007; Tillin & Bishop, 2009). The near maximal contraction induced by both CAs may have increased the release of Ca^{2+} ions from the sarcoplasmic reticulum, therefore activating a greater volume of myosin light chain kinase. This heightens the sensitivity of the actin-myosin complex to Ca^{2+} ions and increases the ATP availability at the complex. As a result, the rate of actin-myosin cross-bridging is increased.

Furthermore, there were no significant differences between HBD and BS when the ICRIs were individualised. Accommodating resistance is theorised to induce an overspeed eccentric phase which enhances the SSC as a greater stretch reflex is elicited and the GTO is overridden resulting in greater force production during the concentric phase (Simmons, 2007). The accommodating resistance may also induce a preparatory muscle stiffness during both exercises where there is an increase in motor unit activation at the top of the lift however, at the bottom of the lift, when the load is decreased, the motor units are still activated therefore resulting in a surplus of neural activation thus evoking a PAP response (Baker & Newton, 2009). In addition, due to the bands actively pulling the loads downwards with greater force than the effect of gravity during the eccentric phase of both exercises, the muscles may have been better able to utilise the stored elastic strain energy during the concentric phase as result of the reduced effects of “sticking points” (Wyland

et al., 2015). Collectively, this may explain why there were no differences between the HBD and BS.

The lifting technique of the BS required participants to perform a controlled eccentric phase, to avoid injury, and to lift as explosively as possible during the concentric phase. During the HBD the participants performed the concentric phase as explosively as possible however, the eccentric phase was completed as quickly as possible with the aim of minimising the amortisation phase and avoiding stopping or putting the bar on the floor between each repetition. This was important with respect to eliciting an overspeed eccentric phase whilst attempting to evoke a within-repetition preparatory stiffness which accommodating resistance is theorised to induce. The lack of difference between the BS and HBD demonstrates the requirement for further research examining the effects of a controlled eccentric phase in comparison to a fast eccentric phase on the voluntary PAP response.

Study 1 demonstrated a PAP response 2-6 minutes following the completion of the HBD exercise, therefore a 3 minute ICRI should have induced a PAP response. The fact that there was no observed PAP response at group level when a moderately loaded CA was combined with accommodating resistance suggests that strength level or the magnitude of the load could be determining factors in eliciting PAP since these are the differences between study 1 and the current study. The ICRIs utilised in this study may not have been long enough to enable PAP to manifest, especially for the given sample population. Stronger, more experienced athletes are typically able to recover from heavy load resistance exercise quicker (Chiu et al., 2003; Seitz, de Villarreal, et al., 2014; Tillin & Bishop, 2009) whereas weaker, less experienced individuals are likely to require a longer

ICRI for PAP to predominate fatigue. This may explain why no PAP response was observed on a group level.

A further limitation of the present study is the absence of any thermoregulatory data. Scientific evidence suggests that an increase in muscle temperature enhances muscular force and power (Cochrane, Stannard, Sargeant, & Rittweger, 2008). Furthermore, an increase in muscular temperature may have evoked greater muscular activation, elevated the phosphorylation of myosin RLCs and enhanced the storage and release of elastic strain energy (Bridgeman, McGuigan, Gill, & Dulson, 2017). In addition, research suggests that an increase in core temperature, due to the natural change in body temperature from morning to evening, can mediate enhanced power outputs (Kilduff, West, Williams, & Cook, 2013; West, Cook, Beaven, & Kilduff, 2014). However, given that the warm up was standardised and of a low intensity, it can be assumed that any individualised PAP response was not a result of increased muscular temperature but due to the selected CAs within the study.

In conclusion, the results of this study did not express a PAP response at any of the chosen ICRI. However, there is evidence to suggest a PAP response following HBD and BS combined with accommodating resistance when the ICRI are individualised. Although there is evidence to suggest possible underpinning mechanisms of PAP, the results from this study must be interpreted with caution. Further research is required to ascertain the optimal barbell and accommodating resistance loads required to evoke a PAP response as well as identifying the optimal ICRI in athletes of varying strength levels. Moreover, future research should consider individualising the loads as this may result in further performance enhancements for athletes. In addition, more research is required to

determine the underpinning mechanisms of PAP. Lastly, research should investigate the longitudinal effect of this training modality by utilising individualised ICRIIs.

4.6 Practical Applications

Based on the results of the present study, strength and conditioning coaches should individualise the ICRI between the CA and subsequent plyometric action when implementing PAP within their training programs. Both moderately loaded HBD and BS exercises combined with accommodating resistance are appropriate methods of eliciting PAP if the ICRIIs are individualised. Based on current literature, it may be possible to evoke a PAP response 1.5-4 minutes post-CA when utilising this training modality. Strength and conditioning specialists should ensure that they identify the optimal ICRIIs, loads and exercises for their athletes to maximise results.

Chapter 5: Within- and between-session reliability of ultrasound imaging measures in
vastus lateralis and gastrocnemius medialis muscles.

5.1 Introduction

The force generating capability of skeletal muscle is strongly related to the organisation of its muscle fibres (Blazevich, Cannavan, et al., 2007). It is, therefore, of importance to understand how different training modalities can enhance athletic performance (Blazevich, Cannavan, et al., 2007). In particular, muscle architectural measures of MT, P_{ang} and L_f have all been reported to correlate highly with the ability to generate force (Earp et al., 2010). Research has demonstrated that MT and P_{ang} increase in response to heavy resistance training (Blazevich, Cannavan, et al., 2007; Duclay et al., 2009; Seynnes et al., 2007). Such adaptations have also been accompanied by increases in CSA, maximum force production and PPO (Aagaard et al., 2001; Alegre et al., 2006; Andersen et al., 2005). However, an increase in P_{ang} reduces the amount of force transmitted from the muscle fibres to the tendon due to the increased oblique angle of pull (Blazevich, 2006; Folland & Williams, 2007; Ikegawa et al., 2008).

In contrast, L_f has been reported to decrease in response to heavy resistance exercise (Blazevich et al., 2003; Blazevich, Gill, Deans, et al., 2007; Rutherford & Jones, 1992). However, L_f has been reported to increase in response to lighter resistance exercise, jump training and sprint training (Alegre et al., 2006; Blazevich et al., 2003). This may be advantageous since longer L_f are associated with the ability to generate greater forces at higher shortening velocities, which may improve PPO (Blazevich, 2006; Earp et al., 2010). Heavy resistance training appears to be associated with increases in P_{ang} and decreases in muscle L_f , whereas training which involves higher velocity contractions appear to be associated with increases in L_f and decreases in muscle P_{ang} . It is possible that muscle architectural adaptations are velocity-specific (Blazevich et al., 2003). Therefore, complex training may induce advantageous adaptations to muscle architecture since it combines heavy load resistance exercise with more explosive plyometric exercise.

To date there is only one study which has investigated the long-term effects of complex training on muscle architecture (Stasinaki et al., 2015).

Muscle architectural measures are typically assessed using ultrasound imaging techniques (Blazevich, Gill, Deans, et al., 2007). Previous research has indicated the importance of intra-rater reliability as well as intra- and inter-individual variability when assessing muscle architecture using ultrasound (Legerlotz, Smith, & Hing, 2010; McMahon, Turner, & Comfort, 2016). Therefore, accurate and reliable assessment of muscle architecture is paramount. Additionally, it is important that the minimum detectable change (MDC) is known in order give confidence in studies reporting intervention-induced changes in muscle architecture (McMahon et al., 2016).

The VL and GM provide stability around the knee and ankle, respectively, which is important for injury prevention (Rudolph, Axe, Buchanan, Scholz, & Snyder-Mackler, 2001; Schoenfeld, 2010a). The muscular contractions of the VL and GM directly relate to athletic movement skills such as, running, sprinting, jumping and multidirectional speed (Ishikawa et al., 2003; Schoenfeld, 2010a) which are all of importance within rugby league. Although the reliability of muscle architecture measures of the VL and GM have been demonstrated in younger (Legerlotz et al., 2010) and older (Raj, Bird, & Shield, 2012) populations, when the muscles are in a relaxed state, there is little comprehensive data with respect to sporting populations. As such, the transferability of these results is limited.

Therefore, the purpose of this study was to determine the within-session and between-session reliability of MT, P_{ang} , and L_f of the VL and GM in adults who regularly engage in sport using brightness mode (B-mode) ultrasound imaging. These results were consequently used to assist in the analysis of the long-term complex training intervention

in the subsequent study. The MDC was calculated for MT, P_{ang} and L_f for each muscle. This information was required to distinguish between true change in the muscle architecture variables, as a result of a long-term complex training programme, and change due to measurement error in the final study (Nair, Hornby, & Behrman, 2012).

5.2 Methods

5.2.1 Experimental Protocol

The study involved two laboratory testing sessions separated by one week. The sessions were conducted on the same day and at the same time of day to control for circadian variations (Atkinson & Reilly, 1996). The images were taken by the same researcher who undertook appropriate training. Prior to any measurements being taken for the VL, the participants lay on a massage bed in a supine position for 20 minutes. Similarly, before any measurements were recorded for the GM, the participants lay on a massage bed in a prone position for 20 minutes. This was done to allow fluid shift to occur (Reeves et al., 2004).

During the first session, an initial two images were recorded for the VL (measure 1, M1). A further two images were recorded following a short 20 minute break (measure 2, M2); this enabled the within-session reliability to be calculated. During the second session, two images were recorded (measure 3, M3) which enabled the between-session reliability to be calculated. This process was repeated for the GM. Therefore, a total of 144 images, 72 for each muscle, were analysed.

5.2.2 Subjects

Twelve ($n = 12$) healthy male participants who regularly engaged in sport were recruited for this study (age: 26.83 ± 4.45 years, height: 179.00 ± 5.59 cm, body mass: 88.21 ± 8.21 kg). This population was chosen as a convenience sample since the primary outcome was

to determine the measurement error of the researcher conducting the ultrasonography assessments. Additionally, this sample size was chosen since a similar sample size was expected for the subsequent complex training study. Inclusion criteria required participants who were currently playing sport and had no inflammatory conditions or musculoskeletal injuries to the lower extremity. The study received full institutional approval from the University's Sport, Health and Exercise Science Ethics Committee. Prior to any experimental procedures, the participants gave their voluntary written informed consent (Appendix D) and completed a pre-exercise medical questionnaire (Appendix F).

5.2.3 Measurements

Muscle architecture was examined using B-mode ultrasonography apparatus (MyLab 50 Xvision, Esaote, Genova, Italy). A single cross-sectional image was recorded using a linear array ultrasound probe which was set at a scanning frequency of 7.5MHz. The probe was aligned parallel to the muscle fascicles and perpendicular to the skin therefore giving a sagittal plane image along the length of the muscle (Blazevich, 2006; Blazevich, Gill, Deans, et al., 2007). To acquire the best possible image, the alignment of the probe was manipulated and considered appropriate when several muscle fascicles could be determined without interruption across the image (Blazevich, 2006; Blazevich, Gill, Deans, et al., 2007).

Vastus Lateralis: The participants lay in a supine position with their knees flexed at 30° and were supported to ensure that the muscles were relaxed and to reduce fascicle curvature (Blazevich, 2006). The probe was placed at 50% of the distance from the greater trochanter of the femur to the articular cleft between the femoral and tibial condyles (Miyatani, Kanehisa, Ito, Kawakami, & Fukunaga, 2004).

Gastrocnemius Medialis: The participants lay in a prone position with their muscles relaxed and their feet over the edge of the massage bed; the ankle joint was kept in a neutral position (90°) (Legerlotz et al., 2010). The probe was placed at 30% of the distance from the articular cleft between the femoral and tibial condyles to the lateral malleolus (Takai et al., 2013).

5.2.4 Data Analysis

The still ultrasound images of the muscles were extracted offline (Figure 5.1 and 5.2). Image analysis and measurements were conducted using publicly available imaging software (ImageJ, 1.48v, National Institutes of Health; <http://rsb.info.nih.gov/ij/>). MT was assessed by measuring the distance between the superficial aponeurosis and the deep aponeurosis at the central location of the muscle on the 2D ultrasound image (Blazevich, 2006; Blazevich, Gill, Deans, et al., 2007). Muscle fibre P_{ang} was defined as the intersection between the muscle fascicles and deep aponeurosis (Kwah, Pinto, Diong, & Herbert, 2013). L_f was defined as the length of the muscle fascicle between the superficial and deep aponeurosis. The visible portion of the muscle fascicle in each 2D ultrasound image was measured by tracking the curvature of a single muscle fascicle using a segmented line. The non-visible portion was estimated by linear extrapolation which involved measuring the distance between the visible muscle fascicle to the intersection between a line drawn from the muscle fascicle and a line drawn from the aponeuroses (Reeves et al., 2004).

5.2.5 Statistical Analyses

The average of the two images for the muscle architecture variables for each muscle were calculated for each time-point (M1, M2, M3) (Table 5.1). The within-session and between-session reliability were examined using a custom-made spreadsheet (Hopkins,

2000) to assess the typical error (TE) of measurement and to assess the ICC. Furthermore, the coefficient of variation ($CV = \text{standard deviation}/\text{mean} \times 100$) and the minimum detectable change ($MDC = TE \times 1.96 \times \sqrt{2}$) were calculated independently from the custom-made spreadsheet.

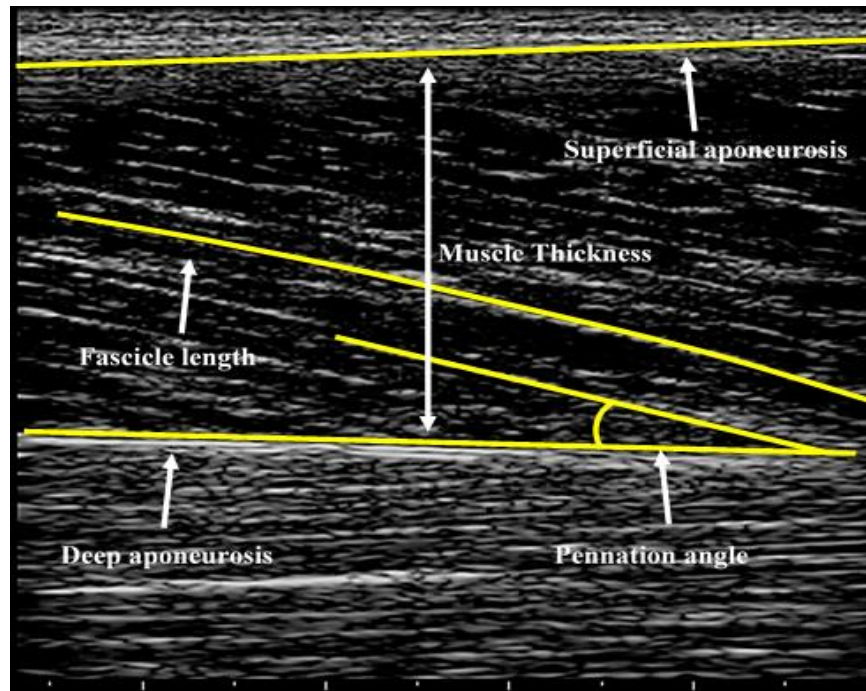


Figure 5.1 Sagittal plane ultrasound image of the vastus lateralis.

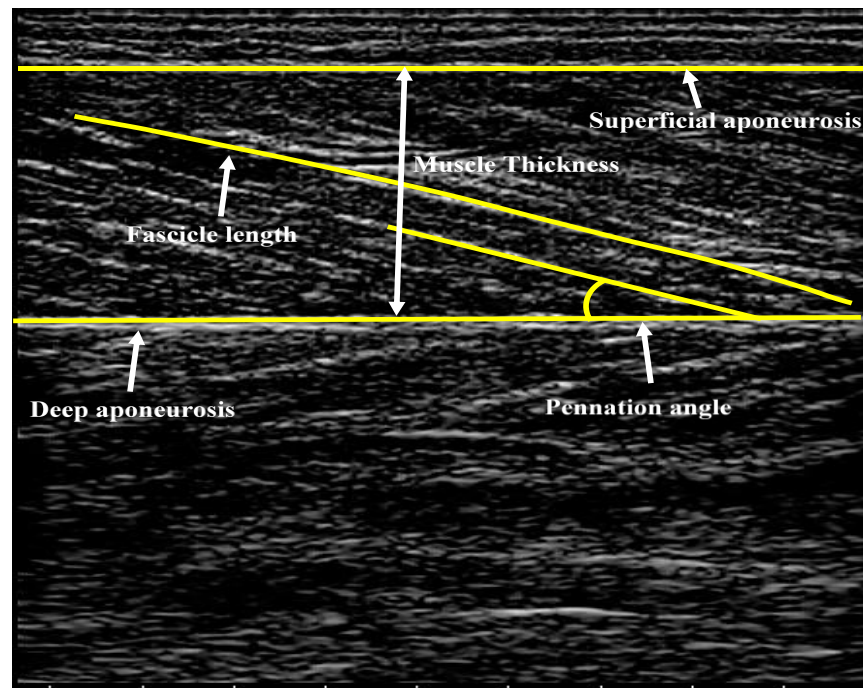


Figure 5.2 Sagittal plane ultrasound image of the gastrocnemius medialis.

Table 5.1 Descriptive statistics for the muscle architectural variables for the vastus lateralis and gastrocnemius medialis. Data are presented as mean $\pm$ SD.

Muscle Architecture Variable	Measure 1	Measure 2	Measure 3
VL Muscle Thickness (cm)	3.11 $\pm$ 0.32	3.13 $\pm$ 0.36	3.08 $\pm$ 0.36
VL Pennation Angle (°)	16.56 $\pm$ 0.89	16.69 $\pm$ 0.88	15.94 $\pm$ 0.83
VL Fascicle Length (cm)	10.92 $\pm$ 1.34	10.95 $\pm$ 1.15	11.03 $\pm$ 1.00
GM Muscle Thickness (cm)	1.87 $\pm$ 0.24	1.87 $\pm$ 0.25	1.90 $\pm$ 0.24
GM Pennation Angle (°)	23.93 $\pm$ 2.67	24.16 $\pm$ 2.93	23.71 $\pm$ 2.92
GM Fascicle Length (cm)	4.82 $\pm$ 0.66	4.86 $\pm$ 0.62	4.80 $\pm$ 0.65

VL = Vastus lateralis; GM = Gastrocnemius medialis

5.3 Results

The ICCs between each measure were interpreted as poor for values less than 0.5, moderate for values between 0.5 and 0.75, good for values between 0.75 and 0.9, and excellent for values greater than 0.9 (Koo & Li, 2016). As such, the within- and between-session ICCs for each variable ranged from good to excellent across both muscles: VL MT = 0.98, 0.99; VL P_{ang} = 0.92, 0.87; VL L_f = 0.94, 0.91; GM MT = 0.99, 0.98; GM P_{ang} = 0.99, 0.97; GM L_f = 0.97, 0.93, respectively. Additionally, 95% confidence intervals were calculated for the calculated ICCs and CVs (Tables 5.2, 5.3 and 5.4).

Although good to excellent levels of reliability were demonstrated, quantifying the error associated with the ultrasound imaging technique was paramount in determining the minimum change required to distinguish between true change and change due to measurement error. As such, the within- and between-session MDCs for each variable across both muscles were: VL MT = 0.16 cm, 0.12 cm; VL P_{ang} = 0.76°, 0.99°; VL L_f = 0.84 cm, 0.94 cm; GM MT = 0.08 cm, 0.11 cm; GM P_{ang} = 0.97°, 1.45°; GM L_f = 0.36 cm, 0.50 cm, respectively. Additionally, 95% confidence intervals were calculated for the calculated TEs (Tables 5.2, 5.3 and 5.4).

Table 5.2 Summary of the within-session and between-session reliability for muscle thickness of the vastus lateralis and gastrocnemius medialis.

Muscle Thickness					
	Muscle	ICC (CI)	CV% (CI)	TE (CI)	MDC
Within-session reliability	VL	0.98 (0.92 to 1.00)	1.55 (0.67 to 2.43)	0.06 cm (0.04 to 0.10)	0.16 cm
	GM	0.99 (0.96 to 1.00)	1.29 (0.56 to 2.03)	0.03 cm (0.02 to 0.05)	0.08 cm
Between-session reliability	VL	0.99 (0.95 to 1.00)	1.18 (0.56 to 2.03)	0.04 cm (0.03 to 0.08)	0.12 cm
	GM	0.98 (0.93 to 0.99)	1.73 (0.75 to 2.72)	0.04 cm (0.03 to 0.07)	0.11 cm

VL = Vastus lateralis; GM = Gastrocnemius medialis; ICC = Intra-class correlation coefficient; CI = 95% confidence interval; TE = Typical error; CV = Coefficient of variation; MDC = Minimum detectable change.

Table 5.3 Summary of the within-session and between-session reliability for pennation angle of the vastus lateralis and gastrocnemius medialis.

