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Concurrent Training: Neuroendocrine and molecular mechanisms of strength and endurance training incompatibility

Thomas William Jones

PhD

2014

Concurrent Training: Neuroendocrine and molecular mechanisms of strength and endurance training incompatibility

Thomas William Jones

A thesis submitted in partial fulfilment of the requirements of the University of Northumbria at Newcastle for the degree of Doctor of Philosophy

Research undertaken in the Faculty of Health and Life Sciences

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Abstract

Combining strength and endurance training within the same regimen is aptly referred to as “concurrent training”. Research conducted over the previous 3 decades has indicated concurrent training can result in attenuated development of strength, power and hypertrophy when compared to strength training in isolation. Despite extensive research the mechanisms contributing to this so called “interference effect” are yet to be fully elucidated, as is the influence of manipulating acute training programme variables within a concurrent regimen. As such, the purposes of this thesis were to investigate and draw conclusions regarding underlying physiological mechanisms relating to the interference effect. Additionally, this thesis sought to examine the effects of manipulating programme variables, including frequency and sequencing of exercise within concurrent training regimens on strength related adaptation.

The findings of this thesis indicate overall training volume and frequency of endurance training within a concurrent intervention influences the presence and magnitude of the inhibition of strength development. Concurrent training volumes of 3 $d \cdot wk^{-1}$ elicited muted strength development, whereas lower frequencies did not. Whilst interference was not attributable to neuromuscular factors, it was reported that cortisol was only elevated following higher training frequencies, indicating training stress and catabolism may contribute to interference. Additionally, the sequencing of strength and endurance training can influence endocrine and signalling responses associated with strength adaptation, and it appears strength prior to endurance elicits greater increases in growth associated signalling.

The findings of this thesis indicate that overall training stress influences the presence and magnitude of interference experienced, and is reflected in catabolic endocrine responses. Additionally, strength prior to endurance training promotes more favourable anabolic signalling than *vice versa*, which over time may contribute to greater strength type adaptations.

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List of Abbreviations

4E-BP1	4E binding protein 1
ACC	acetyl-CoA carboxylase
AMP	adenosine monophosphate
AMPK	adenosine monophosphate activated protein kinase
ANOVA	analysis of variance
AR	androgen receptors
AT	anaerobic threshold
ATP	adenosine triphosphate
BF	*biceps femoris*
bw	body weight
CamK	calcium-activated protein kinase
CHO	carbohydrate
CI	confidence interval
CMJ	countermovement jump
CON	control
CSA	cross sectional area
CT1	concurrent training at a ratio of 1:1
CT3	concurrent training at a ratio of 3:1 in favour of strength training
eEF2	eukaryotic elongation factor 2
EDTA	ethylenediaminetetraacetic acid
eIF4E	eukaryotic initiation factor 4E
ELISA	enzyme-linked immunosorbent assay
EMG	electromyography
END-ST	endurance training followed by strength training
GH	growth hormone
GLUT4	glucose transporter type 4
H^+	hydrogen

HDAC	histone deacetylases
HRR	heart rate reserve
ICC	intraclass correlation
IGF-1	insulin-like growth factor-1
JAK2	janus kinase 2
kDa	kilo-dalton
Lac^-	blood lactate concentrations
LKB1	liver kinase B1
MAP	maximal aerobic power
MEF	myocyte-enhancing factor
mRNA	messenger ribonucleic acid
mTOR	mammalian target of rapamycin
MVC	maximal voluntary contraction
OTS	overtraining syndrome
p-	phosphorylated
p38	mitogen-activated protein kinase
PGC-1α	peroxisome proliferator-activated receptor gamma, co activator 1 alpha
PI3k	phosphoinositol 3-kinase
PKB	protein kinase B
$p\dot{V}O_{2max}$	power at maximal oxygen uptake
r	Pearson's correlation coefficient
RFD	rate of force development
RM	repetition maximum
RPE	rate of perceived exertion
RPM	revolutions per minute
S6k1	70-kDa S6 protein kinase
ST	strength training alone
ST-END	strength training followed by endurance training

T:C ratio	testosterone:cortisol ratio
TMB	tetramethylbenzidine
TSC2	tuberous sclerosis complex 2
TTE	time to exhaustion
$\dot{V}O_{2max}$	maximal oxygen uptake
VL	*vastus lateralis*
v$\dot{V}O_{2max}$	velocity at maximal oxygen uptake
wk	week

Publications and Conference Communications

Data within this thesis has formed the following peer reviewed publications and conference presentations:

Jones, T. W., Howatson, G., Russell, M. and French, D. N. (2013). "Validity and reproducibility of a lower limb isokinetic muscular endurance testing protocol". *Isokinetics and Exercise Science*, 21 (4). pp 311 – 316.

Jones, T. W., Howatson, G., Russell, M. and French, D. N. (2013). "Performance and neuromuscular adaptations following differing ratios of concurrent strength and endurance training". *Journal of Strength and Conditioning Research*, 27 (12), pp 3342 – 51.