Pennation Angle					
	Muscle	ICC (CI)	CV% (CI)	TE (CI)	MDC
Within-session reliability	VL	0.92 (0.75 to 0.98)	1.38 (0.60 to 2.16)	0.27° (0.19 to 0.47)	0.76°
	GM	0.99 (0.96 to 1.00)	1.11 (0.48 to 1.75)	0.35° (0.25 to 0.59)	0.97°
Between-session reliability	VL	0.87 (0.61 to 0.96)	1.83 (0.79 to 2.86)	0.36° (0.25 to 0.60)	0.99°
	GM	0.97 (0.92 to 1.00)	1.51 (0.65 to 2.37)	0.52° (0.37 to 0.89)	1.45°

VL = Vastus lateralis; GM = Gastrocnemius medialis; ICC = Intra-class correlation coefficient; CI = 95% confidence interval; TE = Typical error; CV = Coefficient of variation; MDC = Minimum detectable change.

Table 5.4 Summary of the within-session and between-session reliability for fascicle length of the vastus lateralis and gastrocnemius medialis.

Fascicle Length					
	Muscle	ICC (CI)	CV% (CI)	TE (CI)	MDC
Within-session reliability	VL	0.94 (0.80 to 0.98)	2.24 (0.97 to 3.51)	0.30 cm (0.21 to 0.51)	0.84 cm
	GM	0.97 (0.88 to 0.99)	2.36 (1.02 to 3.69)	0.13 cm (0.09 to 0.22)	0.36 cm
Between-session reliability	VL	0.91 (0.73 to 0.97)	2.45 (1.06 to 3.85)	0.34 cm (0.24 to 0.58)	0.94 cm
	GM	0.93 (0.78 to 0.99)	2.95 (1.05 to 4.32)	0.18 cm (0.13 to 0.39)	0.50 cm

VL = Vastus lateralis; GM = Gastrocnemius medialis; ICC = Intra-class correlation coefficient; CI = 95% confidence interval; TE = Typical error; CV = Coefficient of variation; MDC = Minimum detectable change.

5.4 Discussion

Muscular strength and power are associated with muscle architectural variables, namely MT, P_{ang} , and L_f (Earp et al., 2010). Therefore, accurate assessment of such variables is imperative in determining the effects of strength training and conditioning or rehabilitative and reconditioning training interventions on muscle force generating capabilities both acutely and chronically. The results of the present study are comparable with previous studies measuring the VL and GM using B-mode ultrasonography (Blazevich, Gill, Deans, et al., 2007; Legerlotz et al., 2010; Raj et al., 2012). However, it should be noted that the data presented in this study are specific to the sample population and the methodological procedures adhered to.

As demonstrated by Maganaris, Baltzopoulos and Sargeant (1998) in the triceps surae muscles, probe alignment with respect to the region (proximal, central and distal) and section (medial, mid-sagittal and lateral) of the muscle under examination affects the values obtained for muscle architecture variables. Additionally, joint angle and whether a muscle is being assessed under resting or voluntary isometric contraction conditions can also influence these measurements (Maganaris et al., 1998). Previous research has reported that inconsistent probe alignment could contribute to unreliable muscle architecture measurements (Azizi & Roberts, 2009; Kwah et al., 2013; Stark & Schilling, 2010). Therefore, it is important to consider these factors when comparing the results of the current research to previous studies (Table 5.5).

Table 5.5 Methodological procedures in ultrasound imaging reliability studies.

Study	Subjects	Muscle	Methods
Blazevich, Gill, Deans, et al. (2007)	14 males and 15 females (recreationally active)	VL	Subjects lay supine; legs flexed but relaxed at 45°; sagittal plane scans at 22%, 39%, 56% of the distance from the superior border of the patella to the anterior superior iliac spine
Raj et al. (2012)	11 males and 10 females (older adults)	VL	Subjects sat; knees flexed but relaxed at 90°; sagittal plane scan at 62.5% proximal between the anterior superior iliac spine and the superior aspect of the patella
		GM	Subjects lay prone on a bench; feet hanging off the edge at an ankle joint of 15° dorsiflexion; sagittal plane scan at 30% proximal between the lateral malleolus of the fibula and lateral condyle of the tibia
Legerlotz et al. (2010)	13 males and 8 females (healthy children)	GM	Subjects lay prone on examination table; feet hanging off edge of table and knees fully extended; ankle joint relaxed at 90° (neutral); sagittal plane scan at 30% of tibia length, defined as the distance from the popliteal crease to the midpoint of the lateral malleolus

VL = Vastus lateralis; GM = Gastrocnemius medialis

The present study demonstrated good to excellent within-session and between-session reliability for MT, P_{ang} , and L_f . The muscle architectural measurements for the VL are comparable with Blazevich, Gill, Deans, et al. (2007) who reported a between-session ICC range of 0.88–0.97, 0.90–0.99, and 0.76–0.86 for MT, P_{ang} and L_f , respectively in recreationally active adults. Furthermore, TEs of 0.074–0.097 cm, 0.24–1.22°, and 1.02–1.94 cm for MT, P_{ang} and L_f , respectively, were reported. Similarly, Raj et al. (2012) reported ICCs of 0.96, 0.87 and 0.80 for VL MT, P_{ang} and L_f , respectively in older adults. Although the results of the present study agree with the reliability measures for VL MT and P_{ang} reported in previous research, the reliability of VL L_f is greater in the current study. This could be due to methodological differences as L_f was predicted using

trigonometric functions in the previous research whereas the current study estimated L_f by linear extrapolation. The method of linear extrapolation has been reported to induce an error of 2-7% (Reeves et al., 2004) which is in agreement with the present study. Therefore, it appears that linear extrapolation may have a greater reliability in comparison to trigonometric equations. It is conceivable that this can be explained by the curvature of the muscle not being taken into consideration by the trigonometric equations (Blazevich, 2006).

The muscle architectural measurements for the GM are consistent with Legerlotz et al. (2010) who reported within-session ICCs of 0.94-0.98, 0.85-0.96, and 0.87-0.96 for MT, P_{ang} and L_f , respectively, in healthy children. Similarly, Raj et al. (2012) reported ICCs of 0.97, 0.85, and 0.90 for GM MT, P_{ang} and L_f , respectively, in older adults. The present study is in agreement with previous research; therefore, it is conceivable that B-mode ultrasonography and image analysis is a reliable method of characterising muscle architecture despite varying sample populations and methodological differences. Furthermore, the present study displayed excellent CVs which were below 3% across all of the muscle architectural variables for VL and GM (Atkinson & Nevill, 1998).

However, it has been recognised that measurements which express a high degree of inter-individual variability tend to result in higher ICCs than expected (Atkinson & Nevill, 1998; Legerlotz et al., 2010). In addition, the CV assumes that the greatest variation occurs in individuals who achieve the highest test scores and underestimates true variation between tests (Atkinson & Nevill, 1998). As such, TE and MDC were reported in the present study to provide a quantifiable measure of meaningful change when using B-mode ultrasonography for muscle architecture assessment. The variation in the muscle architectural measures are represented by the TE with 95% CIs; such variation is usually

due to biological factors and the contribution of noise from the equipment (Hopkins, 2000). This information is useful as any differences observed between these muscle architectural parameters which are greater than the TE are likely to be due to a given intervention. Furthermore, the MDC represents the minimal change that is required to distinguish between true change in the muscle architectural measures as a result of a given intervention and change due to the error in the measurement (Nair et al., 2012). Therefore, consideration of both TE and MDC are important as a change which has not exceeded the threshold of error may be due to inter-trial variation and consequently does not represent a meaningful change (Hachana et al., 2013).

An interesting finding of this study was that the reliability of the VL P_{ang} was greater than that of the GM. Although the ICCs for the within- and between-session reliability were greater for the GM, the TEs and MDCs were also greater for the GM in comparison to VL. This can be explained by a higher degree of inter-individual variability expressed within the P_{ang} measure for the GM (Atkinson & Nevill, 1998). However, the within- and between-session reliability of the GM L_f appeared to be better than that of the VL as the ICCs were greater and the TEs and MDCs were lower than that of the VL. This is in agreement with Raj et al. (2012) and could be explained by the shorter L_f associated with the GM therefore meaning that less extrapolation outside the field of view from the captured ultrasound image is required to determine L_f . Typically, the between-session reliability tended to be lower than the within-session reliability for each muscle architectural parameter. This is to be expected due an increased duration of time inducing a greater error of measurement as a result of biological factors and intra-rater variations (Kwah et al., 2013; Stark & Schilling, 2010). Furthermore, these reliability measures can be used by future researchers for sample size estimation when investigating muscle architectural adaptations to acute and chronic exercise interventions (Hopkins, 2000).

Collectively, the limited evidence suggests that B-mode ultrasonography and the analysis of the images is a reliable method for measuring muscle architectural variables across different sample populations. However, the CIs were wider than desirable across some variables in the present study; for example the within- and between-session P_{ang} and L_f for VL and GM (Tables 5.3 and 5.4). This could be attributed to changes in the orientation of the ultrasound transducer (Klimstra, Dowling, Durkin, & MacDonald, 2007). In addition, the sample size of this study was small which may have also introduced greater measurement errors than expected. Nevertheless, this information is still useful as sport science studies typically utilise smaller sample sizes. Furthermore, a similar sample size was expected for the final long-term complex training study.

5.5 Conclusion

The methodological procedures used in the present study to assess the muscle architecture of the VL and GM in males who regularly engage in sport have a high level of within-session and between-session reliability. Therefore, researchers investigating changes in muscle architecture measurements, on a group level, using B-mode ultrasonography at various time points in males who play regular sport, can do so with confidence. However, it is important to note that appropriate training of ultrasonography imaging and analysis techniques must first be undertaken. Surprisingly, some of the reported TEs and MDCs were greater than expected, notably for within- and between-session for GM P_{ang} , between-session VL P_{ang} , and within- and between-session VL L_f . As such, it is imperative for researchers to consider reliability variables, such as TE and MDC, to provide a greater understanding of meaningful change. This information will help to ascertain whether reported changes in muscle architecture of the VL and GM in the subsequent complex training programme are meaningful or if they are simply a product of the inherent error associated with ultrasound imaging techniques.

Chapter 6: The effects of two complex training modalities on physical performance and muscle architecture characteristics in rugby league players over a 6-week mesocycle.

6.1 Introduction

Muscular strength and power are important determinants of successful performance in rugby league (Baker & Newton, 2009). As such, it is generally accepted that resistance training and plyometric training should be incorporated into an athlete's training regime to maximise force and power production (Ebben & Blackard, 1997; MacDonald et al., 2012, 2013). Furthermore, empirical evidence has demonstrated that the combination of strength and power training can be just as, or possibly more, effective than strength and power training alone (Dodd & Alvar, 2007; Juárez et al., 2009; MacDonald et al., 2012; Mihalik et al., 2008; Santos & Janeira, 2008; Talpey et al., 2016). Complex training alternates heavy resistance exercise on a set for set basis with biomechanically similar plyometric exercise (Docherty et al., 2004; MacDonald et al., 2012). This is an efficient training strategy since strength and power can be trained during a single session.

Complex training is underpinned by PAP, a phenomenon which refers to the short-term augmentation of force and power output in skeletal muscle following a near maximal voluntary contraction during a CA (Hodgson et al., 2005; Tillin & Bishop, 2009). Although the heavy load CA induces PAP, fatigue is simultaneously induced which inhibits the response (Tillin & Bishop, 2009). Therefore, it is important to utilise an appropriate ICRI between the CA and subsequent plyometric activity when implementing complex training programmes; this enables the PAP response to predominate fatigue (Docherty et al., 2004; Tillin & Bishop, 2009). Traditional complex training (TCT) studies examining the acute effects of PAP typically recommend ICRI of 4-12 minutes to evoke a PAP response in the lower body when heavy load BS are utilised (Crewther et al., 2011; Kilduff et al., 2008; Seitz, de Villarreal, et al., 2014). More recent research has reported ICRI of 2-6 minutes following the HBD exercise (Scott et al., 2017). However,

these ICRIIs may not be of practical value in applied training scenarios where time is often limited.

Accommodating resistance is theorised to modify the force-velocity profile of heavy resistance exercises by adding a percentage of the total resistance through latex bands or chains (Baker, 2008). This means that as the barbell continues through the ROM during the concentric phase, additional resistance will be applied (Baker, 2008; Wyland et al., 2015). Consequently, the effects of biomechanically disadvantageous positions, known as “sticking points”, are reduced; this results in increased acceleration and velocity during the concentric phase of the lift, enabling greater power outputs to be achieved (Nijem et al., 2016; Wyland et al., 2015). In addition, empirical evidence suggests that PAP can be realised as early as 90 seconds following moderately loaded CAs combined with accommodating resistance (Baker, 2008; Scott, Ditroilo, & Marshall, 2018) which may be of more practical value in applied training settings. However, there is no evidence documenting the effectiveness of chronic complex training programmes which incorporate accommodating resistance in comparison to a TCT programme.

Longitudinal studies have reported increases in muscular strength and power following 4-11 weeks of complex training however, ICRIIs between 30 seconds and 3 minutes were implemented which may not have been long enough for PAP to predominate fatigue (Alves et al., 2010; Dodd & Alvar, 2007; MacDonald et al., 2012, 2013; Stasinaki et al., 2015; Walker et al., 2010). Some of these studies have demonstrated that complex training may not be more effective than traditional resistance training or plyometric training alone (Dodd & Alvar, 2007; MacDonald et al., 2012, 2013). In addition, the ICRIIs utilised in these studies were consistent with those recommended in early PAP literature (Ebben & Blackard, 1997; Ebben & Watts, 1998; Fatouros et al., 2000; Fleck

& Kontor, 1986). It is conceivable that if more current complex training guidelines had been adhered to then superior results may have been achieved.

Although complex training appears to improve strength and power, there is little evidence with respect to chronic muscle morphology adaptations associated with this training modality. It has been previously reported that a 6-week complex training programme increases type II muscle fibre CSA, MT and P_{ang} but decreases L_f (Stasinaki et al., 2015). Typically, it is thought that greater muscle CSA, MT, P_{ang} and L_f are associated with greater levels of strength and power (Cormie et al., 2010a, 2011a). Additionally, strength and power trained athletes generally exhibit greater K_{leg} which has been related to enhanced performance of SSC activities due to a more efficient and rapid transfer of force from the muscle to the skeleton (Butler, Crowell, & Davis, 2003; Hobara et al., 2008; Markovic & Mikulic, 2010). It is conceivable that strength and power training induces favourable adaptations to K_{leg} which is likely to be beneficial for rugby league players since match-play involves multiple SSC actions such as, jumping, kicking, change of pace, sprinting, change of direction and collisions (Gabbett, Jenkins, & Abernethy, 2011c; Gabbett et al., 2008; Johnston et al., 2014). Complex training may be an effective training strategy for enhancing muscle architecture and K_{leg} since strength and power can be addressed during a single session; this is important in practical settings where time is often limited. As such, further research is required to determine the chronic effects of complex training on muscle architecture and K_{leg} adaptations.

Therefore, the purpose of this research was to examine the effects of a chronic complex training programme which incorporates accommodating resistance in comparison to a TCT programme with respect to physical performance and muscle morphology characteristics. Previous research investigating the effects of chronic complex training programmes have used ICRIs based on early PAP literature; however, the current study

aimed to utilise ICRIIs based on previous research by the authors. To date, there is no research which has investigated the superiority of a complex training programme which incorporates accommodating resistance in comparison to more conventional methods. It was hypothesised that both training programmes would induce similar physical performance and muscle morphology adaptations due to ICRIIs being based on more current research. However, the use of complex training incorporated with accommodating resistance may be advantageous due to the shorter ICRIIs associated with this modality in acute studies.

6.2 Methods

6.2.1 Experimental Approach to the Problem

This study examined the effects of a 6-week in-season accommodating resistance complex training (ARCT) programme in comparison to a TCT programme in rugby league players. Another group of rugby league players served as a CON and did not undertake any training; the study, therefore, adopted a between-subjects design. The training interventions comprised of 2 training sessions per week where the volume was identical between training groups. However, the ICRIIs for the ARCT group and the TCT group were 90 seconds and 4 minutes, respectively; these were based on previous research which demonstrated acute PAP responses using the corresponding training modalities (Baker, 2008; Scott et al., 2018, 2017). Strength, power, reactive strength index (RSI), speed, K_{leg} and muscle architecture were assessed before and after the 6-week training period in each group. These measures were quantified using a 1RM BS, CMJs and DJs, a 20-metre sprint and a vertical hop test. Muscle architecture of the VL and the GM were determined using B-mode ultrasonography (Figure 6.1).

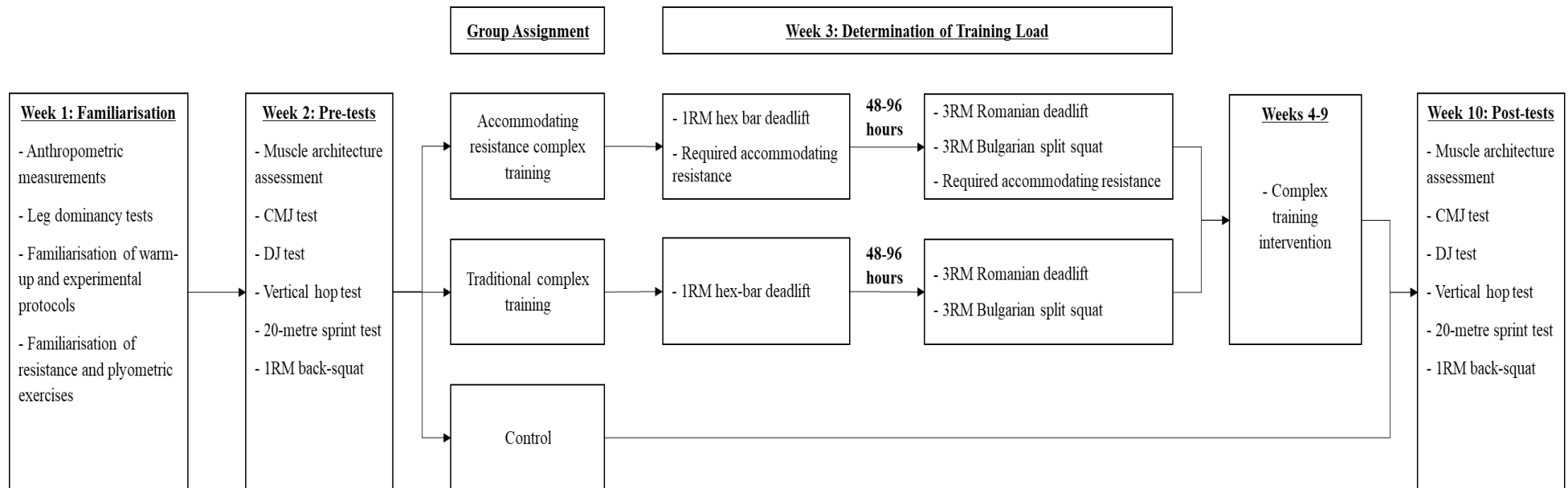


Figure 6.1 A schematic representation depicting the design and time frame of the study. CMJ = countermovement jump; DJ = drop jump; RM = repetition maximum.

6.2.2 Subjects

Twenty-four rugby league players ($n = 24$) were recruited from a University level rugby league team who play in the BUCS Premier North Division (age: 23.00 ± 3.86 years; height: 181.38 ± 7.32 cm; weight: 91.31 ± 10.06 kg). The players were randomly assigned to 1 of 3 groups: ARCT ($n = 8$), TCT ($n = 8$), or CON ($n = 8$; Table 6.1). The participants were moderately trained with at least 6-months previous experience in a structured resistance training programme, had no lower limb musculoskeletal injuries, and were able to perform the resistance and plyometric exercises with correct technique under the supervision of a qualified strength and conditioning coach. Throughout the study, the participants were asked to refrain from any additional lower limb resistance training. Each participant completed a pre-exercise medical questionnaire (Appendix F) and voluntarily gave their written informed consent (Appendix E) to partake in the study. The study received full institutional approval from the University's Sport, Health and Exercise Science Ethics Committee.

Table 6.1. Anthropometric characteristics of the participants. Data are presented as mean $\pm$ SD.

	ARCT ($n = 8$)	TCT ($n = 8$)	CON ($n = 8$)
Age (years)	20.25 ± 1.04	22.75 ± 3.62	26.00 ± 3.96
Height (cm)	178.06 ± 8.69	185.34 ± 4.74	180.75 ± 6.85
Weight (kg)	84.74 ± 10.65	96.17 ± 10.45	92.24 ± 9.95

ARCT = accommodating resistance complex training group;

TCT = traditional complex training group; CON = control group.

6.2.3 Procedures

Familiarisation: Prior to any experimental testing, the participants attended a familiarisation session during which, anthropometric measurements of height (The

Leicester Height Measure, Seca, Birmingham, UK) and body mass (Seca digital scales, Birmingham, UK) were recorded. For the purpose of ultrasonography assessment, leg dominance was determined using the step up, balance recovery and ball kick tests (Hass et al., 2005). Leg dominance was defined as the leg which was dominant in two of the three tests. Finally, the participants were familiarised with the warm-up, testing protocols, as well as the resistance and plyometric exercises within the training programme.

Testing: The participants were assessed on the same day and at the same time of day before and after the 6-week training period to control for circadian rhythm (Atkinson & Reilly, 1996). In addition, the participants were asked to refrain from engaging in any strenuous or unaccustomed exercise 48 hours prior to testing, to avoid the intake of caffeine 6 hours prior to testing and avoid the intake of alcohol 12 hours prior to testing.

Muscle architecture was examined using B-mode ultrasonography apparatus (MyLab 50 Xvision, Esaote, Genova, Italy). A single cross-sectional image was recorded using a 45 mm linear array ultrasound probe which was set at a scanning frequency of 7.5 MHz. To aid acoustic coupling and reduce the pressure between the probe and the muscle, a water-soluble transmission gel was applied to the probe. The probe was aligned parallel to the muscle fascicles and perpendicular to the skin therefore giving a sagittal plane image along the length of the muscle (Blazevich, 2006; Blazevich, Gill, Deans, et al., 2007). To acquire the best possible image, the alignment of the probe was manipulated and considered appropriate when several muscle fascicles could be determined without interruption across the image (Blazevich, 2006; Blazevich, Gill, Deans, et al., 2007). Prior to any measurements being taken for the VL, the participants lay on a massage bed in a supine position, described below, for 20 minutes. Similarly, before any measurements were recorded for the GM, the participants lay on a massage bed in a prone position,

described below, for 20 minutes. This was done to allow fluid shift to occur (Reeves et al., 2004).

For the VL, the probe was placed at 50% of the distance from the greater trochanter of the femur to the articular cleft between the femoral and tibial condyles (Miyatani et al., 2004). The participants lay in a supine position with their knees flexed and supported at 30° to ensure that the muscles were relaxed and reduce fascicle curvature (Blazeovich, 2006). For the GM, the probe was placed at 30% of the distance from the articular cleft between the femoral and tibial condyles to the lateral malleolus (Takai et al., 2013). The participants lay face down in a prone position with their muscles relaxed and their ankle joints in a neutral position (90°) over the edge of the massage bed (Legerlotz et al., 2010). A total of four images were recorded for each muscle. The same researcher has demonstrated a high level of reliability in the current laboratory for the measurements of MT (VL ICC = 0.99; GM ICC = 0.98), muscle P_{ang} (VL ICC = 0.87; GM ICC = 0.97), and L_f (VL ICC = 0.91; GM ICC = 0.93) which was determined on two separate testing days (n = 12).

Prior to the completion of the physical performance tests, the participants underwent a standardised warm-up (Table 6.2) consisting of a 3 minute cycle on a Wattbike ergometer (Wattbike Ltd, Nottingham, United Kingdom) at a low intensity of 60 W, a series of dynamic stretches which specifically focussed on the musculature associated with the chosen tests, and 3-4 submaximal CMJs. PPO was assessed by performing a CMJ on a strain gauge force plate (AMTI, BP600900; dimensions 900 x 600 mm, Watertown, Massachusetts, USA) where sampling frequency was set at 1000Hz. The participants performed the CMJ with their hands on their hips to ensure that it was only the lower body contributing force and power production. The eccentric phase of the jump was performed by flexing the knees to a self-selected depth of approximately 90° knee flexion

(Hori et al., 2009). Instruction was given to minimise the amortisation phase and explode upwards as forcefully and as quickly as possible during the concentric phase. The participants were instructed to keep their legs straight during the flight phase of the CMJ and to land in the same position as take-off. To reduce the risk of injury, instruction was given to cushion the landing by bending the knees as soon as the feet made contact with the ground. Three CMJs were performed with a one minute recovery interval between efforts. Only the CMJ with the greatest PPO was selected for further analysis. The determination of PPO using a CMJ has recently demonstrated excellent reliability in the current laboratory (ICC = 0.96; Scott et al., 2017).

Table 6.2. Standardised warm-up for experimental protocol and training sessions.

Exercise	Sets x reps (intensity)
Cycling	1 x 3 minutes (60 W)
Body weight squats	1 x 6
Mountain climbers	1 x 6 e/s
Thoracic rotations	1 x 6 e/s
Glute bridge	1 x 6
Band pull apart	1 x 6
Submaximal CMJs	1 x 3-4
Corresponding resistance exercise	1 x 6 (50% 1RM); 1 x 4 (70% 1RM)

e/s = each side; CMJ = countermovement jump; RM = repetition maximum.

Warm-up sets of the corresponding resistance exercise were administered during the training sessions.

A DJ was used to assess RSI, where the participants were required to step from a 0.4-metre platform with the aim of making a double footed ground contact with the force plate and rebounding as quickly and forcefully as possible whilst minimising GCT and maximising jump height. Instruction was given to the participants to perform the DJ to a

self-selected depth upon ground contact with their hands on their hips throughout the jump, keep their legs straight during the flight phase of the jump, maintain an upright torso and cushion the landing by bending their knees as soon as the feet made contact with the ground. If the heel struck the force plate first then the jump was excluded. Three DJs were performed with a one minute recovery between efforts. Only the DJ with the greatest RSI was selected for further analysis. The determination of RSI using a DJ has previously demonstrated excellent reliability (ICC = 0.97; Flanagan, Ebben, & Jensen, 2008).

A vertical hop test was used to assess K_{leg} which involved hopping unilaterally on a force plate in time to a digital metronome set at 2.2Hz. To eliminate any cushioning effects of footwear and any contribution from the upper body, the participants performed the test barefoot with their hands on their hips throughout the test. Once steady-state hopping was achieved, GRF data were collected for 10 seconds. Trials were only accepted if at least 5 of the hops were within a $\pm 2\%$ of the prescribed frequency. Data were recorded independently for the right and left limbs. The determination of K_{leg} using a vertical hop test has previously demonstrated a high level of reliability (ICC = 0.80; Pruyn et al., 2013).

Sprint times were measured using wireless Brower timing gates (Brower Timing Systems, Brower Test Centre System, Draper, Utah, USA). Five sets of timing gates were placed at the start and at 5-, 10-, 15-, and 20-metres to record sprint times at each interval. The participants decided when to start the sprint from a static position 0.5-metres behind the timing gate, with time being recorded when the infra-red beam between units was broken, and participants were instructed to complete the 20-metre sprint as quickly as possible. Two 20-metre sprints were performed with a 5 minute recovery interval between attempts. Only the fastest 20-metre sprint trial was used for further analysis. The 20-metre

sprint has previously demonstrated excellent reliability (ICC = 0.96; Gabbett, Kelly, & Sheppard, 2008).

Finally, lower body muscular strength was assessed using a 1RM BS. The procedures for 1RM testing adhered to the guidelines recommended by the NSCA (Appendix G; Brown, 2007). Briefly, this involved progressively increasing the load on the bar until the participants could only perform one successful repetition with correct technique. A recovery interval of 2-4 minutes was allowed between each 1RM attempt. The 1RM was only accepted if the exercise was completed with correct technique and a squat-depth where thighs were parallel to the ground. The 1RM BS assessment has previously demonstrated excellent reliability (ICC = 0.99; Comfort & McMahon, 2015).

Determination of Training Load: The resistance exercises used within the training programme were HBD, RDL, and Bulgarian split squat (BSS). The required loads for each participant were determined over two sessions which were separated by 48-96 hours. The first session consisted of a 1RM HBD whilst the second session comprised of a 3RM RDL and a 3RM BSS. Prior to the determination of training load, the participants underwent the same standardised warm-up utilised during the testing protocol. Similarly, the procedures for RM assessment adhered to the guidelines recommended by the NSCA (Brown, 2007). Predicted 1RM scores for RDL and BSS were calculated using the NSCA training load chart (Appendix I; Landers, 1985).

Lastly, the accommodating load from the elastic bands for the corresponding resistance exercises were measured using Seca weighing scales (Seca digital scales, Birmingham, UK) which were previously calibrated following the manufacturer guidelines. Similar to previous research (Baker, 2008; Scott et al., 2018; Wallace et al., 2006) the participants stood on the scales with the bar and the mass was recorded. The bands (Pullum Sports,

Leighton Buzzard, Bedfordshire) were then attached to the bar and the participants stood at the end of range for each lift and mass was recorded. Band tension was defined as the difference between these two measures. This process was repeated with bands of various tension until the accommodating resistance reached up to 23% 1RM at end range for the corresponding resistance exercise.

Training Programmes: The participants completed two training sessions per week over a 6-week period which was designed and delivered by a Certified Strength and Conditioning Specialist. Although the exercises, volume, and recovery between complex pairs and training sessions were consistent between groups, the prescribed intensities and ICRI varied. The TCT group performed each resistance exercise at 93% of 1RM with an ICRI of 4 minutes, whereas the ARCT group performed each resistance exercise at 70% of 1RM + 0-23% of 1RM from elastic band resistance throughout the full ROM with an ICRI of 90 seconds (Table 6.3). The adherence rate for the ARCT and TCT groups were 94.8% and 95.8%, respectively. In addition, no participant missed more than one training session.

The use of a 4 minute ICRI for the TCT group was based on study 1, where there were significant improvements in PPO during the CMJ at 2, 4 and 6 minutes following the HBD. In addition the greatest increase in peak GRF at PPO was identified at 4 minutes. This evidence, accompanied by previous research recommending an ICRI of 4-12 minutes using this training modality (Bevan et al., 2010; Crewther et al., 2011; Kilduff et al., 2007, 2008; Seitz, de Villarreal, et al., 2014) was used to justify this chosen ICRI. The greatest group improvement in PPO was demonstrated at 90 seconds in study 2 using ARCT and 35% of individuals expressed their greatest PAP response at this ICRI. This evidence, accompanied by that of Baker (2008), was used to justify the incorporation of a shorter, more practical ICRI for this training modality. In real-world training scenarios

Table 6.3. Overview of the complex training programmes.

ARCT				TCT			
Complex pairs	Sets x reps	Intensity	ICRI	Complex pairs	Sets x reps	Intensity	ICRI
1a. Hex-bar deadlift	3 x 3	70 + 0-23% 1RM	90 seconds	1a. Hex-bar deadlift	3 x 3	93% 1RM	4 minutes
1b. Drop jumps (40 cm)	3 x 6	Body weight		1b. Drop jumps (40 cm)	3 x 6	Body weight	
2a. Romanian deadlift	3 x 3	70 + 0-23% 1RM	90 seconds	2a. Romanian deadlift	3 x 3	93% 1RM	4 minutes
2b. Pike jumps	3 x 6	Body weight		2b. Pike jumps	3 x 6	Body weight	
3a. Bulgarian split squat	3 x 3	70 + 0-23% 1RM	90 seconds	3a. Bulgarian split squat	3 x 3	93% 1RM	4 minutes
3b. Lunge jumps	3 x 6	Body weight		3b. Lunge jumps	3 x 6	Body weight	

These training sessions were performed twice per week. A 4 minute recovery interval was allowed between complex sets. A 48-96 hour recovery period was allowed between training sessions.

ARCT = accommodating resistance complex training; TCT = traditional complex training; ICRI = intra-complex recovery interval.

multiple complex pairs would be used in training sessions; as such, more than one complex pair was selected to replicate the real-world application of complex training. The RDL and BSS were chosen as supporting exercises in the complex training programmes due to their specificity with respect to the musculature and movement patterns associated with rugby league. Rugby league match-play involves a large number of accelerations, decelerations and changes of direction, resulting in a high volume of eccentric loading (Gabbett et al., 2012; Twist & Highton, 2013; Waldron et al., 2011). Such activities involve high levels of braking force and are performed unilaterally (Brughelli, Cronin, Levin, & Chaouachi, 2008; Delaney et al., 2015). Therefore, the RDL was selected since it has demonstrated high levels of hamstring activation during eccentric contractions (McAllister et al., 2014; Schoenfeld et al., 2015). The BSS was selected since it is a unilateral exercise which has been reported to express high levels of muscular activity in the hamstring, gluteal and quadriceps muscle groups which are of importance for hip extension and flexion as well as knee flexion and extension (Jones, Ambegaonkar, Nindl, Smith, & Headley, 2012; McCurdy et al., 2010). Furthermore, it has been suggested that the BSS can enable 85% of force to be produced on a single leg (Speirs, Bennett, Finn, & Turner, 2016).

6.2.4 Data Analysis

All GRF data were analysed using customised coding scripts in MATLAB (MATLAB, version R2014a, MathWorks, Inc., Natick, MA). The vertical component of the GRF data was not filtered since no noise was evident in the signal. Therefore, the dependent variables could be calculated whilst controlling the effects of different filtering techniques (Hori et al., 2009). The instants of touchdown and take-off during the jumping and hopping trials were determined based on a 5 N threshold.

Peak Power Output: The participants' mass was calculated by taking an average of the GRF data 2 seconds prior to the start of the CMJ. Equations (1) and (2) were used to calculate PPO:

$$1) A_{inst.} (m \cdot s^{-2}) = [GRF_{inst.} (N) / m (kg)] - g (9.81 m \cdot s^{-2})$$

where $A_{inst.}$ is instantaneous acceleration, $GRF_{inst.}$ is instantaneous ground reaction force, m is the mass of the participant, and g is the acceleration due to gravity.

$$2) P_{inst.} (W) = GRF_{inst.} (N) \times V_{inst.} (m \cdot s^{-1})$$

where $P_{inst.}$ is instantaneous power, and $V_{inst.}$ is instantaneous velocity which was calculated by integration of instantaneous acceleration using the Simpson's rule. The start of the CMJ was determined as the instant where the instantaneous GRF was reduced by 10% of the participant's body weight. Integration started from the start of the jump and finished at the point of landing, where the intervals were equal to the band width. PPO was determined by obtaining the greatest value for instantaneous power.

Reactive Strength Index: Equations (3) and (4) were used to calculate RSI:

$$3) RSI = JH (m) / GCT (s)$$

where GCT is ground contact time which was determined by finding the difference in time between initial ground contact and take-off during the DJ, and JH is jump height which was calculated using the flight time method, equation (4) (Linthorne, 2001):

$$4) JH (m) = [g (9.81 m \cdot s^{-2}) \times FT^2 (s)] / 8$$

where g is the acceleration due to gravity, and FT is flight time which was determined by finding the difference in time between take-off and landing.

Leg Stiffness: Equations (5) and (6) were used to calculate K_{leg} :

$$5) K_{leg} = GRF_{max} / \Delta z$$

where GRF_{max} is the peak GRF produced during the corresponding vertical hop, and Δz is the maximum negative vertical displacement of the centre of mass during ground contact of the corresponding vertical hop which was calculated using equation (6) (Dalleau, Belli, Viale, Lacour, & Bourdin, 2004):

$$6) \Delta z = \frac{-GRF_{max}}{m} \cdot \frac{GCT^2}{\pi^2} + g \cdot \frac{GCT^2}{8}$$

The calculation of K_{leg} was performed on 5 consecutive hops and expressed as a mean. This value was used for further analysis.

Muscle Architecture: Image analysis was conducted using publicly available imaging software (ImageJ, 1.48v, National Institutes of Health; <http://rsb.info.nih.gov/ij/>). MT was assessed by measuring the distance between the superficial aponeurosis and the deep aponeurosis at the central location of the muscle on the 2D ultrasound image (Blazevich, 2006; Blazevich, Gill, Deans, et al., 2007). Muscle P_{ang} was defined as the intersection between the muscle fascicles and deep aponeurosis (Kwah et al., 2013). Lastly, L_f was defined as the length of the muscle fascicle between the superficial and deep aponeurosis. The visible portion of the muscle fascicle in each 2D ultrasound image was measured by tracking the curvature of a single muscle fascicle using a segmented line. The non-visible portion was estimated by linear extrapolation which involved measuring the distance between the visible muscle fascicle to the intersection between a line drawn from the muscle fascicle and a line drawn from the aponeuroses (Reeves et al., 2004). A mean was calculated for each variable from the 4 images recorded of each muscle and was used for further analysis.

6.2.5 Statistical Analyses

Preliminary analysis was conducted to ensure that the data were normally distributed and that the assumptions of the statistical tests were met. To control for between group

differences identified at pre-testing, statistical analysis was conducted using a 2-way ANOVA (group x time) where the pre-testing score was a covariate. Any significant interaction effects observed were further analysed using pairwise comparisons with Sidak corrections to correct for type I errors. Significance was set at $p \leq 0.05$. These statistical procedures were conducted using SPSS 24 (SPSS Inc., Chicago, IL). In addition, Cohen's d effect sizes were calculated to supplement the within- and between-group changes for each variable. Cohen's d effect sizes were interpreted as trivial (≤ 0.19), small (0.20-0.49), medium (0.50-0.79), large (0.80-1.29) or very large (≥ 1.30) (Cohen, 1988).

6.3 Results

6.3.1 Physical Performance

6.3.1.1 Strength

1RM BS scores significantly increased following the ARCT condition (adjusted mean [M_{adj}] = 17.51 ± 6.42 kg, $p < 0.001$, CI = 12.74 to 22.28 kg) and the TCT condition (M_{adj} = 17.71 ± 7.70 kg, $p < 0.001$, CI = 11.99 to 23.43 kg). There was no significant difference following the CON condition (M_{adj} = 0.97 ± 7.27 kg, $p = 0.71$, CI = -4.23 to 6.37 kg). Furthermore, there was a significant difference between the ARCT condition and the CON condition at post-testing (M_{adj} = 16.54 ± 9.70 kg, $p < 0.001$, CI = 7.52 to 25.56 kg). Similarly, there was a significant difference between the TCT condition and the CON condition at post-testing (M_{adj} = 16.74 ± 10.59 kg, $p = 0.001$, CI = 6.89 to 26.59 kg). Within-group effect sizes were interpreted as medium following the ARCT and TCT conditions (Table 6.4). Between-group effect sizes were interpreted as very large for the ARCT and TCT conditions in comparison to the CON condition (Table 6.5).

Table 6.4 Within-group effect sizes for physical performance parameters of strength, power, leg stiffness and speed before and after the training interventions. Data are presented as mean $\pm$ SD.

		ARCT	TCT	CON
1RM Back Squat (kg)	Pre	134.38 $\pm$ 24.41	118.75 $\pm$ 27.09	153.75 $\pm$ 36.23
	Post	151.88 $\pm$ 25.35	138.13 $\pm$ 25.63	154.06 $\pm$ 35.05
	Cohen's d (CI)	0.70 (-0.34, 1.67)	0.73 (-0.28, 1.75)	0.01 (-0.97, 0.99)
PPO (W)	Pre	4431.62 $\pm$ 682.11	4293.70 $\pm$ 661.62	4841.51 $\pm$ 471.64
	Post	4652.50 $\pm$ 600.11	4485.40 $\pm$ 722.33	4818.29 $\pm$ 325.19
	Cohen's d (CI)	0.34 (-0.64, 1.33)	0.28 (-0.71, 1.26)	-0.06 (-1.04, 0.92)
RSI (AU)	Pre	1.03 $\pm$ 0.26	0.82 $\pm$ 0.14	1.01 $\pm$ 0.26
	Post	1.24 $\pm$ 0.34	0.99 $\pm$ 0.41	1.08 $\pm$ 0.29
	Cohen's d (CI)	0.62 (-0.39, 1.62)	0.55 (-0.44, 1.55)	0.24 (-0.73, 1.24)
K_{leg} Right (kN·m⁻¹)	Pre	17.59 $\pm$ 2.93	18.36 $\pm$ 1.95	17.25 $\pm$ 3.82
	Post	18.73 $\pm$ 3.20	19.01 $\pm$ 2.07	16.54 $\pm$ 3.30
	Cohen's d (CI)	0.37 (-0.62, 1.36)	0.32 (-0.66, 1.31)	-0.29 (-1.27, 0.70)
K_{leg} Left (kN·m⁻¹)	Pre	17.47 $\pm$ 3.41	18.52 $\pm$ 1.42	17.67 $\pm$ 3.21
	Post	19.00 $\pm$ 3.61	19.12 $\pm$ 1.30	17.75 $\pm$ 3.49
	Cohen's d (CI)	0.44 (-0.56, 1.43)	0.44 (-0.55, 1.43)	0.02 (-0.96, 1.00)
5-metre Sprint (s)	Pre	1.07 $\pm$ 0.08	1.11 $\pm$ 0.10	1.04 $\pm$ 0.04
	Post	1.01 $\pm$ 0.05	1.04 $\pm$ 0.05	1.06 $\pm$ 0.03
	Cohen's d (CI)	0.89 (-0.14, 1.91)	0.87 (-0.16, 1.89)	-0.56 (-1.56, 0.44)
10-metre Sprint (s)	Pre	1.81 $\pm$ 0.09	1.92 $\pm$ 0.13	1.82 $\pm$ 0.05
	Post	1.77 $\pm$ 0.09	1.85 $\pm$ 0.10	1.83 $\pm$ 0.04
	Cohen's d (CI)	0.44 (-0.55, 1.43)	0.60 (-0.40, 1.60)	0.22 (-0.76, 1.20)
15-metre Sprint (s)	Pre	2.49 $\pm$ 0.12	2.63 $\pm$ 0.15	2.51 $\pm$ 0.07
	Post	2.44 $\pm$ 0.13	2.57 $\pm$ 0.16	2.54 $\pm$ 0.04
	Cohen's d (CI)	0.39 (-0.59, 1.38)	0.39 (-0.60, 1.38)	-0.55 (-1.55, 0.45)
20-metre Sprint (s)	Pre	3.14 $\pm$ 0.14	3.36 $\pm$ 0.21	3.18 $\pm$ 0.07
	Post	3.09 $\pm$ 0.20	3.25 $\pm$ 0.19	3.20 $\pm$ 0.06
	Cohen's d (CI)	0.29 (-0.69, 1.28)	0.55 (-0.45, 1.55)	-0.30 (-1.28, 0.69)

ARCT = accommodating resistance complex training; TCT = traditional complex training; CON = control; CI = 95% confidence interval; RM = repetition maximum; PPO = peak power output; RSI = reactive strength index; AU = arbitrary units; K_{leg} = leg stiffness.