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Author's Declaration

I declare that the work contained in this thesis is all my own work with the exception where due acknowledgement has been made. This work has not been submitted for any other award

Name:

Signature:

Date:

Thesis word count: 48, 187

1. Introduction

1.1 Introduction

Strength training or resistance training as it has been often referred to, is the use of external loads within a training paradigm to induce a variety of physical and physiological adaptations. Strength training encompassing high external loads over short durations stimulates a variety of desirable neuromuscular, biochemical, cell signalling, and molecular responses (Häkkinen *et al.*, 1988; Leveritt *et al.*, 1999; Bosco *et al.*, 2000; Kraemer & Ratamess, 2003a; Bickel *et al.*, 2005; Kraemer & Ratamess, 2005; Coffey & Hawley, 2007; Seynnes *et al.*, 2007; Häkkinen *et al.*, 2008). Over time these responses typically result in a variety of architectural and systemic adaptations, including i) neural changes, and ii) muscle hypertrophic adaptations; both of which can be responsible for improved strength in trained muscles (Komi, 1986; Sale *et al.*, 1992; Häkkinen, 1994).

In contrast to strength training, endurance training typically involves prolonged work periods at submaximal intensities, and represents the opposite end of the exercise continuum. Endurance training instead stimulates a variety of physiological responses which result in mitochondrial proliferation, improved cardiac function and enhanced aerobic performance (Burgomaster *et al.*, 2005). In comparison to the neuromuscular mechanisms regulating strength training adaptations, these endurance performance increments are largely the result of improved maximal oxygen uptake, muscle aerobic enzyme activities, intramuscular glycogen stores and increased capillary and mitochondrial density and size of the muscles (Holloszy & Booth, 1976; Holloszy & Coyle, 1984; Astrand & Rodahl, 1986).

In some circumstances, a range of athletes involved in competitive sport, and recreational exercisers alike, endeavour to improve both strength and endurance

performance concurrently; aptly referred to as ‘concurrent training’. Training regimens of this nature include exercise sessions specifically designed to augment an individual’s strength and endurance capabilities, these may take place in the form of combining strength and endurance training within the same session or in separate sessions but within the same training cycle. It was initially thought that adaptations associated with both strength and endurance training could be obtained simultaneously, which has been previously reported (McCarthy *et al.*, 1995; McCarthy *et al.*, 2002; Millet *et al.*, 2002; Balabinis *et al.*, 2003). However, over the last 3 decades much research has demonstrated that conducting strength and endurance training concurrently can actually attenuate the development of strength, power and muscle hypertrophy when compared to strength training in isolation (Hickson, 1980; Dudley & Djamil, 1985; Hennessy & Watson, 1994; Kraemer *et al.*, 1995; Horne *et al.*, 1997; Bell *et al.*, 2000; Häkkinen *et al.*, 2003; Izquierdo *et al.*, 2005). This is typically demonstrated by greater strength responses in individuals performing strength training alone than those who perform both strength and endurance training within the same comparable training regimen. Hickson (1980) was the first to report data indicating the inhibiting effect that endurance training can have on strength responses. Dr Hickson’s seminal study was also the first controlled scientific investigation which specifically examined the possible muting effect of endurance training on strength adaptation. It was reported that those who performed strength training alone made greater gains in maximal strength than participants performing the same strength training regimen but with the addition of endurance training. This inhibitory effect of endurance training on strength development within a concurrent training programme was coined the “interference effect” (Hickson, 1980). In the thirty-four years since it was first acknowledged, the interference effect

(or interference phenomenon as it is sometimes called (Leveritt *et al.*, 1999)) has been researched extensively. As a result, a variety of potential mechanisms for interference have been proposed.

The most prominent of these include; residual neuromuscular fatigue (Häkkinen *et al.*, 2003), an increased catabolic hormonal state (Kraemer *et al.*, 1995; Bell *et al.*, 2000), overtraining (Dudley & Djamil, 1985), fibre type transformations (Nelson *et al.*, 1990; Sale *et al.*, 1990; Kraemer *et al.*, 1995) and the inhibition of intra muscular protein synthesis via molecular and cell signalling pathways (Nader & Esser, 2001; Baar, 2006; Nader, 2006; Baar, 2009; Hawley, 2009). It is thought neural fatigue as a result of endurance training may compromise the ability of the neuromuscular system to rapidly develop force during strength training, resulting in decremented adaptation to strength training stimulus (Häkkinen *et al.*, 2003), this may also occur as a result of overtraining. Also related to overtraining is increased endocrine indicated catabolism leading to diminished anabolic signalling and protein synthesis (Kraemer *et al.*, 1995; Bell *et al.*, 2000). Endurance training in a concurrent regimen may also have a direct negative affect on protein metabolism. Recent research has indicated strength and endurance training stimulate divergent molecular signalling networks (Nader & Esser, 2001; Baar, 2006; Nader, 2006; Baar, 2009; Hawley, 2009). More specifically endurance training and the activation of energy modulating networks may suppress anabolic and tissue growth related networks associated with strength training adaptation.