6.3.1.2 Power

PPO significantly increased following the ARCT condition ($M_{\text{adj}} = 206.55 \pm 249.62$ W, $p = 0.02$, CI = 35.84 to 377.26 W) and the TCT condition ($M_{\text{adj}} = 193.18 \pm 242.56$ W, p

= 0.037, CI = 13.01 to 373.35 W). There was no significant difference following the CON condition ($M_{\text{adj}} = 103.05 \pm 280.86$ W, $p = 0.313$ CI = -105.57 to 311.67 W). No significant ($p > 0.05$) differences were observed between any of the experimental conditions at post-testing. Between-group effect sizes were interpreted as large for the ARCT and TCT conditions in comparison to the CON condition (Table 6.5).

6.3.1.3 Reactive Strength Index

RSI significantly improved following the ARCT condition ($M_{\text{adj}} = 0.22 \pm 0.28$, $p = 0.039$, CI = 0.01 to 0.43). There was no significant improvement following the TCT condition ($M_{\text{adj}} = 0.28 \pm 0.39$ m·s⁻¹, $p = 0.057$, CI = -0.01 to 0.57) nor was a significant difference identified following the CON condition ($M_{\text{adj}} = 0.06 \pm 0.28$, $p = 0.52$, CI = -0.14 to 0.27). No significant ($p > 0.05$) differences were observed between any of the experimental conditions at post-testing. Within-group effect sizes were interpreted as medium following the ARCT and TCT conditions (Table 6.4). Between-group effect sizes were interpreted as medium for the ARCT condition in comparison to the CON condition (Table 6.5).

6.3.1.4 Leg Stiffness

Right leg: There was a significant improvement following the ARCT condition ($M_{\text{adj}} = 1.14 \pm 1.20$ kN·m⁻¹, $p = 0.015$, CI = 0.25 to 2.03 kN·m⁻¹). There was no significant improvement following the TCT condition ($M_{\text{adj}} = 0.76 \pm 1.26$ kN·m⁻¹, $p = 0.12$, CI = -0.18 to 1.69 kN·m⁻¹) nor was there any significant difference identified following the CON condition ($M_{\text{adj}} = -0.79 \pm 1.21$ kN·m⁻¹, $p = 0.081$, CI = -1.69 to 0.11). Furthermore, there was a significant difference between the ARCT condition and the CON condition at post-testing ($M_{\text{adj}} = 1.93 \pm 1.70$ kN·m⁻¹, $p = 0.015$, CI = 0.34 to 3.51 kN·m⁻¹). Between-group effect sizes were interpreted as very large for the ARCT condition in comparison

to the CON condition and large for the TCT condition in comparison to the CON condition (Table 6.5).

Left leg: There was a significant improvement following the ARCT condition ($M_{\text{adj}} = 1.49 \pm 1.37 \text{ kN}\cdot\text{m}^{-1}$, $p = 0.007$, CI = 0.47 to 2.51 $\text{kN}\cdot\text{m}^{-1}$). There was no significant improvement following the TCT condition ($M_{\text{adj}} = 0.83 \pm 1.51 \text{ kN}\cdot\text{m}^{-1}$, $p = 0.14$, CI = -1.15 to 2.63 $\text{kN}\cdot\text{m}^{-1}$) nor was there any significant difference identified following the CON condition ($M_{\text{adj}} = 0.09 \pm 1.36 \text{ kN}\cdot\text{m}^{-1}$, $p = 0.85$, CI = -0.99 to 1.10 $\text{kN}\cdot\text{m}^{-1}$). No significant ($p > 0.05$) differences were observed between any of the experimental conditions at post-testing. Between-group effect sizes were interpreted as large for the ARCT condition in comparison to the CON condition and medium for the TCT condition in comparison to the CON condition; additionally, there was a medium effect size for the ARCT condition in comparison to the TCT condition (Table 6.5).

6.3.1.5 Speed

5-metre sprint: There was a significant improvement following the ARCT condition ($M_{\text{adj}} = -0.04 \pm 0.04 \text{ s}$, $p = 0.01$, CI = -0.07 to -0.01 s) and the TCT condition ($M_{\text{adj}} = -0.07 \pm 0.04 \text{ s}$, $p < 0.001$, CI = -0.10 to -0.04 s). No significant difference was identified following the CON condition ($M_{\text{adj}} = -0.01 \pm 0.05 \text{ s}$, $p = 0.64$, CI = -0.05 to 0.03 s). Furthermore, there was a significant difference between the TCT condition and the CON condition at post-testing ($-0.06 \pm 0.07 \text{ s}$, $p = 0.05$, CI = -0.12 to -0.00 s). Within-group effect sizes were interpreted as large following the ARCT and TCT conditions; additionally, there was a negative medium effect size following the CON condition (Table 6.4). Between-group effect sizes were interpreted as very large for the ARCT condition in comparison to the CON condition and large for the TCT condition in comparison to the CON condition (Table 6.5).

Table 6.5 Between-group effects sizes for physical performance parameters of strength, power, leg stiffness and speed between based on the differences observed in the change score.

		ARCT vs. CON	TCT vs. CON	ARCT vs. TCT
1RM Back Squat (kg)	Difference in change score	17.19	19.06	1.88
	Cohen's d (CI)	3.54 (1.97, 5.11)	3.04 (1.60, 4.47)	-0.26 (0.72, -1.25)
PPO (W)	Difference in change score	244.11	214.93	29.18
	Cohen's d (CI)	1.08 (0.04, 2.13)	0.82 (-0.20, 1.84)	0.12 (-0.86, 1.10)
RSI (AU)	Difference in change score	0.15	0.11	0.04
	Cohen's d (CI)	0.73 (-0.28, 1.74)	0.39 (-0.60, 1.38)	0.17 (-0.82, 1.15)
K_{leg} Right (kN·m⁻¹)	Difference in change score	1.84	1.36	0.48
	Cohen's d (CI)	1.66 (0.53, 2.80)	1.13 (0.07, 2.18)	0.39 (-0.60, 1.31)
K_{leg} Left (kN·m⁻¹)	Difference in change score	1.46	0.53	0.93
	Cohen's d (CI)	1.02 (-0.03, 2.06)	0.62 (-0.39, 1.62)	0.59 (-0.41, 1.59)
5-metre sprint (s)	Difference in change score	-0.08	-0.09	0.01
	Cohen's d (CI)	1.34 (0.25, 2.42)	1.28 (0.20, 2.35)	-0.06 (-1.04, 0.92)
10-metre sprint (s)	Difference in change score	-0.06	-0.08	0.02
	Cohen's d (CI)	0.69 (-0.32, 1.70)	1.46 (0.36, 2.56)	-0.25 (-1.24, 0.73)
15-metre sprint (s)	Difference in change score	-0.07	-0.09	0.02
	Cohen's d (CI)	0.79 (-0.23, 1.81)	1.30 (0.23, 2.38)	-0.17 (-1.15, 0.81)
20-metre sprint (s)	Difference in change score	-0.08	-0.13	0.05
	Cohen's d (CI)	0.76 (-0.26, 1.77)	1.60 (0.40, 2.63)	- 0.47 (-1.46, 0.52)

ARCT = accommodating resistance complex training; TCT = traditional complex training; CON = control; CI = 95% confidence interval; RM = repetition maximum; PPO = peak power output; RSI = reactive strength index; AU = arbitrary units; K_{leg} = leg stiffness.

10-metre sprint: There was a significant improvement following the TCT condition ($M_{\text{adj}} = -0.07 \pm 0.07$ s, $p = 0.02$, CI = -0.12 to -0.02 s). There was no significant improvement following the ARCT condition ($M_{\text{adj}} = -0.04 \pm 0.08$ s, $p = 0.14$, CI = -0.10 to 0.02 s) nor were any significant difference identified following the CON condition ($M_{\text{adj}} = 0.00 \pm$

0.08 s, $p = 0.99$, CI = -0.06 to 0.06 s). No significant ($p > 0.05$) differences were observed between any of the experimental conditions at post-testing. Within-group effect sizes were interpreted as medium following TCT condition (Table 6.4). Between-group effect sizes were interpreted as medium for the ARCT condition in comparison to the CON condition and very large for the TCT condition in comparison to the CON condition (Table 6.5).

15-metre sprint: There was no significant improvement following the ARCT condition ($M_{\text{adj}} = -0.05 \pm 0.10$ s, $p = 0.14$, CI = -0.13 to 0.20 s), the TCT condition ($M_{\text{adj}} = -0.06 \pm 0.09$ s, $p = 0.08$, CI = -0.01 to 0.13 s) or the CON condition ($M_{\text{adj}} = 0.01 \pm 0.09$ s, $p = 0.88$, CI = -0.06 to 0.07). No significant ($p > 0.05$) differences were observed between any of the experimental conditions at post-testing. There was a negative medium within-group effect size following the CON condition (Table 6.4). Between-group effect sizes were interpreted as medium for the ARCT condition in comparison to the CON condition and very large for the TCT condition in comparison to the CON condition (Table 6.5).

20-metre sprint: There was no significant improvement following the ARCT condition ($M_{\text{adj}} = -0.04 \pm 0.12$ s, $p = 0.33$, CI = -0.13 to 0.05 s), the TCT condition ($M_{\text{adj}} = -0.08 \pm 0.12$ s, $p = 0.07$, CI = -0.17 to 0.01 s) or the CON condition ($M_{\text{adj}} = -0.01 \pm 0.12$ s, $p = 0.91$, CI = -0.10 to 0.09 s). No significant ($p > 0.05$) differences were observed between any of the experimental conditions at post-testing. Within-group effect sizes were interpreted medium following the ARCT condition (Table 6.4). Between-group effect sizes were interpreted as medium for the ARCT condition in comparison to the CON condition and very large for the TCT condition in comparison to the CON condition (Table 6.5).

6.3.2 Muscle Architecture

6.4.2.1 Vastus Lateralis

Muscle thickness: There was a significant increase following the ARCT condition ($M_{adj} = 0.21 \pm 0.17$ cm, $p = 0.002$, CI = 0.09 to 0.33 cm) and the TCT condition ($M_{adj} = 0.23 \pm 0.19$ cm, $p = 0.003$, CI = 0.09 to 0.37 cm). However, there was no significant change following the CON condition ($M_{adj} = -0.14 \pm 0.18$ cm, $p = 0.82$, CI = -0.15 to 0.12 cm). Furthermore, there was a significant difference between the TCT condition and the CON condition at post-testing ($M_{adj} = 0.24 \pm 0.26$ cm, $p = 0.05$, CI = 0.00 to 0.48 cm). Within-group effect sizes were interpreted as medium following the TCT condition (Table 6.6). Between-group effect sizes were interpreted as very large for the ARCT and TCT conditions in comparison to the CON condition (Table 6.7).

Pennation angle: There was no significant differences following the ARCT condition ($M_{adj} = -0.17 \pm 1.12^\circ$, $p = 0.68$, CI = -0.67 to 1.00°), the TCT condition ($M_{adj} = -0.26 \pm 1.18^\circ$, $p = 0.54$, CI = -1.14 to 0.61°) or the CON condition ($M_{adj} = -0.12 \pm 1.16^\circ$, $p = 0.78$, CI = -0.74 to 0.98°). No significant ($p > 0.05$) differences were observed between any of the experimental conditions at post-testing.

Fascicle length: There was a significant increase following the ARCT condition ($M_{adj} = 0.80 \pm 0.46$ cm, $p < 0.001$, CI = 0.44 to 1.12 cm) and the TCT condition ($M_{adj} = 1.18 \pm 0.47$ cm, $p < 0.001$, CI = 0.83 to 1.53 cm). There was no significant difference following the CON condition ($M_{adj} = 0.09 \pm 0.48$ cm, $p = 0.60$, CI = -0.27 to 0.45 cm). Furthermore, there was a significant difference between the ARCT condition and the CON condition at post-testing ($M_{adj} = 0.69 \pm 0.67$ cm, $p = 0.027$, CI = 0.07 to 1.31 cm). Similarly, there was a significant difference between the TCT condition and the CON condition at post-testing ($M_{adj} = 1.09 \pm 0.68$ cm, $p = 0.001$, CI = 0.46 to 1.72 cm). Within-group effect sizes

were interpreted large following the TCT condition (Table 6.6). Between-group effect sizes were interpreted as very large for the ARCT and TCT conditions in comparison to the CON condition; additionally, there was a medium effect for the TCT condition in comparison to the ARCT condition (Table 6.7).

6.4.2.2 Gastrocnemius Medialis

Muscle thickness: There was no significant differences following the ARCT condition ($M_{\text{adj}} = 0.06 \pm 0.11$ cm, $p = 0.12$, CI = -0.02 to 0.14 cm), the TCT condition ($M_{\text{adj}} = 0.06 \pm 0.12$ cm, $p = 0.17$, CI = -0.03 to 0.15 cm) or the CON condition ($M_{\text{adj}} = 0.02 \pm 0.11$ cm, $p = 0.62$, CI = -0.06 to 0.10 cm). No significant ($p > 0.05$) differences were observed between any of the experimental conditions at post-testing. Between-group effect sizes were interpreted as medium for the ARCT condition in comparison to the CON condition (Table 6.7).

Pennation angle: There was no significant differences following the ARCT condition ($M_{\text{adj}} = 0.46 \pm 1.42^\circ$, $p = 0.37$, CI = -0.59 to 1.52°), the TCT condition ($M_{\text{adj}} = 0.40 \pm 1.39^\circ$, $p = 0.43$, CI = -1.43 to 0.63°) or the CON condition ($M_{\text{adj}} = 0.13 \pm 1.40^\circ$, $p = 0.80$, CI = -0.92 to 1.17). No significant ($p > 0.05$) differences were observed between any of the experimental conditions at post-testing. Between-group effect sizes were interpreted as medium for the TCT condition in comparison to the CON condition (Table 6.7).

Fascicle length: There was no significant differences following the ARCT condition ($M_{\text{adj}} = -0.01 \pm 0.21$ cm, $p = 0.89$, CI = -0.17 to 0.14 cm), the TCT condition ($M_{\text{adj}} = -0.07 \pm 0.22$ cm, $p = 0.42$, CI = -0.23 to 0.10 cm) or the CON condition ($M_{\text{adj}} = -0.05 \pm 0.20$ cm, $p = 0.47$, CI = -0.20 to 0.10 cm). No significant ($p > 0.05$) differences were observed between any of the experimental conditions at post-testing.

Table 6.6 Within-group effect sizes for muscle architecture measurements of the vastus lateralis and gastrocnemius medialis before and after the training interventions. Data are presented as mean $\pm$ SD.

		Vastus Lateralis			Gastrocnemius Medialis		
		Muscle Thickness (cm)	Pennation Angle (°)	Fascicle Length (cm)	Muscle Thickness (cm)	Pennation Angle (°)	Fascicle Length (cm)
ARCT	Pre	2.99 $\pm$ 0.54	16.32 $\pm$ 2.71	10.70 $\pm$ 1.75	1.95 $\pm$ 0.16	24.65 $\pm$ 2.09	4.93 $\pm$ 0.62
	Post	3.21 $\pm$ 0.45	16.08 $\pm$ 1.61	11.50 $\pm$ 1.65	2.01 $\pm$ 0.17	24.86 $\pm$ 2.14	4.93 $\pm$ 0.64
	Cohen's d (CI)	0.44 (-0.55, 1.43)	-0.11 (-1.09, 0.87)	0.47 (-0.52, 1.46)	0.36 (-0.62, 1.35)	0.10 (-0.88, 1.08)	0.00 (-0.98, 0.98)
TCT	Pre	2.89 $\pm$ 0.54	15.78 $\pm$ 1.22	10.66 $\pm$ 0.85	2.06 $\pm$ 0.16	24.29 $\pm$ 2.98	5.33 $\pm$ 0.52
	Post	3.15 $\pm$ 0.31	15.54 $\pm$ 1.86	11.78 $\pm$ 1.22	2.12 $\pm$ 0.21	23.88 $\pm$ 1.98	5.32 $\pm$ 0.64
	Cohen's d (CI)	0.59 (-0.41, 1.59)	-0.15 (-1.13, 0.83)	1.07 (0.02, 2.11)	0.32 (-0.66, 1.31)	-0.16 (-1.14, 0.82)	-0.02 (-1.00, 0.96)
CON	Pre	3.16 $\pm$ 0.38	16.42 $\pm$ 0.94	11.25 $\pm$ 1.24	1.91 $\pm$ 0.25	23.86 $\pm$ 3.34	5.00 $\pm$ 0.67
	Post	3.15 $\pm$ 0.40	16.23 $\pm$ 0.82	11.32 $\pm$ 1.20	1.94 $\pm$ 0.24	23.99 $\pm$ 3.33	4.95 $\pm$ 0.65
	Cohen's d (CI)	-0.03 (-1.01, 0.95)	-0.22 (-1.20, 0.77)	0.06 (-0.92, 1.04)	0.12 (-0.86, 1.10)	0.04 (-0.94, 1.02)	-0.08 (-1.06, 0.90)

ARCT = accommodating resistance complex training group; TCT = traditional complex training group; CON = control group; CI = 95% confidence interval.

Table 6.7 Between-group effects sizes for differences in the change score of muscle architecture measurements of the vastus lateralis and gastrocnemius medialis.

		Vastus Lateralis			Gastrocnemius Medialis		
		Muscle Thickness (cm)	Pennation Angle (°)	Fascicle Length (cm)	Muscle Thickness (cm)	Pennation Angle (°)	Fascicle Length (cm)
ARCT vs. CON	Difference in change score	0.22	-0.06	0.72	0.04	0.08	0.05
	Cohen's d (CI)	2.16 (0.92, 3.39)	0.05 (-0.93, 1.03)	1.86 (0.69, 3.03)	0.62 (-0.39, 1.62)	0.04 (-0.94, 1.02)	0.24 (-0.74, 1.22)
TCT vs. CON	Difference in change score	0.27	-0.06	1.05	0.03	-0.55	0.03
	Cohen's d (CI)	1.45 (0.35, 2.56)	0.06 (-0.92, 1.04)	2.51 (1.20, 3.82)	0.30 (-0.68, 1.29)	-0.53 (-1.53, 0.46)	0.25 (-0.74, 1.22)
ARCT vs. TCT	Difference in change score	-0.05	0.003	-0.32	0.01	0.62	0.02
	Cohen's d (CI)	-0.25 (-1.24, 0.73)	-0.01 (-0.99, 0.97)	-0.57 (-1.57, 0.43)	0.09 (-0.89, 1.07)	0.31 (-0.67, 1.30)	0.07 (-0.91, 1.05)

ARCT = accommodating resistance complex training group; TCT = traditional complex training group; CON = control group; CI = 95% confidence interval.

6.4 Discussion

This study examined the effects of a 6-week ARCT and TCT programme on strength, power, speed, K_{leg} and muscle architecture in rugby league players. The ICRIs utilised for both training programmes were based on recommendations by previous research (Baker, 2008; Scott et al., 2018, 2017). In agreement with the hypothesis of this study, significant improvements in strength, power and 5-metre sprint time were observed as well as significant increases in VL MT and L_f for both training groups. However, only the TCT group expressed significant improvements in 10-metre sprint time. An unexpected and novel finding of this study was that the ARCT group demonstrated significant improvements in RSI and K_{leg} , whereas the TCT group did not. As such, ARCT appears to enable a more efficient and rapid transfer of force from the muscle to the skeleton during SSC actions. This is important given the large amount of SSC activities involved in rugby league match-play (Gabbett et al., 2011c; Gabbett et al., 2008; Johnston et al., 2014).

6.4.1 Strength, Power and Speed Adaptations

The results of the current study are substantiated by previous research investigating the effects of complex training on physical attributes which have reported improved levels of 1RM strength (MacDonald et al., 2012; Stasinaki et al., 2015; Walker et al., 2010), power outputs (Dodd & Alvar, 2007; MacDonald et al., 2013; Stasinaki et al., 2015; Walker et al., 2010) and speed (Dodd & Alvar, 2007; Alves et al., 2010). The enhancement of strength, power and speed is largely attributed to both neural and muscular adaptations (Stasinaki et al., 2015). The present study did not investigate neural or muscular adaptations such as, central motor drive or muscle fibre CSA and distribution. Therefore, it is not possible to explain the observed improvements in physical performance due to complex training in relation to such neuromuscular adaptations. Future research is

required to elucidate the chronic neuromuscular adaptations associated with complex training. The present study did, however, assess muscle architecture adaptations which may partially explain some of the observed improvements in physical performance.

6.4.2 Muscle Architecture Adaptations

In agreement with Stasinaki et al. (2015), the current study demonstrated a significant small and medium increase in VL MT following the ARCT and TCT conditions, respectively. The observed increase in VL MT was greater than the between-session MDC (0.12 cm) previously reported by the researcher, demonstrating that a meaningful change is likely to have occurred. Interestingly, MT has been reported to be indicative of muscle CSA (Cormie et al., 2010a). Increases in muscle fibre CSA are highly correlated with force generation capabilities and greater power outputs due to a greater number of sarcomeres in parallel (Goldspink, 1999; Seynnes et al., 2007). Furthermore, an increase in muscle CSA is synonymous with hypertrophy (Folland & Williams, 2007) which may explain the observed improvements in strength and power. However, this assumption must be interpreted with caution since hypertrophic changes were not directly assessed in this study. This reinforces the need for future research examining the effects of complex training on muscular adaptations.

Similarly, increases in muscle P_{ang} are associated with the arrangement of a greater number of sarcomeres in parallel and the packing of muscle fibres within a given anatomical CSA (Cormie et al., 2011a; Folland & Williams, 2007). The current study expressed non-significant trivial changes in VL P_{ang} following the complex training conditions. There was no change greater than the between-session MDC (0.99°) previously reported by the researcher for VL P_{ang} . Although this conflicts with the significant increase reported by Stasinaki et al. (2015), a greater muscle P_{ang} is reported to decrease muscle fibre shortening velocity consequently reducing force transmission

from muscle fibres to the tendon due to the increased oblique angle of pull (Blazevich, 2006; Folland & Williams, 2007; Tillin & Bishop, 2009). The improvements observed in physical performance in the present study cannot be attributed to any change in muscle P_{ang} however, the lack of change may have been beneficial due to the high shortening velocities required during explosive actions. It is therefore likely that an increase in VL MT was due to an increase in L_f as opposed to P_{ang} .

Also in conflict with Stasinaki et al. (2015), the present study demonstrated significant small and large increases in VL L_f following the ARCT and TCT conditions, respectively. However, only the TCT condition observed an increase greater than the between-session MDC (0.94 cm) previously reported by the researcher. Therefore, it is likely that a meaningful change occurred following the TCT condition whereas the change following the ARCT condition is likely to be negligible. Greater muscle L_f is synonymous with a greater number of sarcomeres in series which may have occurred as a result of the high eccentric loads during the TCT condition (Goldspink, 1999; Schoenfeld, 2010b; Seynnes et al., 2007). This enables the production of large forces at high shortening velocities, resulting in greater power outputs (Blazevich, 2006; Cormie et al., 2011a). A plausible explanation for this is a shift to the right in the length-tension curve of the VL muscle (Brughelli & Cronin, 2007; Byrne et al., 2001). The optimum length of peak tension consequently occurs at longer sarcomere lengths and less work is done on the descending limb of the curve where force production is inhibited (Brughelli & Cronin, 2007; Byrne et al., 2001). This may partially explain some of the observed improvements in physical performance. For example, during the 1RM BS there will be more overlapping between actin and myosin filaments at the end range of the eccentric phase than prior to the intervention. Therefore, the effect of the sticking point during this movement is

reduced, enabling increased force and power production (Anderson et al., 2008; Nijem et al., 2016; Wyland et al., 2015).

The difference in VL L_f between the ARCT and TCT conditions could be explained by an increased amount of time spent under tension with a greater constant barbell load during the TCT condition (Tran et al., 2006) thus, inducing greater eccentric muscle contractions. Previous research has reported that faster individuals typically possess longer muscle L_f (Abe et al., 2000; Earp et al., 2010; Kumagai et al., 2000). The TCT condition expressed a significant medium increase in 10-metre sprint time and a non-significant medium increase in 20-metre sprint time post-intervention; in contrast, the ARCT condition demonstrated non-significant medium and small increases for 10- and 20-metre sprint times, respectively. It is possible that the greater improvement in sprint times could be attributed to longer muscle L_f enhancing force production at high shortening velocities (Blazevich, 2006; Cormie et al., 2011a).

There were no significant differences in any of the measured GM muscle architecture variables which is in contrast to Stasinaki et al. (2015) who reported a significant increase in GM P_{ang} and decrease in L_f . Non-significant small and trivial effects were observed following both complex training conditions, none of which were greater than the between-session MDCs previously reported by the researcher for MT (0.11 cm), P_{ang} (1.45°), and L_f (0.45 cm). The GM acts as a stabiliser of the lower leg during closed chain resistance exercises such as the BS (Clark, Lambert, & Hunter, 2012; Schwanbeck, Chilibeck, & Binsted, 2009). Due to its biarticular nature, the contribution of the GM to such exercises are dependent on knee and joint angles (Kawakami, Ichinose, & Fukunaga, 1998; Signorile, Applegate, Duque, Cole, & Zink, 2002). It is likely that the contribution of the GM to the exercises within the current study were minimal (Riemann, Limbaugh, Eitner, & LeFavi, 2011). Consequently, a stimulus large enough to induce muscle

architecture adaptations may not have been provided. The loaded (30% of 1RM) power exercises, squat jumps and leg press throw, utilised by Stasinaki et al. (2015) is likely to have induced greater levels of activation during plantar flexion which may explain the observed muscle architecture adaptations to the GM (Fiebert et al., 2000; Riemann et al., 2011).

There are a number of plausible explanations for the differences observed in muscle architecture between the present study and previous research including, the exercise selection, intensity and the ICRI's utilised. Specifically, Stasinaki et al. (2015) implemented 85% and 30% 1RM loads for resistance and power exercises, respectively. Since muscle architecture adaptations are thought to be velocity-specific (Blazevich et al., 2003) it is possible that the body weight plyometric exercises within the current study induced faster contraction velocities which may have evoked the observed adaptations. An ICRI of 3 minutes may not have been an appropriate time-frame for PAP to manifest, despite Study 1 demonstrating a PAP response following a 2-6 minute ICRI, especially given the training status of the participants. Moreover, the exercises utilised included Smith machine box squats and incline leg press which may not have induced a PAP response; there is little, if any, research documented with respect to these exercises as a PAP stimulus. Clark et al. (2012) demonstrated that free weight exercises are superior to machine based exercises with respect to muscle activation; it is therefore likely that machine based exercises do not provide enough of a stimulus to elicit PAP.

6.4.3 Leg Stiffness and RSI Adaptations

An unexpected and novel finding of the present study was the significant small and medium enhancement in K_{leg} and RSI, respectively, following the ARCT condition. It has been suggested that an increase K_{leg} enables a more rapid and efficient return of the stored elastic strain energy from the stretch reflex (Goodwin & Jeffreys, 2016; Markovic &

Mikulic, 2010; Wilson & Lichtwark, 2011). This is due to a reduction in the length of time required to stretch the MTU, consequently decreasing electromechanical delay and increasing RFD (Bojsen-Møller et al., 2005; Folland & Williams, 2007). In relation to the spring-mass model, this would require a decrease in GCT and more effective use of the SSC to reduce centre of mass displacement (Lloyd, Oliver, Hughes, & Williams, 2012; McMahon & Cheng, 1990). Improvement in fast-SSC actions in the ARCT group could be attributed to an enhanced ability to pre-tense the muscle which refers to the pre-emptive phase of activation where the muscle spindles are activated and sensitised prior to ground contact and the key phase of force production (Goodwin & Jeffreys, 2016; Komi, 2003). Previous research has demonstrated that plyometric training can induce significant improvements in excitability of the soleus muscle during fast-SSC actions (Voigt et al., 1998). The enhancement in K_{leg} may also explain the observed improvements in RSI since it is likely that the participants developed an increased tolerance to the high eccentric forces placed on the MTU leading to less deformation, a more rapid release of elastic energy and decreased GCT (Lloyd et al., 2012).

The observed improvements in K_{leg} and RSI following the ARCT condition in comparison to the TCT condition could be explained by the lifting technique of the resistance exercises. Accommodating resistance is theorised to induce an overspeed eccentric phase which enhances the SSC since a greater stretch reflex is elicited and the GTO is overridden, resulting in greater force production during the concentric phase (Simmons, 2007; Stevenson et al., 2010). Furthermore, due to the bands actively pulling the load downwards with greater force than the effect of gravity during the eccentric phase, the muscles may be better able to utilise stored elastic energy during the concentric phase of the lift since the effects of biomechanically disadvantageous positions are reduced (Wyland et al., 2015). Consequently, the increased utilisation of the SSC during the

resistance exercises may have contributed to more favourable adaptations (Bosco, Tarkka, & Komi, 1982).

Interestingly, adaptations to K_{leg} are predominantly influenced by ankle stiffness (Arampatzis, Schade, Walsh, & Brüggemann, 2001; Farley, Houdijk, Van Strien, & Louie, 1998). Plyometric training has been reported to enhance ankle joint stiffness (Kubo, Morimoto, Komuro, Yata, et al., 2007) whereas heavy resistance exercise has demonstrated improvements in knee extensor tendon stiffness (Kubo, Yata, Kanehisa, & Fukunaga, 2006). However, increased knee extensor tendon stiffness this has been found to inversely correlate with pre-stretch augmentation (Kubo, Morimoto, Komuro, Tsunoda, et al., 2007). It is conceivable that favourable MTU stiffness adaptations occurred following the ARCT condition which may help explain the observed improvements in physical performance. Therefore, future research is required to examine the effects of complex training on MTU stiffness of the ankle and knee joints independently due to its influence on the performance of SSC activities (Markovic & Mikulic, 2010).

6.4.4 Limitations

The limitations of the present study include the training status of the participants and the relatively short duration of the training intervention. Less experienced individuals have a greater reserve for adaptation, therefore any form of resistance training is likely to induce favourable adaptations (Bompa & Buzzichelli, 2015; Tredrea, 2017). It has been suggested that physical performance is more dependent on muscle size in less experienced individuals whereas the quality of muscle tissue, such as L_f and the percentage CSA of type II muscle fibres, is more important in experienced individuals (Methenitis et al., 2016). Future research should investigate the effects of complex training on the quality of muscle tissue in more experienced athletes. It is likely that 6-weeks of resistance

training is not enough to observe hypertrophic responses (Aagaard, 2003; MacDonald et al., 2012). It is therefore recommended that future research implements training interventions with several mesocycles and testing sessions to enable appropriate progressive overload within the prescribed training programmes. Lastly, the ICRIIs utilised for the RDL and BSS exercises were assumed to be the same as that of the HBD exercise which may not have been appropriate due different levels of muscle activation. Consequently, future research is required to determine optimal ICRIIs for such exercises.

6.4.5 Conclusions

In conclusion, the present study demonstrated that ARCT and TCT are effective when appropriate ICRIIs are implemented. The shorter ICRI associated with ARCT may enhance its practical application. There is also evidence to suggest that ARCT is advantageous with respect to improvements in K_{leg} and RSI however, more research is required to elucidate this finding. Specifically, future research should investigate the effect of complex training modalities on ankle and knee MTU stiffness independently since this may contribute to physical performance. Additionally, muscle architecture adaptations may be influenced by the amount of time spent under tension, as evidenced in the TCT condition, which may explain the observed improvements in sprint performance. It is plausible that optimal training adaptations may occur with ARCT performed with a slower eccentric phase as this may enhance SSC activity as well as increasing L_f however, further research is required to confirm this.

6.5 Practical Applications

Based on the results of the present study, strength and conditioning coaches should use ICRIIs based on scientific research when implementing complex training. Due to shorter ICRIIs enhancing the time-efficiency of ARCT, this complex training modality may be of more practical value for strength and conditioning practitioners. Whilst the ARCT

condition demonstrated superior improvements in K_{leg} and RSI, greater adaptations to L_f were observed following the TCT condition which may explain the enhancements in sprint performance. Therefore, strength and conditioning specialists should implement complex training modalities based on the training variables which they are aiming to improve. ARCT performed with a slower eccentric phase may be an optimal approach in achieving favourable stiffness and architectural adaptations however, further research is required to determine this. Finally, strength and conditioning coaches should identify appropriate ICRIIs for all exercises within their training programmes.

Chapter 7: General Discussion and Conclusions

7.1 Overview

The aims of the present thesis were to:

1. To determine the differences in the voluntary PAP response between the HBD and BS exercises and identify the optimal recovery interval required for PAP to manifest.
2. To examine if moderately loaded HBD and BS exercises combined with accommodating resistance can elicit the voluntary PAP response at shorter recovery intervals of more practical value in real-world scenarios.
3. To examine the difference in the magnitude of the voluntary PAP response between stronger, more experienced and weaker, less experienced athletes.
4. To examine muscle activation as a result of the voluntary PAP response using surface EMG.
5. To investigate the chronic adaptations to muscle architecture and athletic performance following two different 6-week complex training interventions where the recovery intervals implemented are based on scientific evidence.

This thesis was divided into four distinct experimental studies: two acute PAP studies, a reliability study assessing ultrasonography imaging techniques, and a chronic complex training study. The first study was designed to identify whether a concentric-only contraction, induced by the HBD exercise, could elicit a greater PAP response at an earlier ICRI in comparison to the BS exercise. This study also aimed to ascertain whether there were any differences in the voluntary PAP response between stronger and weaker athletes when these CAs were utilised. To examine whether any PAP response could be due to increased motor unit recruitment, muscle activation was assessed during the subsequent plyometric activity using surface EMG. The second study was designed to investigate whether moderately loaded CAs combined with accommodating resistance could elicit a

voluntary PAP response following shorter ICRI. Similarly, this study compared the PAP response of the HBD and the BS exercises, and also assessed motor unit recruitment during the subsequent plyometric action using surface EMG. Study 3 was conducted to quantify the measurement error associated with ultrasound imaging techniques when assessing the muscle architecture of the VL and GM. This information was used to assist in the analysis of the subsequent training intervention study. Study 4 was designed to examine physical performance and muscle architectural characteristics before and after two different complex training programmes. Specifically, the study compared the adaptations induced by an ARCT programme and a TCT programme where the ICRI implemented were informed by scientific evidence.

7.2 Review of Experimental Chapters

7.2.1 The effect of exercise selection and training status on the PAP response

The key findings of the first experimental study included a significant increase in PPO at ICRI of 2, 4, and 6 minutes following the HBD condition for stronger and weaker players however, no improvement for the BS condition was identified. Unexpectedly, the CON condition demonstrated a significant decrease in PPO at an ICRI of 16 minutes. Furthermore, a significant increase in GRF at PPO was identified following both conditions at an ICRI of 4 minutes. Interestingly, there was a significant decrease in velocity at PPO for both conditions at an ICRI of 16 minutes and for the CON condition at 14 minutes. Finally, there was no significant improvement in neural activity for the VL, BF, TA or GM following either CA nor were any difference identified in the voluntary PAP response between stronger and weaker athletes. Consequently, it appears that a single set of 3 repetitions of HBD at 93% of 1RM can elicit a PAP response at an ICRI of 2-6 minutes. This may be advantageous since the optimal ICRI when using the BS as a voluntary PAP is reported to be 4-12 minutes in stronger, well-trained individuals

(Crewther et al., 2011; Kilduff et al., 2007, 2008; Seitz, de Villarreal, et al., 2014). These research findings suggest that HBD is an effective CA at eliciting PAP in the lower body for stronger and weaker athletes.

7.2.2 The effect of accommodating resistance on the PAP response

No voluntary PAP response was observed following moderately loaded HBD or BS combined with accommodating resistance. There were no significant improvements identified in any of the CMJ or EMG variables under examination at the selected ICRIIs in comparison to baseline measures. However, a fatigue response observed immediately (30 seconds) after the completion of the HBD exercise as GRF at PPO significantly decreased in comparison to baseline. Both CAs also demonstrated a significantly lower GRF at PPO at 30 seconds in comparison to the CON condition. Interestingly, the BS and HBD demonstrated significantly greater velocities at PPO and jump heights in comparison to the CON condition at 30 seconds; however, it is important to note that there was no significant differences in comparison to baseline. Significant improvements in CMJ performance and muscle activity were observed in CMJ performance and muscle activity when the ICRIIs were individualised. That is, the baseline jump in comparison to the ICRI at which each individual peaked (baseline vs. maximum potentiation response) for each variable. In addition, there were no significant differences in the voluntary PAP response between the HBD and BS when the ICRIIs were individualised (baseline vs. maximum potentiation response).

7.2.3 The effects of two complex training modalities on physical performance and muscle architecture characteristics in rugby league players over a 6-week mesocycle

The main findings of this study were that significant improvements in strength, power and 5-metre sprint performance were observed following the ARCT and TCT

interventions; however, only the TCT condition demonstrated significant improvements in 10-metre sprint times. There were also significant improvements in VL MT and VL L_f following both training interventions but not for VL P_{ang}, nor was there any significant changes in any muscle architecture variables for the GM. It is important to note that the TCT condition induced a change in VL L_f which was greater than the MDC reported in chapter 5 but the ARCT condition did not. Therefore, it is likely that a meaningful change occurred following the TCT condition whereas the change following the ARCT condition is likely to be negligible. An unexpected and novel finding of this study was that significant improvements were observed in RSI and K_{leg} following the ARCT condition but not the TCT condition. Finally, there were no differences between the ARCT and TCT interventions for any of the variables under examination.

7.3 Key Themes Established from the Thesis

7.3.1 Characteristics of the CA

Schmidtbleicher (1992) stated that near maximal concentric only contractions performed at high velocities induce the greatest neural adaptations. The results presented in chapter 3 of this thesis suggest that the HBD exercise is an effective stimulus for inducing the voluntary PAP response. This is likely to be due to the lifting technique of the exercise inducing a near maximal concentric only muscular contraction. The participants were able to lift a significantly greater load during the concentric phase in comparison to the BS, whilst minimising the eccentric work by dropping the bar at the top of the lift. The decrease in the amount of time spent under tension may have reduced the effects of neuromuscular fatigue therefore enabling PAP to manifest (Tran et al., 2006).

A suggested outcome from chapter 3 was to investigate the effect of exercises which induce large forces at high velocities on the voluntary PAP response. Previous research has investigated this using Olympic style lifts as a PAP stimulus (Andrews et al., 2011;

McCann & Flanagan, 2010; Seitz, Trajano, et al., 2014). However, Olympic style lifts are technically demanding and may be prohibitive in eliciting PAP in practical training settings. Therefore, the purpose of chapter 4 was to examine whether a single set of HBD or BS combined with accommodating resistance could elicit a PAP response at shorter ICRIIs. Although voluntary PAP responses were observed on an individual level, there was no PAP response identified on a group level. This could be explained by the characteristics of the chosen exercises.

There is currently no available evidence with respect to the optimal combined barbell and accommodating resistance loads when using this training modality to elicit PAP. Chapter 4 of this thesis utilised a barbell load of 70% of 1RM combined with an accommodating resistance load of 0-23% 1RM throughout the ROM. However, anecdotal evidence suggests that band tension of approximately 10% of 1RM at the bottom of the lift is essential in the storage and release of elastic energy from connective tissue (Simmons, 2007). The lack of any observed PAP response on a group level in chapter 4 could be due to the dissipation of stored elastic energy at the bottom of the lifts where the bands were slack and no additional resistance applied to the bar. This may have reduced the effects of any overspeed eccentric phase and the reuse of stored elastic energy during the concentric phase.

A potential method of ensuring that stored elastic energy is reused from band tension or an overspeed eccentric phase is box squats. Although no empirical evidence exists with respect to the biomechanical analysis of the box squat combined with accommodating resistance, anecdotal evidence (Simmons, 2007) provides a rationale for the enhanced use of stored elastic energy associated with this exercise. During the conventional BS, an individual typically performs the eccentric phase by lowering themselves to a certain depth where zero velocity is reached and at that point overcome the load (Stevenson et

al., 2010). However, during the box squat the movement is more continuous as an individual is moving when contact is made with the box. Therefore, it is possible to begin overcoming the load the instant where contact is made with the box, enabling a greater return of stored elastic energy. Although kinetic and kinematical analysis of this exercise is required to substantiate this, it is plausible that this may be an effective method of eliciting the voluntary PAP response.

Lastly, the participants were instructed to perform the eccentric phase of the HBD as quickly as possible in attempt to induce an overspeed eccentric phase. However, research has demonstrated that the performing the eccentric phase of an exercise in a more controlled manner when utilising accommodating may evoke greater type IIb muscle fibre recruitment as evidenced by increased EMG activity (Anderson et al., 2008; Cronin, McNair, & Marshall, 2003). It is conceivable that the eccentric phase of the HBD, whilst performed at a greater velocity, should have been executed in a more controlled manner as this may have elicited the voluntary PAP response. Collectively, there is limited research with respect to the optimal training prescription for inducing a PAP response when implementing accommodating resistance. As such, future research is required to provide strength and conditioning practitioners with comprehensive guidelines as to the optimal training variables when evoking PAP using accommodating resistance loads.

7.3.2 Individualised Nature of the Voluntary PAP Response

Chapter 4 of this thesis did not demonstrate a voluntary PAP response on a group level however, a key finding of this chapter was that PAP was expressed on an individual basis. This finding is in agreement with previous research (Bevan et al., 2010; Chiu et al., 2003; Comyns et al., 2006; Crewther et al., 2011; McCann & Flanagan, 2010) and could be explained by the strength level of the participants within this experimental chapter. In chapter 3 of this thesis, 18 participants could perform the HBD at a load $\geq 1.5 \times$ body

mass and 10 participants could perform the HBD at a load $\geq 2 \times$ body mass. However, in chapter 4 of this thesis 16 participants could perform the HBD at a load $\geq 1.5 \times$ body mass and only 4 participants could perform the HBD at a load $\geq 2 \times$ body mass. This may explain the observed voluntary PAP response observed on a group level in chapter 3 and lack of PAP expressed on a group level in chapter 4. The results from chapters 3 and 4 of this thesis appear to support previous research which suggests that the strength level of an individual is a factor which influences the voluntary PAP response (Jo et al., 2010; Kilduff et al., 2007, 2008; Ruben et al., 2010; Seitz, de Villarreal, et al., 2014; Seitz & Haff, 2015b; Wilson et al., 2013).

Stronger individuals have been reported to have a greater resistance to the fatigue induced by heavy load CAs (Chiu et al., 2003; Hamada et al., 2000; Jo et al., 2010; Seitz, de Villarreal, et al., 2014; Tillin & Bishop, 2009). This may affect the balance between PAP and fatigue, enabling PAP to predominate at an earlier ICRI. In contrast, weaker individuals require longer ICRI for PAP to predominate fatigue. The ICRI under examination in chapter 3 were 2-16 minutes. However, in chapter 4 the ICRI under investigation were 0.5-3 minutes. This may further explain the differences in the voluntary PAP response between the first two experimental chapters of this thesis.

Another possible reason for stronger individuals being able to express a greater magnitude of PAP is due to a greater percentage of type II muscle fibre distribution which may result in increased phosphorylation of myosin MLCs (Aagaard & Andersen, 1998; Maughan, Watson, & Weir, 1983; Moore & Stull, 1984). The phosphorylation of myosin RLCs renders the actin-myosin complex more sensitive to myoplasmic Ca^{2+} (Szczena et al., 2002; Hodgson et al., 2005; Tillin & Bishop, 2009). Therefore, myosin RLC phosphorylation exerts its greatest effect under conditions where Ca^{2+} concentrations are relatively low, as demonstrated during twitch or low frequency tetanic contractions

(Baudry et al., 2008; Hodgson et al., 2005; Sale, 2002; Tillin & Bishop, 2009). In contrast, phosphorylation of myosin RLC will have no effect under conditions where Ca^{2+} concentrations are high, as is the case during high frequency tetanic contractions (Abbate, Sargeant, Verdijk, & de Haan, 2000; Sale, 2002; Vandenberg, Grange, & Houston, 1993). The PAP response is likely to have no effect due to a saturated concentration of Ca^{2+} within the muscle cell rendering any increase in Ca^{2+} sensitivity inconsequential (Baudry & Duchateau, 2004; Ferreira, Panissa, Miarka, & Franchini, 2012; Sale, 2002). Few studies have examined the relationship between myoplasmic Ca^{2+} concentrations and the voluntary PAP response. Perhaps a direction for future research should be to investigate the effect of different CAs on Ca^{2+} concentrations within the muscle cell, although this would be problematic with respect to the methodological procedures associated with measuring myoplasmic Ca^{2+} concentration.

7.3.3 Possible Mechanisms of PAP

Although the underpinning mechanisms of PAP are not well understood at this time, it is thought that it could be due to increased phosphorylation of myosin RLCs heightening the sensitivity of actin and myosin to Ca^{2+} availability, increased excitability of α -motor neurons, and short-term decreases in muscle fibre P_{ang} (Docherty et al., 2004; Tillin & Bishop, 2009; Wilson et al., 2013). Chapters 3 and 4 of this thesis examined surface EMG during the CMJs to assess whether there was enhanced motor unit activation as a result of the voluntary PAP response. There was no increased EMG activity for any of the muscles under examination in either of the first two studies. Although there were increases in the EMG activity on an individual level in chapter 4, there was a low between-session reliability reported for this variable for each muscle. Therefore, the possibility of a type I error cannot be ruled out and it is likely that the observed response can be explained by the heteroscedasticity of the data and not as a result of the treatment.

Therefore, it is not possible to make any conclusions with respect to the contribution of the neural system to the voluntary PAP response based on the findings of the first two experimental chapters.

There are a number of limitations associated with surface EMG including the location and orientation of the electrodes, skin-electrode impedance, cross-talk and inter-electrode distance (Burden, 2008; De Luca, 1997). Although these factors were controlled for as best as possible, this is likely to explain the low between-session reliability of the EMG measurements. Several of these factors could have been eliminated by performing each experimental condition on a single testing day; however, given the nature of PAP research it would have been difficult to justify this due to the high levels of neuromuscular fatigue associated with maximal strength and plyometric training. Future research investigating the voluntary PAP response is likely to require more detailed methodologies which utilise motor cortical and motor nerve stimulation (Thomas et al., 2015) to elucidate the contribution of the neural system to this phenomenon.

An unexpected finding in chapter 4 of this thesis was the significantly greater velocity at PPO and jump height following the exercise conditions in comparison to the CON condition at 30 seconds. Additionally, the GRF at PPO following the exercise conditions was significantly less than the CON condition at 30 seconds. Larger muscle P_{ang} are associated with slower contraction velocities and greater force generating capabilities due to a greater amount of contractile tissue attaching to a given area of tendon or aponeurosis (Kawakami et al., 1995); however, smaller muscle P_{ang} are synonymous with greater shortening velocities and increased mechanical advantage in relation to force transmission from the muscle to the tendon due to a reduction in the angle of pull (Blazevich, 2006; Earp et al., 2010; Folland & Williams, 2007; Tillin & Bishop, 2009). This finding in chapter 4 could possibly be explained temporal alterations to muscle P_{ang} .

Initially, muscle P_{ang} may temporarily decrease, enabling greater velocities to be achieved during the CMJ however, during the PAP time course muscle P_{ang} may increase and enhance force production. Whilst speculative, there is a lack of research investigating the contribution of short-term changes in muscle P_{ang} to the voluntary PAP response. The more plausible explanation for the observed differences between the experimental and CON conditions is due to inter-trial variability as opposed to the effect of PAP. Nevertheless, future research specifically examining muscle P_{ang} as a PAP mechanism is warranted.

The most probable mechanism underpinning the voluntary PAP response is the phosphorylation of myosin RLCs (Baudry & Duchateau, 2007; Docherty et al., 2004; Hodgson et al., 2005). There is a large body of scientific evidence which has demonstrated improvements in force and power production during CMJ performance following a CA (Comyns et al., 2006; Crewther et al., 2011; Kilduff et al., 2008; Seitz, de Villarreal, et al., 2014). Phosphorylation of myosin RLCs is theorised to increase the number of cross-bridges, the rate of cross-bridge cycling and heighten the sensitivity of the actin-myosin complex to sarcoplasmic Ca^{2+} (Bevan et al., 2010; Docherty et al., 2004; Hodgson et al., 2005; Szczesna, 2002; 2003; Tillin & Bishop, 2009). This is likely to explain the enhanced force and power production observed during explosive activities such as CMJs, as evidenced in chapters 3 and 4 of this thesis. However, it is not possible to definitively state this since the phosphorylation of myosin RLCs was not directly assessed in previous research or in this thesis. The exact mechanism of the voluntary PAP response is likely to remain unknown at this stage due to technological and methodological constraints. Research should continue to investigate the mechanisms of PAP as stringently as possible with the available scientific procedures to achieve this.

7.3.4 Limitations of the CMJ as a Measure of PAP

Whilst improvements in PPO and force production were identified during the CMJs in chapter 3 of this thesis, there was no actual improvement in jump performance (i.e. jump height). Previous research has demonstrated that an increase in CMJ variables, such as PPO, peak GRF and peak velocity, does not necessarily equate to an increase in jump height (Kirby, McBride, Haines, & Dayne, 2011; McBride, Kirby, Haines, & Skinner, 2010; Salles, Baltzopoulos, & Rittweger, 2011). This could be explained by inter-subject differences in CMJ technique; for example, jump height has been reported to be influenced by squat depth and forward trunk lean during the countermovement (Gheller et al., 2015; Kirby et al., 2011; McBride et al., 2010). A greater countermovement depth induces an increased forward trunk lean, torque and power from hip musculature, impulse, muscular activation and decreased knee torque (Lees, Vanrenterghem, & De Clercq, 2004; Salles et al., 2011; van Zandwijk, Bobbert, Munneke, & Pas, 2000). It is possible that the PAP response may interfere with CMJ technique and consequently jump height (Gheller et al., 2015). However, PPO does not appear to be affected to the same extent by jump technique (Salles et al., 2011) therefore it is conceivable that the enhanced power production capabilities of the muscles in a potentiated state needs to be applied correctly to explosive actions for improved performance. Although not a mechanism of PAP, perhaps an individual's quality of movement may influence the magnitude of PAP elicited and the subsequent ability to appropriately apply the increased force produced during explosive actions. Consequently, the relationship between movement quality and the voluntary PAP response is an area which requires future investigation.

The results presented in chapter 3 of this thesis also demonstrated fatigue responses at ICRI of 16 and 14 minutes for PPO and velocity at PPO, respectively, during the CON trial. The decline in CMJ variables was largely evident following ICRI of 6-8 minutes.

Whilst fatigue may have been a factor for the decrease observed in the variables under examination, it is also possible that the research design contributed towards this. The motivation of the participants to perform a maximal CMJ once every 2 minutes for 16 minutes may have decreased and subsequently had a negative impact upon the overall performance. Although there were no significant decreases in the selected CMJ variables following either the HBD or BS conditions, the decline in the outcome variables during the selected ICRI was also evident after 6-8 minutes. It is possible that the induced PAP response counteracted any significant decrement in CMJ performance as a result of either fatigue or motivation; this may also explain the lack of PAP observed at later ICRI. Regardless of the factors affecting any performance decrement, it is advisable for future acute PAP research to examine CMJs at one or two selected recovery intervals.

7.3.5 Practical Application of PAP

The limited scientific evidence investigating the chronic effects of complex training has demonstrated this training modality to be either just as, or more, effective than resistance or plyometric training alone (Dodd & Alvar, 2007; MacDonald et al., 2012, 2013). Chapter 6 of this thesis aimed to implement PAP by designing two 6-week evidenced based complex training programmes. Although chapter 4 of this thesis established the highly individualised nature of the voluntary PAP response, it was not possible to identify the optimal complex training variables for each participant due to time constraints. In real-world training scenarios, especially in team sports such as rugby league, there is limited time for strength and conditioning coaches to work with their athletes due to multiple training modes and congested fixture schedules throughout the season (Baker, 2001a; Gamble, 2006; Kelly & Coutts, 2007; McLellan et al., 2011; Moreira et al., 2015). The practical implementation of individualised complex training variables is therefore problematic for strength and conditioning practitioners, particularly in team sports where

there are large groups of athletes. Under such circumstances it is advisable for strength and conditioning coaches to implement ICRIIs based on scientific evidence. Individualisation of the ICRI is more likely to be applicable to individual sports where strength and conditioning coaches have smaller groups of athletes to work with and consequently more time to identify optimal ICRIIs for each athlete.

Complex training is portrayed as a time efficient training modality due to both extremes of the force-velocity curve being trained in a single session (Comyns et al., 2010; Ebben, 2002; Ebben & Watts, 1998; Robbins et al., 2009). This appears to be contradictory since an appropriate ICRI is required for PAP to be realised. A possible solution is to perform an exercise which targets different muscle groups from the CA during the ICRI (Table 7.1). For example, a lower body CA followed by an upper body exercise before the completion of the lower body plyometric activity. The optimal ICRI required to elicit a voluntary PAP response in the upper body is reported to be 3-16 minutes (Seitz & Haff, 2015a) which is similar to that of the lower body. This may be an opportunity to alternate between upper and lower body exercises to elicit a PAP response in both extremities therefore maximising training efficiency. Alternatively, a sport specific activity could be performed between the CA and plyometric action. Theoretically, the upper body exercise or the sport specific activity would cause minimal interference with respect to the balance between PAP and fatigue induced by the lower body CA, and vice versa, due to the activation of different muscle groups. Future research is required to examine such training strategies since the alternation between upper and lower body exercises would reduce local muscle fatigue, but a greater amount of central fatigue may be elicited which could inhibit explosive performance during the plyometric exercises.

Table 7.1 An example of two possible strategies for implementing a set of complex training during a combined strength and plyometric session.

Strategy 1	Strategy 2
1a. Hex-bar deadlift	1a. Hex-bar deadlift
1b. Bench press	1b. Sport specific activity (e.g. hand eye coordination/reaction drill)
1c. Box jumps	
1d. Explosive push-ups	1c. Box jumps

The results from chapter 6 of this thesis demonstrated that two lower body complex training sessions per week was effective in improving physical performance parameters of strength, power and speed. However, it is unlikely that athletes will complete two lower body maximum strength and plyometric sessions per week in real world training scenarios given the importance of upper body strength and power for successful performance and the multiple training modalities implemented to prepare athletes for competition (Baker & Newton, 2006, 2008; McLellan et al., 2011; Moreira et al., 2015). Training programmes may benefit from the inclusion of upper and lower body exercises in a single session.

To further reduce the issues associated with the ICRI, strength and conditioning practitioners could potentially adopt a non-linear or undulating periodisation approach to implementing complex training whereby fluctuations in training variables occur on a daily or weekly basis (Grgic, Mikulic, Podnar, & Pedisic, 2017). As opposed to only performing complex pairs throughout a mesocycle to develop maximum strength and power, as prescribed in chapter 6, additional training variables could be addressed with a predominant training emphasis on strength and power. If there are only one or two complex pairs within a training session then athletes will spend less time waiting for PAP to be realised at a specific ICRI and taken advantage of during a given plyometric activity.

As presented in Table 7.2, a possible weekly training plan could involve upper and lower body complexes where the ICRI is used as an opportunity to develop strength in different muscle groups or to improve a sport specific skill. Additionally, the undulating periodisation approach enables other training variables such as, hypertrophy and muscular endurance, to be targeted. This is just one example of multiple ways in which strength and conditioning coaches could programme the implementation of PAP with the aim of enhancing time efficiency of the training session.

Whilst the ICRI is a limitation for the practical implementation of PAP, another key consideration is the strength level of the athlete, as evidenced by chapters 3 and 4 of this thesis. The utilisation of complex training is most likely to be appropriate following the completion of anatomical adaptation, hypertrophy and strength development phases during general and specific preparation stages of the season. Theoretically, an increased strength level should enhance the ability of an individual to express the voluntary PAP response and take advantage of it during training scenarios. Therefore, complex training may be most effective during pre-competitive and competitive stages of the season where the development and maintenance of strength and power is paramount.

Collectively, scientific evidence appears to demonstrate that the voluntary PAP response can be elicited following the completion of a CA (Comyns et al., 2006; Crewther et al., 2011; Kilduff et al., 2008; Seitz, de Villarreal, et al., 2014). However, the practical application of PAP remains limited by a number of training variables, most notably the ICRI and the strength level of an individual. Future research, therefore, should investigate the effectiveness and efficiency of different programming strategies when implementing PAP. The effect of such training programmes on the acute voluntary PAP response would also be of interest.

Table 7.2 An example of PAP implementation using specialised CAs within an upper and lower body workout where an undulated periodisation approach is utilised.

	Purpose	Exercise	Sets x Reps	Intensity
Day 1	Strength/Power (Complex)	1a. Hex-bar deadlift	3-5 x 3	70 + 23% 1RM
		1b. Bent over row	3-5 x 3	70 + 23% 1RM
		1c. Box jumps	3-5 x 5	BW
		1d. Explosive seated sled drag	3-5 x 10-m	10 kg
	Hypertrophy	2. Glute bridge	3-6 x 6-12	67-85% 1RM
	Muscular Endurance	3. Chin-ups	2-3 x 12-15	BW
Day 2	Strength/Power (Complex)	1a. Bench press	3-5 x 3	70 + 23% 1RM
		1b. Romanian Deadlift	3-5 x 3	70 + 23% 1RM
		1c. Medicine ball power drop	3-5 x 5	5-10 kg
		1d. Pike jumps	3-5 x 5	BW
	Hypertrophy	2. Military Press	3-6 x 6-12	67-85% 1RM
	Muscular Endurance	3. DB box step ups	2-3 x 12-15	65% 1RM
Day 3	Strength/Power (Complex)	1a. Power cleans	3-5 x 3	90% 1RM
		1b. Rebound net catch	3-5 x 10 e/s	N/A
		1c. Drop jumps to reverse overhead medicine ball throw	3-5 x 5	BW / 5-10 kg
	Power (Superset)	2a. Loaded squat jumps	3-5 x 3-5	40 kg
		2b. Explosive jammer press	3-5 x 3-5	75-85% 1RM
	Hypertrophy	3. Single arm DB row	3-6 x 6-12	67-85% 1RM
	Muscular Endurance	4. Barbell lunges	2-3 x 12-15	65% 1RM

DB = Dumbbell; RM = repetition maximum; BW = body weight; e/s = each side; 10-m = 10 metres

7.4 Conclusions

The present thesis has provided novel information with regard to the influence of exercise selection on the voluntary PAP response, the individualised nature of the voluntary PAP response and the importance of designing appropriate complex training programmes. The use of the HBD as a PAP stimulus appears to be advantageous since it is a less technically demanding and safer exercise which enables a greater absolute load to be lifted. Consequently, a greater magnitude of PAP is may be realised at earlier ICRI of 2-6 minutes in comparison to more traditional CAs, such as the BS, which require longer ICRI of 4-12 minutes. Whilst there is evidence to suggest that the combination of moderately loaded CAs and accommodating resistance may evoke a PAP response as early as 90 seconds post-CA, a high level of inter-individual variability was demonstrated within the response. Therefore, strength and conditioning practitioners are advised to determine optimal complex training variables for their athletes before designing training programmes. However, this is likely to be most appropriate in individual sports or sports where strength and conditioning coaches work with a small group of athletes.

The practical implementation of PAP is therefore problematic, especially in team sports. Given the limited time available for strength training in such environments, strength and conditioning practitioners are challenged to design training programmes which can take advantage of the voluntary PAP response in a time efficient and effective manner. It is unlikely that individualised complex training programmes can be devised for each athlete; however, it is possible to design training programmes in such a way that the ICRI is used as an opportunity to develop strength in different muscle groups or to improve sport specific skill. Additionally, a non-linear or undulated periodisation approach may enhance the practical implementation of PAP by reducing the number of complex pairs in a given session and enable other training variables to be addressed. In conclusion, it

appears that there is a strong body of scientific evidence which supports the existence of the voluntary PAP response, but the way in which it is implemented is of the utmost importance. Consequently, future research is required to investigate time efficient complex training programmes and their effectiveness on performance.

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APPENDICES

Appendix A: Literature Matrix of PAP and Complex Training Studies

Acute PAP Studies – Lower Body

Authors	Subjects	Protocol	Measures	Results
Andrews et al. (2011)	19 female collegiate athletes	3 x 4 CMJs vs. 3 x 3 back squat at 75% 1RM vs. 3 x 3 hang cleans at 60% 1RM (3 minutes between sets).	CMJ height from video analysis after each set.	Non-significant differences in CMJ performance. Significantly less decline (0.3cm) in CMJ height across set following hang cleans.
Baker (2001)	6 professional rugby league players	2 x 6 40kg jump squat vs. The same session, but with 1 x 3 60kg jump squat between the two lighter sets.	Jump squat (average power output during concentric phase).	Significantly greater peak power output post heavy jump squat compared to all other occasions.
Baker (2008)	10 professional rugby league players	4 x 2 80kg jump squats alternated with 4 x 2 paused box squats (68% 1RM + 6-19.6% from elastic resistance). 3 minutes per complex cycle.	80kg jump squat (peak power output).	Significant increase in peak power output in sets 2, 3 and 4 compared to set 1. Significant increase in average peak power output in sets 2, 3 and 4 compared to set 1.
Bevan et al. (2010)	16 professional rugby union players	3 back squats at 91% 1RM.	5- and 10-metre sprint at 4, 8, 12 and 16 minutes post.	Significant improvement in 5- and 10-metre sprint times when recovery intervals were individualised.

Chui et al. (2003)	24 (12 male/12 female; 7 athletes/17 recreationally trained)	5 x 1 back squat at 90% 1RM (2 minutes between sets).	Rebound jump squat and concentric only jump squat (peak power output and average power output) performed at 30, 50, and 70% 1RM back squat (5 and 18.5 minutes post intervention).	No effect on group as a whole, except rebound jump squat average power output at 30% load. Significant increase in percentage of potentiation peak power output in athletes for concentric only jump squats at all loads and average power output at 30%. Significant increase in peak power output, average power output, and average force for rebound jump squat at 30%, 18.5 minutes post.
Clark et al. (2006)	9 strength trained males	6 x 6 20kg loaded counter movement jump (3 minutes recovery). 2 nd set replaced with 40kg in experimental condition.	Loaded CMJ (height and average and peak power output during final 50ms prior to take off).	Significantly greater jump height for experimental condition after 3rd set post in comparison to control condition. Significantly greater peak power output for experimental condition after 3rd and 4th sets post in comparison to control condition.
Comyns et al. (2006)	18 subjects (9 male/9 female) sprinters, jumpers and rugby players)	5RM back squat.	Sledge countermovement jump (flight time and peak GRF) performed before, 30 seconds, 2, 4, and 6 minutes post.	Significant decrease in flight time 30 seconds and 6 minutes post. Only men showed an increase at 4 minutes but results were not significant.

Comyns et al. (2007)	12 professional rugby players	3 back squats at 65%, 80%, and 93% 1RM performed on separate occasions.	Sledge drop jumps (flight time, leg stiffness, contact time, and reactive strength index) performed before and 4 minutes post.	Significant decrease in contact time at 93% 1RM. Significant increase in leg stiffness at 93% 1RM. Significant decrease in flight time in all conditions.
Crewther et al. (2011)	9 sub elite male rugby players	3RM back squat.	CMJ (height), 100kg horizontal sledge push, 5/10 metre sprint; 15 seconds, 4, 8, 12, 16 minutes post.	Significant decrease in CMJ height at 15 seconds. Significant increase in CMJ height at 4, 8, and 12 minutes. Significant improvement in 5- and 10-metre sprint time when recovery intervals individualised.
Crum et al. (2012)	20 males (could quarter squat at least 2.4 x body mass)	3 x quarter squats at 50% 1RM vs. 3 x quarter squats at 65% 1RM.	CMJ (height, peak power, mean power, peak force, peak rate of force development, peak velocity) at 0.5, 3, 5, 10 and 15 minutes.	No significant improvement in any of the CMJ variables measured.
De Villareal et al. (2007)	12 trained male	1) 3 sets of 5 optimal loaded CMJs (load which maximises	CMJ height, drop jump height and loaded CMJ height (load which maximises peak power	Significant improvement in CMJ height for conditions 2, 3 and 5 at 5 minutes post.

	volleyball players	peak power output) vs. 2) 2 sets of 4 half squats at 80% 1RM; 2 sets of 3 half squat at 85% 1RM vs. 3) 2 sets of 4 half squats at 80% 1RM; 2 sets of 2 half squat at 90% 1RM; 2 sets of 1 half squat at 95% 1RM vs. 4) 3 sets of 5 drop jumps from optimal height vs. 5) Specific warm-up for volley ball match vs. 6) 3 sets of 5 half squats at 30% 1RM vs. 7) Control.	output) at 5 minutes and 6 hours post.	Significant improvement in DJ height for conditions 1, 2 and three at 5 minutes and 6 hours post; significant improvement for condition 5 at 5 minutes post. Significant improvement in loaded CMJ height for conditions 1, 2, 3, and 5 at 5 minutes post; significant improvement for condition 1 at 6 hours post.
Dinsdale & Bissas (2010)	12 University athletes	3 x hang clean at 90% 1RM vs. control.	CMJ (height), 0-6 minutes (T0-6) post intervention (separate test occasions).	CMJ height significantly decreased in tests T0, T2, and T3.
Duthie et al. (2002)	11 strength trained women	3 test sessions; 3 x 4 jump squat followed by 3 x 3RM half squats vs. 3 x 3RM half squats followed by 3 x 4	Jump squat at 30% of half squat 1RM (height, peak power output, and peak GRF).	Non-significant difference in jump squat variables between each training method.

		jump squats vs. alternation on the latter, set by set.		
Esformes et al. (2010)	13 athletes	1 x 3RM back squat vs. 24 contacts of plyometrics vs. no activity (5 minutes rest). 10 minutes between complexes and repeat 3 times.	CMJ (height).	CMJ height significantly greater following sets 1 and 3 of squats compared to set 1 of plyometrics and set 1 of squats compared to set 3 of control.
Esformes & Bampouras (2013)	27 semi-professional male rugby union players	3RM parallel squats vs. 3RM quarter squat.	CMJ (height, impulse, peak power, flight time) at 5 minutes post.	Both conditions significantly improved all measured CMJ variables. Parallel squat condition significantly greater improvements in all measured CMJ variables in comparison to quarter squat condition.
Fukutani et al. (2014)	8 university Olympic lifters	Heavy condition of 4 sets of back squats (5 reps at 45% and 60% 1RM; 3 reps at 75% and 90% 1RM) vs. moderate condition of 3 sets of back squats (5 reps at 45% and 60% 1RM; 3 reps at 75%). 2 minutes between each set.	CMJ height and peak twitch torque; twitch 30 seconds post and CMJ 90 seconds post. M-wave amplitude of rectus femoris and vastus lateralis during CMJ. EMG analysis of rectus femoris, vastus lateralis	Significant increase in CMJ height and peak twitch torque. Heavy condition significantly greater CMJ height and peak twitch torque in comparison to moderate condition.

			biceps femoris and gluteus maximus during CMJ.	
			Joint angles of ankle, knee and hip during CMJ.	
Gilbert & Lees (2005)	15 male athletes	5 x back squat at 1RM vs. 5 x back squat at peak power (5 minutes between reps for both) vs. control.	Isometric MVC (rate of force development) and CMJ height at 2, 10, 15, 20 and 60 minutes post.	In 1RM condition, CMJ significantly increased at 15 and 20 minutes (peaking at 20 minutes). A significant decrease was observed at 2 and 10 minutes. In peak power condition there was a significant increase at 2 minutes.
Gourgoulis et al. (2003)	20 active males	5 x 2 half squats at 20, 40, 60, 80, and 90% 1RM; 5 minutes between sets.	2 CMJs pre and post squats. CMJs post squats performed immediately.	2.39% significant improvement in jump height (not power). Greater improvement in-group of stronger subjects (4.01 vs. 0.42%).
Jensen & Ebben (2003)	21 NCAA div 1 athletes (11 males, 10 females)	5RM back squat.	Countermovement jump (height and GRF) performed pre, 10 sec, 1, 2, 3, and 4 minutes post.	Reduced performance at 10 sec (significant in females). Progressive increase thereafter.
Jones & Lees (2003)	8 males experienced in strength training	5 back squats at 85% 1RM vs. No exercise control.	Kinematic, kinetic, and EMG analysis of countermovement jump and	Non-significant differences in jump performance or EMG regardless of time point and condition.

			drop jump at pre, 3, 10, and 20 minutes post squats.	
Kilduff et al., (2008)	23 professional rugby league players	3RM back squat.	CMJ (peak power output). Performed before, 15 seconds, 4, 8, 12, 16, and 20 minutes post.	Significant decrease at 15 seconds. Significant increase at 8 and 12 minutes post squat. Significant correlation between 3RM strength and amount of potentiation post 12 minutes.
Kilduff et al. (2008)	20 professional rugby players	3 x 3 back squat at 87% 1RM.	CMJ (peak power output, peak RFD and height) performed before and 15 seconds, 4, 8, 12, 16, 20, and 24 minutes post.	Significant increase post 8 minutes in all measures. Significant decrease post 15 seconds. Significant correlation between 3RM strength and amount of potentiation post 8 minutes.
Mangus et al., (2006)	11 male weight lifters	One half squat at 90% 1RM vs. One quarter squat at 90% 1RM.	CMJ (height) performed 3 minutes post.	No significant differences between 2 experimental and control conditions.
McBride et al. (2005)	15 NCAA division 3 football players	3 x back squats at 90% 1RM vs. 3 x loaded CMJs at 30% 1RM.	40-metre sprint at 4 minutes post.	Significant improvement in 40-metre sprint time for back squat condition but not loaded CMJ condition.

McCann & Flanagan (2010)	16 NCAA div 1 volleyball players (8 male/8 female)	5RM back squat vs. 5RM hang clean.	CMJ (height, peak force, impulse) with 4 or 5 minute recovery.	Non-significant between exercises. Significant increase CMJ height after 4 minutes following both conditions. Significant increase in CMJ height and peak force when recovery intervals individualised.
Mitchell & Sale (2011)	11 male university rugby union players	5RM back squat.	CMJ jump height and peak twitch torque of knee extensors 4 minutes post.	Significant improvement in CMJ jump height and peak twitch torque.
Moir et al. (2011)	11 female NCAA div 2 volleyball players	3 x back squats at 90% 1RM vs. 12 x back squats at 37% 1RM.	CMJ (height and vertical stiffness). 3 CMJs pre and 10 CMJs post intervention (2 minutes recovery).	Non-significant increase in CMJ height, but higher load condition resulted in significantly greater increase in vertical stiffness.
Naclerio et al. (2015)	11 sport science students (7 male/4 female)	1 x back squat at 80% 1RM vs. 1 set of 3 back squats at 80% 1RM vs. 3 sets of 3 back squats at 80% 1RM.	CMJ performed at 15 seconds and 1, 2, 3, 5, 8 and 12 minutes post.	No significant improvement. Significant improvements for all conditions when recovery intervals individualised. Low volume condition significantly less than high volume and moderate volume at 3 and 5 minutes, respectively. Higher effect sizes between 1 and 8 minutes for moderate and high volume conditions.

Radcliffe & Radcliffe (1996)	35 NCAA div 1 athletes (24 male/11 female)	4 x 4 back squat at 75-85% 4RM vs. 4 x 4 power snatch at 75-85% 4RM vs. 4 x 4 loaded jumps at 15-20% body weight vs. 4 x 4 tuck jumps vs. standard warm-up (control).	Standing long jump distance.	In male subjects there was significantly greater standing long jump performance following snatch condition compared to control.
Scott & Doherty (2004)	19 males	4 separate sessions of 5RM back squat.	Pre and post countermovement jumps and standing long jump tests (5 minutes recovery).	Non-significant main effects on jump height and distance.
Seitz, de Villareal & Haff (2014)	18 junior elite rugby league players	3 x back squats at 90% 1RM.	Squat jumps performed 15 seconds and 3, 6, 9, and 12 minutes post.	Significant decrease in absolute and relative peak power output, and squat jump height at 15 seconds. Significant increase in in absolute and relative peak power output, and squat jump height at 3, 6, 9, and 12 minutes for players who could squat > 2 x body mass. Significant increase in in absolute and relative peak power output, and squat jump height at 6 and 9 minutes for players who could squat < 2 x body mass. Stronger individuals had significantly greater absolute and relative peak power output, and

				squat jump height at 3, 6 and 9 minutes in comparison to weaker individuals.
Seitz, Trajano & Haff (2014)	13 junior elite rugby league players	3 x back squats at 90% 1RM vs. 3 x power cleans at 90% 1RM.	20-metre sprint at 7 minutes post.	Significant improvement in sprint time, velocity and average acceleration for both conditions. Power clean condition significantly greater improvements in comparison to back squat condition.
Smilios et al., (2005)	10 male regional sports players	4 test sessions involving; 3x5 loaded half squats or jump squats at 30% and 60% 1RM (3 minutes recovery).	Squat jump and countermovement jump height pre, 1 minute after each set and 5 and 10 minutes post session.	Significant increase in squat jump height with half squats at 60% 1RM after 1st set. Significant increase in countermovement jump with jump squats at 60% 1RM after sets 2 and 3. Significant increase in countermovement jump with jump squats at 30% 1RM after sets 1 and 2. Significant increase in countermovement jump with half squats at 60% 1RM after set 1.
Stone et al. (2008)	7 elite weight lifters (4 male/ 3 female)	Mid-thigh clean pull at 60, 80,100,120, 80kg for women and 60, 140, 180, 220, 180kg	Mid-thigh clean pull (peak GRF, RFD, peak power output, and peak velocity).	Trend for better performance in set 5 vs. Set 2.

		for men. (5 reps at each load, with 2 minutes between sets).		Significant increase in peak velocity set 5 vs. Set 2.
Till & Cooke (2009)	12 academy soccer players	5RM conventional deadlift vs. 5 x tuck jumps vs. 3 x isometric MVCs (3 seconds each).	20-metre sprint at 4, 5 and 6 minutes post. CMJ at 7, 8, and 9 minutes post.	No significant improvements in any of the measured variables. No significant differences between stronger and weaker athletes. Individualised responses improved up to 8.2% but decreased up to 7.1%.
Turner et al. (2015)	23 males	3 sets of 10 alternate leg bounds vs. weighted (10% of body mass) vs. control.	20-metre sprint 15 seconds and 2, 4, 8, 12 and 16 minutes post.	Significantly improved 10- and 20-metre sprint performance at 4 and 8 minutes for the weighted plyometric condition. Significantly improved 10-metre sprint performance at 4 minutes for the plyometric condition. Weighted plyometric condition improved significantly more in comparison to plyometric condition.
Walker et al. (2010)	10 recreationally strength trained men	3 x 80% 1RM back squat followed by 3 squat jumps (3 minutes recovery). This was repeated for 4 sets.	3 squat jumps (height) 3 minutes post.	Significant increase in set 2, after training only.

Weber et al. (2008)	12 male NCAA div 1 athletes	5 back squats at 85% 1RM vs. 5 squat jumps.	7 squat jumps (height and peak GRF) pre and 3 minutes post.	Significant increases in squat jump peak GRF, mean and peak jump height post squats. Significant decrease in mean and peak squat jump height following squat jump protocol.
Wyland et al. (2015)	20 recreationally trained university students	5 sets of 3 x back squats at 85% 1RM vs. 5 sets of 3 back squats at 55 + 30% from elastic resistance.	9.1-metre sprint immediately and 1, 2, 3 and 4 minutes post.	Significant improvement in sprint time 4 minutes following the banded condition.
Yetter et al. (2008)	10 strength trained males	5 x 30% 1RM, 4 x 50% 1RM and 3 x 70% 1RM of back squats vs. front squats.	3 x 40-metre sprint at 4 minutes post (3 minutes rest between trials).	Significant greater speeds in 10- to 20-metre interval for back squat condition in comparison to the control condition. Significant greater speeds in 30- to 40-metre interval for back squat condition in comparison to the front squat and control conditions.
Young et al., (1998)	10 males	2x5 loaded countermovement jumps, 5RM back squat and 1x5 loaded countermovement jumps (4mins between all sets).	Loaded countermovement jump height.	2.8% significant increase in final loaded countermovement set. Significant correlation between performance enhancement and 5RM load.

Acute PAP Studies – Upper Body

Authors	Subjects	Protocol	Measures	Results
Baker (2003)	16 rugby league players divided into experimental and control groups	Control session; 2 x 5 bench press throw with 50kg load (3 minute rest). Experimental group performed 6 repetitions at 65% 1RM bench press between bench press throw sets.	Bench press throw (peak power output) using 50kg load.	4.5% increase in peak power output post intervention. Significantly different to other 3 testing conditions.
Baker (2009)	7 professional rugby league players	4x 3 60kg bench press throws alternated with 4 x 3 bench press (65.5% 1RM + 12.2% 1RM from chains). 3 minutes per complex cycle.	60kg bench press throw (peak and average power output).	Significant increase in peak power output in last 3 sets compared to set 1. Significant increase in average power output for set 4 in comparison to set 1.
Baker (2012)	11 professional rugby league players	2 sets of 3 x 60kg concentric only bench press throw alternated with 3 x paused narrow grip bench press at 68% 1RM for normal grip.	60kg bench press throw (peak power output)	Significant increase in peak power output in set 2 in comparison to set 1.
Bevan et al. (2009)	26 professional rugby players	3 x 3 bench press at 87% 1RM.	Bench press throw at 40% 1RM (height and peak power output). 15 seconds,	Significant decrease in peak power output and throw height at 15 seconds.

			4, 8, 12, 16, 20, and 24 minutes.	Significant increase in peak power output and throw height at 8 minutes post.
Brandenburg (2005)	8 male recreational weight trainers	5 reps bench press at 100, 75, and 50% 1RM.	Bench press throw (peak power output) at 45% 1RM.	No significant difference in any of the 4 conditions.
Ebben et al. (2000)	10 male NCAA div 1 basketball players	1 x 3-5RM bench press vs. no prior exercise control.	Force and EMG during a set of 5 medicine ball power drops (5 minutes post bench press).	No significant difference in peak ground reaction force, mean ground reaction force and pectoralis major and triceps EMG.
Esformes et al. (2010)	10 competitive rugby league players	7 second isometric bench press vs. 3RM concentric bench press vs. 3RM eccentric bench press vs. eccentric-concentric bench press.	Bench press throw at 40% 1RM bench press (peak power output). 10 minutes pre and 12 minutes post intervention.	Significant increase in peak power output following isometric condition only.
Evans et al. (2000)	10 college aged males	1 x 5 RM bench press.	2-handed seated medicine ball put pre and 4 minutes post bench press.	Significant increase of 31.4 cm. Strong correlation between improvement and 5RM bench press.
Farup & Sorenson (2010)	8 strength trained males	5 x 1RM bench press (5 minutes between reps).	Isometric MVC bench press throw (30% 1RM) peak power output.	No significant differences in bench press throe peak power output. Significant decrease in RFD post 3, 10, and 20 minutes of the intervention.

Hysomallis & Kidgell (2001)	12 male recreational weight trainers	1 x 5RM bench press vs. No exercise control.	Explosive push up on force platform (3 minutes after bench press).	No significant difference in any force parameter.
Kilduff et al. (2007)	23 professional rugby players	3RM bench press.	Peak power output from 1 bench press throw performed before, 15 seconds, 4, 8, 12, 16, and 20 minutes post.	Significant decrease at 15 seconds post bench press. Significant increase at 8, 12, and 16 minutes post bench press. Significant correlation between 3RM strength and amount of potentiation post 12 minutes.
Markovic et al. (2008)	23 physically active men	1 x 6 reps at 60% 1RM, plus 2 x 3RM bench press (3 minutes between sets). Randomised control group design.	Seated medicine ball throwing velocity with 0.55 and 4kg loads.	Significant increase in medicine ball throw in experimental group.
Matthews et al. (2009)	12 competitive male athletes	5 x bench press at 85% 1RM vs. 2.3kg medicine ball push pass.	Basketball push pass (flight time).	Significant decrease following bench press condition.

Chronic Complex Training Studies

Authors	Subjects	Protocol	Measures	Results
MacDonald et al. (2012)	30 recreationally trained males	2 x 3 week mesocycles of complex training vs. resistance training vs. plyometric training. 2 training sessions per week.	1RM back squat, Romanian deadlift and standing calf raise strength. Quadriceps girth, triceps surae girth, body fat percentage. Pre-, mid- and post-testing.	Significant increase in all strength measures from pre- to mid- and post-testing. Post-testing significantly greater than mid-testing. No difference between groups.
MacDonald et al. (2013)	34 recreationally trained males	2 x 3 week mesocycles of complex training vs. resistance training vs. plyometric training. 2 training sessions per week.	CMJ (height, peak ground reaction force, peak power, relative peak power). Broad jump (distance, peak ground reaction force).	No significant difference between groups at any time point. Significant improvement in CMJ peak ground reaction force from pre- to mid-testing for complex training and plyometric training. Significant improvement in CMJ relative peak power from mid- to post-testing for plyometric training. Significant improvement in broad jump distance from pre- to post-testing for plyometric training.

Alves et al. (2010)	23 elite Portuguese Championship soccer players	6 week complex training mesocycle: 1 session per week vs. 2 sessions per week vs. control.	5- and 15-metre sprint, squat jump height, CMJ height, 505 agility test.	Significant improvement in 5- and 15-metre sprint times for both training groups. Significant increase in squat jump height for both training groups.
Walker et al. (2010)	10 recreationally strength trained men	11 week complex training protocol consisting of 2 sessions per week.	3 x 80% 1RM back squats (peak power) followed by 3 squat jumps (height and EMG of vastus lateralis). This was repeated for 4 sets (3 minutes recovery). Isometric force during bilateral leg extension and EMG of vastus lateralis. Blood testosterone, cortisol, lactate and growth hormone.	Significant improvement in squat jump height, 80% 1RM squat load, peak power during 80% 1RM squat, maximal isometric leg extension force and rate of force development.
Stasinaki et al. (2015)	25 male students	6 week complex training programmes vs. compound training vs. control. Training programmes consisted of 3 sessions per week.	Backward overhead throw, CMJ height, 1RM leg press, bench press and Smith machine box squat. Muscle thickness, pennation angle and fascicle length of the vastus lateralis and gastrocnemius muscles.	Significant increase in backward overhead throw and CMJ height following compound training. Significant increase in 1RM leg press, bench press and Smith machine box squat both training groups. Significant increase in vastus lateralis muscle thickness, pennation angle, and

Vastus lateralis muscle fibre distribution and muscle fibre type cross-sectional area.

gastrocnemius pennation angle for both training groups.

Significant decrease in gastrocnemius fascicle length after complex training.

Significant increase in muscle fibre cross-sectional area following complex training.

No significant changes in fibre type distribution.

Appendix B: Participant Information and Informed Consent Form (Study1)

Department of Sport, Health & Exercise Science	 UNIVERSITY OF Hull Faculty of Science
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Informed Consent Declaration

Project title	The effect of exercise selection and training status on post-activation potentiation in rugby league players.
Principal investigator	Name: Max Ditroilo; Phil Marshall Email address: m.ditroilo@hull.ac.uk; phil.marshall@hull.ac.uk Contact telephone number: 01482 463859; 01482 463030
Student investigator (if applicable)	Name: David Scott Email address: david.scott@hull.ac.uk Contact telephone number: 07519050992; 01482 466314

Please Initial

- ☐ I confirm that I have read and understood all the information provided in the Informed Consent Form (EC2) relating to the above project and I have had the opportunity to ask questions.
- ☐ I understand this project is designed to further scientific knowledge and that all procedures have been risk assessed and approved by the Department of Sport, Health and Exercise Science Research Ethics Committee at the University of Hull. Any questions I have about my participation in this project have been answered to my satisfaction.
- ☐ I fully understand my participation is voluntary and that I am free to withdraw from this project at any time and at any stage, without giving any reason. I have read and fully understand this consent form.

.....		
Name of participant	Date	Signature
.....		
Person taking consent	Date	Signature

Appendix C: Participant Information and Informed Consent Form (Study 2)

Department of Sport, Health & Exercise Science



Informed Consent Declaration

Project title	The effect of accommodating resistance on the post-activation potentiation response in rugby league players.
Principal investigator	Name: Max Ditroilo; Phil Marshall Email address: massimiliano.ditroilo@ucd.ie; phil.marshall@hull.ac.uk Contact telephone number: 01482 463859; 01482 463030
Student investigator (if applicable)	Name: David Scott Email address: david.scott@hull.ac.uk Contact telephone number: 07519050992; 01482 466314

Please Initial

☐

I confirm that I have read and understood all the information provided in the Informed Consent Form (EC2) relating to the above project and I have had the opportunity to ask questions.

☐

I understand this project is designed to further scientific knowledge and that all procedures have been risk assessed and approved by the Department of Sport, Health and Exercise Science Research Ethics Committee at the University of Hull.

☐

Any questions I have about my participation in this project have been answered to my satisfaction.

☐

I fully understand my participation is voluntary and that I am free to withdraw from this project at any time and at any stage, without giving any reason. I have read and fully understand this consent form.

.....

Name of participant

.....

Date

.....

Signature

.....

Person taking consent

.....

Date

.....

Signature

Appendix D: Participant Information and Informed Consent Form (Study 3)

Department of Sport, Health & Exercise Science



Informed Consent Declaration

Project title	Within- and between-session reliability of ultrasound imaging measures in vastus lateralis and gastrocnemius medialis muscles.
Principal investigator	Name: Max Ditroilo; Phil Marshall Email address: massimiliano.ditroilo@ucd.ie; phil.marshall@hull.ac.uk Contact telephone number: 01482 463859; 01482 463030
Student investigator (if applicable)	Name: David Scott Email address: david.scott@hull.ac.uk Contact telephone number: 07519050992; 01482 466314

Please Initial

☐

I confirm that I have read and understood all the information provided in the Informed Consent Form (EC2) relating to the above project and I have had the opportunity to ask questions.

☐

I understand this project is designed to further scientific knowledge and that all procedures have been risk assessed and approved by the Department of Sport, Health and Exercise Science Research Ethics Committee at the University of Hull.

☐

Any questions I have about my participation in this project have been answered to my satisfaction.

☐

I fully understand my participation is voluntary and that I am free to withdraw from this project at any time and at any stage, without giving any reason. I have read and fully understand this consent form.

.....

Name of participant

.....

Date

.....

Signature

.....

Person taking consent

.....

Date

.....

Signature

Appendix E: Participant Information and Informed Consent Form (Study 4)

Department of Sport, Health & Exercise Science



Informed Consent Declaration

Project title	The effects of two complex training modalities on physical performance and muscle architecture characteristics in rugby league players over a 6-week mesocycle.
Principal investigator	Name: Max Ditroilo; Phil Marshall Email address: massimiliano.ditroilo@ucd.ie; phil.marshall@hull.ac.uk Contact telephone number: +353 1 716 3463; 01482 463030
Student investigator (if applicable)	Name: David Scott Email address: david.scott@hull.ac.uk Contact telephone number: 07519050992; 01482 466314

Please Initial

☐

I confirm that I have read and understood all the information provided in the Informed Consent Form (EC2) relating to the above project and I have had the opportunity to ask questions.

☐

I understand this project is designed to further scientific knowledge and that all procedures have been risk assessed and approved by the Department of Sport, Health and Exercise Science Research Ethics Committee at the University of Hull.

☐

Any questions I have about my participation in this project have been answered to my satisfaction.

☐

I fully understand my participation is voluntary and that I am free to withdraw from this project at any time and at any stage, without giving any reason. I have read and fully understand this consent form.

.....

Name of participant

.....

Date

.....

Signature

.....

Person taking consent

.....

Date

.....

Signature

Pre-Exercise Medical Questionnaire

The information in this document will be treated as strictly confidential

Name:

Date of Birth: Age: Sex:

Blood pressure: Resting Heart Rate:

Height (cm): Weight (Kg):

Please answer the following questions by putting a circle round the appropriate response or filling in the blank.

1. How would you describe your present level of **exercise** activity?

Sedentary / Moderately active / Active / Highly active

2. Please outline a typical weeks exercise activity

.....
.....
.....

3. How would you describe your present level of **lifestyle** activity?

Sedentary / Moderately active / Active / Highly active

4. What is your occupation?

5. How would you describe your present level of fitness?

Unfit / Moderately fit / Trained / Highly trained

6. Smoking Habits Are you currently a smoker?

Yes / No

How many do you smoke

..... per day

Are you a previous smoker?

Yes / No

How long is it since you stopped?

..... years

How many did you smoke?

..... per day

7. Do you drink alcohol?

Yes / No

If you answered **Yes** and you are male do you drink more than 28 units a week?

Yes / No

If you answered **Yes** and you are female do you drink more than 21 units a week?

Yes / No

8. Have you had to consult your doctor within the last six months?

Yes / No

- If you answered **Yes**, Have you been advised **not** to exercise? Yes / No
9. Are you presently taking any form of medication? Yes / No
If you answered **Yes**, Have you been advised **not** to exercise? Yes / No
10. Do you have a history of fainting during or following exercise? Yes / No
If **Yes**, please provide details.....
.....
.....
11. To the best of your knowledge do you, or have you ever, or have a family history:
- | | | | |
|---------------------------------|----------|-------------------------|----------|
| a Diabetes? | Yes / No | b Asthma? | Yes / No |
| c Epilepsy? | Yes / No | d Bronchitis? | Yes / No |
| e ★Any form of heart complaint? | Yes / No | f Raynaud's Disease | Yes / No |
| g ★Marfan's Syndrome? | Yes / No | h ★Aneurysm / embolism? | Yes / No |
| I Anaemia | Yes / No | | |
12. ★Are you over 45, and with a history of heart disease in your family? Yes / No
13. Do you currently have any form of muscle or joint injury? Yes / No
If you answered **Yes**, please give details.....
.....
.....
14. Have you had to suspend your normal training in the last two weeks? Yes / No
If the answer is **Yes** please give details.....
.....
.....
15. ★ Please read the following questions:
- | | |
|--|----------|
| a) Are you suffering from any known serious infection? | Yes / No |
| b) Have you had jaundice within the previous year? | Yes / No |
| c) Have you ever had any form of hepatitis? | Yes / No |
| d) Are you HIV antibody positive | Yes / No |
| e) Have you had unprotected sexual intercourse with any person from an HIV high-risk population? | Yes / No |
| f) Have you ever been involved in intravenous drug use? | Yes / No |
| g) Are you haemophiliac? | Yes / No |
16. As far as you are aware, is there anything that might prevent you from successfully completing the tests that have been outlined to you? Yes / No.

IF THE ANSWER TO ANY OF THE ABOVE IS YES:

- a) Discuss with the test administrators or another appropriate member of the department.
- b) Questions indicated by (★) answered yes: Please obtain written approval from your doctor before taking part in the test.

PLEASE SIGN AND DATE AS INDICATED ON THE NEXT PAGE

Participant Signature: Date.....

Test Administrator:..... Date.....

Supervising staff member..... Date.....

Parent (if minor)..... Date:

THIS SECTION IS ONLY REQUIRED FOR RETURN VISITS!

For any future testing sessions it is necessary to verify that the responses provided above are still valid, or to detail any new information. This is to ensure that you have had no new illness or injury that could unduly increase any risks from participation in the proposed physical exercise.

ANSWER THE FOLLOWING QUESTION AT EACH REPEAT VISIT.

Is the information you provided above still correct, and can you confirm that you have NOT experienced any new injury or illness which could influence your participation in this exercise session?

Repeat 1	Yes / No *	Signature: _____	Date: _____
* Additional info required: _____			
Repeat 2	Yes / No *	Signature: _____	Date: _____
* Additional info required: _____			
Repeat 3	Yes / No *	Signature: _____	Date: _____
* Additional info required: _____			
Repeat 4	Yes / No *	Signature: _____	Date: _____
* Additional info required: _____			
Repeat 5	Yes / No *	Signature: _____	Date: _____
* Additional info required: _____			

Appendix G: NSCA 1RM Testing Protocol (Lower Body)

1. Instruct the athlete to warm up with a light resistance that easily allows 5 to 10 repetitions.
2. Provide a 1 minute rest period.
3. Estimate a warm-up load that will allow the athlete to complete three to five repetitions by adding 10% to 20%.
4. Provide a 2 minute rest period.
5. Estimate a conservative, near-maximal load that will allow the athlete to complete two or three repetitions by adding 10% to 20%.
6. Provide a 2 to 4 minute rest period.
7. Make a load increase of 10% to 20%.
8. Instruct the athlete to attempt a 1RM.
9. If the athlete was successful, provide a 2 to 4 minute rest period and go back to step 7. If the athlete failed, provide a 2 to 4 minute rest period; the decrease the load by subtracting 5% to 10%. AND then go back to step 8.

Continue increasing or decreasing the load until the athlete can complete one repetition with proper exercise technique. Ideally, the athlete's 1RM will be measured within three to five testing sets.

Appendix H: SENIAM Recommendations for Sensor Locations

Recommendations for sensor locations in hip or upper leg muscles

Muscle

Name Quadriceps Femoris

Subdivision vastus lateralis

Muscle Anatomy

Origin Proximal parts of intertrochanteric line, anterior and inferior borders of greater trochanter, lateral lip of gluteal tuberosity, proximal half of lateral lip of linea aspera, and lateral intermuscular septum.

Insertion Proximal border of the patella and through patellar ligament.

Function Extension of the knee joint.



[Click on image for larger view](#)

Recommended sensor placement procedure

Starting posture Sitting on a table with the knees in slight flexion and the upper body slightly bend backward.

Electrode size Maximum size in the direction of the muscle fibres: 10 mm.

Electrode distance 20 mm.

Electrode placement

- location Electrodes need to be placed at 2/3 on the line from the anterior spina iliaca superior to the lateral side of the patella.

- orientation In the direction of the muscle fibres

- fixation on (Double sided) tape / rings or elastic band.

the skin

- reference On / around the ankle or the proc. spin. of C7.

electrode

Clinical test Extend the knee without rotating the thigh while applying pressure against the leg above the ankle in the direction of flexion.

Remarks The SENIAM guidelines include also a separate sensor placement procedure for the vastus medialis and the rectus femoris muscle.

[Click here to 'Go Back' to the previous page >>](#)

Recommendations for sensor locations in hip or upper leg muscles

Muscle

Name Biceps femoris
Subdivision Long head and short head

Muscle Anatomy

Origin Long head: distal part of sacrotuberous ligament and posterior part of tuberosity
Short head: lateral lip of linea aspera, proximal 2/3 of supracondylar line and lateral intermuscular septum.
Insertion Lateral side of head of fibula, lateral condyle of tibia, deep fascial on lateral side of leg.
Function Flexion and lateral rotation of the knee joint. The long head also extends and assists in lateral rotation of the hip joint.



[Click on image for larger view](#)

Recommended sensor placement procedure

Starting posture Lying on the belly with the face down with the thigh down on the table and the knees flexed (to less than 90 degrees) with the thigh in slight lateral rotation and the leg in slight lateral rotation with respect to the thigh.

Electrode size Maximum size in the direction of the muscle fibres: 10 mm.

Electrode distance 20 mm.

Electrode placement

- location

The electrodes need to be placed at 50% on the line between the ischial tuberosity and the lateral epicondyle of the tibia.

- orientation

In the direction of the line between the ischial tuberosity and the lateral epicondyle of the tibia.

- fixation on

(Double sided) tape / rings or elastic band.

the skin

- reference

On / around the ankle or the proc. spin. of C7.

electrode

Clinical test

Press against the leg proximal to the ankle in the direction of knee extension.

Remarks

[Click here to 'Go Back' to the previous page >>](#)

Recommendations for sensor locations in lower leg or foot muscles

Muscle

Name Tibialis anterior

Subdivision

Muscle Anatomy

Origin Lateral condyle and proximal 1/2 of lateral surface of tibia, interosseus membrane, deep fascia and lateral intermuscular septum.

Insertion Medial and plantar surface of medial cuneiform bone, base of first metatarsal bone.

Function Dorsiflexion of the ankle joint and assistance in inversion of the foot.



[Click on image for larger view](#)

Recommended sensor placement procedure

Starting posture Supine or sitting.

Electrode size Maximum size in the direction of the muscle fibres: 10 mm.

Electrode distance 20 mm.

Electrode placement

- location The electrodes need to be placed at 1/3 on the line between the tip of the fibula and the tip of the medial malleolus.
- orientation In the direction of the line between the tip of the fibula and the tip of the medial malleolus.
- fixation on the skin (Double sided) tape / rings or elastic band.
- reference electrode On / around the ankle or the proc. spin. of C7.

Clinical test Support the leg just above the ankle joint with the ankle joint in dorsiflexion and the foot in inversion without extension of the great toe. Apply pressure against the medial side, dorsal surface of the foot in the direction of plantar flexion of the ankle joint and eversion of the foot.

Remarks

[Click here to 'Go Back' to the previous page >>](#)

Recommendations for sensor locations in lower leg or foot muscles

Muscle

Name Gastrocnemius

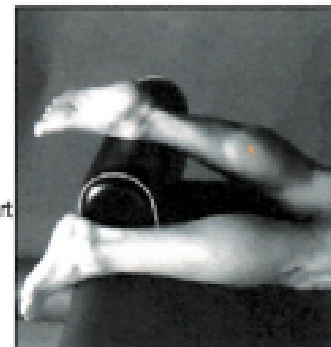
Subdivision Medialis

Muscle Anatomy

Origin Proximal and posterior part of medial condyle and adjacent part of the femur, capsule of the knee joint.

Insertion Middle part of posterior surface of calcaneus.

Function Flexion of the ankle joint and assist in flexion of the knee joint.



[Click on image for larger view](#)

Recommended sensor placement procedure

Starting posture Lying on the belly with the face down, the knee extended and the foot projecting over the end of the table.

Electrode size Maximum size in the direction of the muscle fibres: 10 mm.

Electrode distance 20 mm.

Electrode

placement

- location Electrodes need to be placed on the most prominent bulge of the muscle.

- orientation In the direction of the leg (see picture).

- fixation on (Double sided) tape / rings or elastic band.

the skin

- reference On / around the ankle or the proc. spin. of C7.

electrode

Clinical test Plantar flexion of the foot with emphasis on pulling the heel upward more than pushing the forefoot downward. For maximum pressure in this position it is necessary to apply pressure against the forefoot as well as against the calcaneus.

Remarks The SENIAM guidelines include a separate sensor placement procedure for the lateral gastrocnemius.

[Click here to 'Go Back' to the previous page >>](#)

Appendix I: NSCA Training Load Chart

TRAINING LOAD CHART											
Max reps (RM)	1	2	3	4	5	6	7	8	9	10	12
% 1RM	100%	95%	93%	90%	87%	85%	83%	80%	77%	75%	70%
Load	10	9.5	9.3	9	8.7	8.5	8.3	8	7.7	7.5	7
20	19	18.6	18	17.4	17	16.6	16	15.4	15	14	
30	28.5	27.9	27	26.1	25.5	24.9	24	23.1	22.5	21	
40	38	37.2	36	34.8	34	33.2	32	30.8	30	28	
50	47.5	46.5	45	43.5	42.5	41.5	40	38.5	37.5	35	
60	57	55.8	54	52.2	51	49.8	48	46.2	45	42	
70	66.5	65.1	63	60.9	59.5	58.1	56	53.9	52.5	49	
80	76	74.4	72	69.6	68	66.4	64	61.6	60	56	
90	85.5	83.7	81	78.3	76.5	74.7	72	69.3	67.5	63	
100	95	93	90	87	85	83	80	77	75	70	
110	104.5	102.3	99	95.7	93.5	91.3	88	84.7	82.5	77	
120	114	111.6	108	104.4	102	99.6	96	92.4	90	84	
130	123.5	120.9	117	113.1	110.5	107.9	104	100.1	97.5	91	
140	133	130.2	126	121.8	119	116.2	112	107.8	105	98	
150	142.5	139.5	135	130.5	127.5	124.5	120	115.5	112.5	105	
160	152	148.8	144	139.2	136	132.8	128	123.2	120	112	
170	161.5	158.1	153	147.9	144.5	141.1	136	130.9	127.5	119	
180	171	167.4	162	156.6	153	149.4	144	138.6	135	126	
190	180.5	176.7	171	165.3	161.5	157.7	152	146.3	142.5	133	
200	190	186	180	174	170	166	160	154	150	140	
210	199.5	195.3	189	182.7	178.5	174.3	168	161.7	157.5	147	
220	209	204.6	198	191.4	187	182.6	176	169.4	165	154	
230	218.5	213.9	207	200.1	195.5	190.9	184	177.1	172.5	161	
240	228	223.2	216	208.8	204	199.2	192	184.8	180	168	
250	237.5	232.5	225	217.5	212.5	207.5	200	192.5	187.5	175	
260	247	241.8	234	226.2	221	215.8	208	200.2	195	182	
270	256.5	251.1	243	234.9	229.5	224.1	216	207.9	202.5	189	
280	266	260.4	252	243.6	238	232.4	224	215.6	210	196	
290	275.5	269.7	261	252.3	246.5	240.7	232	223.3	217.5	203	
300	285	279	270	261	255	249	240	231	225	210	
310	294.5	288.3	279	269.7	263.5	257.3	248	238.7	232.5	217	
320	304	297.6	288	278.4	272	265.6	256	246.4	240	224	
330	313.5	306.9	297	287.1	280.5	273.9	264	254.1	247.5	231	
340	323	316.2	306	295.8	289	282.2	272	261.8	255	238	
350	332.5	325.5	315	304.5	297.5	290.5	280	269.5	262.5	245	
360	342	334.8	324	313.2	306	298.8	288	277.2	270	252	
370	351.5	344.1	333	321.9	314.5	307.1	296	284.9	277.5	259	
380	361	353.4	342	330.6	323	315.4	304	292.6	285	266	
390	370.5	362.7	351	339.3	331.5	323.7	312	300.3	292.5	273	
400	380	372	360	348	340	332	320	308	300	280	
410	389.5	381.3	369	356.7	348.5	340.3	328	315.7	307.5	287	
420	399	390.6	378	365.4	357	348.6	336	323.4	315	294	
430	408.5	399.9	387	374.1	365.5	356.9	344	331.1	322.5	301	
440	418	409.2	396	382.8	374	365.2	352	338.8	330	308	
450	427.5	418.5	405	391.5	382.5	373.5	360	346.5	337.5	315	
460	437	427.8	414	400.2	391	381.8	368	354.2	345	322	
470	446.5	437.1	423	408.9	399.5	390.1	376	361.9	352.5	329	
480	456	446.4	432	417.6	408	398.4	384	369.6	360	336	
490	465.5	455.7	441	426.3	416.5	406.7	392	377.3	367.5	343	
500	475	465	450	435	425	415	400	385	375	350	

- Training load chart can be used to calculate estimated 1-repetition maximum (1RM) values from multiple repetitions completed
 - For example, if an athlete completes 8 repetitions of the squat at 160 lbs, the estimated 1RM would be 200 lbs.
- Training load chart can also be used to assign intensity percentages for program design
 - For example, if an athlete's 1RM for the squat is 200 lbs, he/she should be able to successfully complete 10 repetitions of 150 lbs, or 75% max intensity.

Adapted from Landers, J. Maximum based on reps. NSCA J 6(6):60-61, 1984.

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