‘Concurrent’ strength and endurance training and the ‘interference effect’ remain contentious issues in applied sport and exercise science and the wider area of research in this field. There continues to be much debate regarding the overall presence of the interference phenomenon; with some research reporting an absence

of attenuated strength responses (McCarthy, Pozniak & Agre, 2002; Millet *et al.*, 2002; Balabinis *et al.*, 2003), whereas others report significant interference effects (Häkkinen *et al.*, 2003; Izquierdo *et al.*, 2005). Most authors assess maximal strength as a primary outcome measure, yet the examined potential mechanisms underpinning an interference effect vary within research pertaining to concurrent training. As a result this debate also relates to the underlying mechanisms which may contribute to interference.

'Training studies' increase our practical understanding of how the body adapts in applied settings. However studies of this nature are difficult to conduct, as a result in some areas the literature may be limited. Furthermore control and standardisation of experimental conditions is more difficult in training studies which can lead to inconclusive findings. Continued examination of concurrent training and how it might impact strength related adaptation is necessary as the factors influencing interference and the underlying mechanisms are yet to be fully elucidated. A greater understanding of the interference phenomenon will provide useful information which may guide programming and periodization strategies and the impact that they can have in optimising or attenuating performance and structural phenotypes. More specifically, having examined the literature training frequency and sequencing are programme variables that might be seen to regulate the adaptive responses to concurrent training. Research has suggested interference may be limited when training frequency remains low (Sale *et al.*, 1990; Abernethy & Quigley, 1993; Volpe *et al.*, 1993; McCarthy *et al.*, 1995; Gravelle & Blessing, 2000; McCarthy, Pozniak & Agre, 2002). Separate research has also indicated performing strength prior to endurance training has elicited greater improvements in maximal strength than *vice versa* (Cadore *et al.*, 2012a). In contrast greater maximal strength

development has been reported when endurance training was conducted immediately prior to strength training (Collins & Snow, 1993). There is a dearth of research examining both training frequency and sequencing paradigms and further investigation is warranted to further understand how interference may be avoided via manipulation of programme variables.

1.2 Aims and objectives

The primary focus of this thesis was to investigate the factors contributing to the inhibition of strength development which can occur as a result of conducting concurrent strength and endurance training. The purpose of this thesis was to investigate and draw conclusions regarding the potential underlying physiological mechanisms relating to concurrent training strategies and the 'interference phenomenon'. The investigations conducted were also designed to further elucidate the effects of manipulating programme variables within concurrent training regimens on strength related adaptation. Consequently, a line of research encompassing four individual, but sequential investigations was undertaken designed to examine;

1. The impact of differing ratios of strength and endurance training on performance, anthropometric and neuroendocrine responses and adaptations.
2. The effects of acute sequencing of strength and endurance training on strength training performance.
3. The effects of acute sequencing of strength and endurance training on endocrine and signalling pathways associated with strength training adaptation, anabolism and tissue growth.

4. Programme variables in concurrent training regimens and how manipulation of said variables may promote environments conducive to strength training adaptation without concomitant endurance training-induced interference.

Evidence gained from these research avenues will serve to better understand the role of concurrent training in athletic development and performance and may serve to inform practitioners about the best ways to optimise concurrent training paradigms. Furthermore the findings of this thesis will further illuminate the underlying physiological mechanisms contributing to the interference phenomenon.

2. Literature review

2.1 Literature review

Individuals performing combined strength and endurance training (or concurrent training) typically train for the simultaneous development of their strength and endurance capabilities. For both recreational and elite performers involved in sports or events which require heightened strength and endurance capabilities the concomitant development of contrasting performance phenotypes would be particularly advantageous. However, anecdotal observations suggest that the magnitude of strength improvements are attenuated when strength and endurance training are combined. This attenuated strength response was first documented within the scientific population by Dr. Robert Hickson during his post-doctoral research fellowship at Washington University. Alongside Dr. Hickson's habitual strength training he began running with his mentor Dr. John Holloszy. Although Dr. Hickson's strength training habits did not change he experienced a notable decline in his muscle mass and strength capabilities. He approached his mentor about this phenomenon and the two agreed that the attenuated strength and muscle mass as a result of endurance training warranted controlled scientific investigation; and so the scientific interest in concurrent approaches to training began.

Following his post-doctoral fellowship, Dr. Hickson investigated the effects of strength, endurance and a combined strength and endurance training (the term concurrent training was not yet in use) intervention on strength (as assessed by back squat 1 repetition maximum) and maximal oxygen consumption ($\dot{V}O_{2\text{max}}$). Unsurprisingly the strength training condition resulted in greater strength increases than the endurance training condition and *vice versa* for $\dot{V}O_{2\text{max.}}$ No differences in $\dot{V}O_{2\text{max}}$ were observed between the concurrent and endurance conditions following the respective interventions. Data from Dr. Hickson's work indicated that in the

initial stages of the intervention strength increases were similar in the strength and concurrent training groups. This was the case until week 7 of the 10-week intervention. At this point the strength responses in the participants performing the concurrent condition plateaued, whereas those conducting strength training alone continued to get stronger. In the remaining weeks of the concurrent training regimen participants strength actually decreased and those in the strength alone group got progressively stronger throughout the intervention (Figure 2.1).

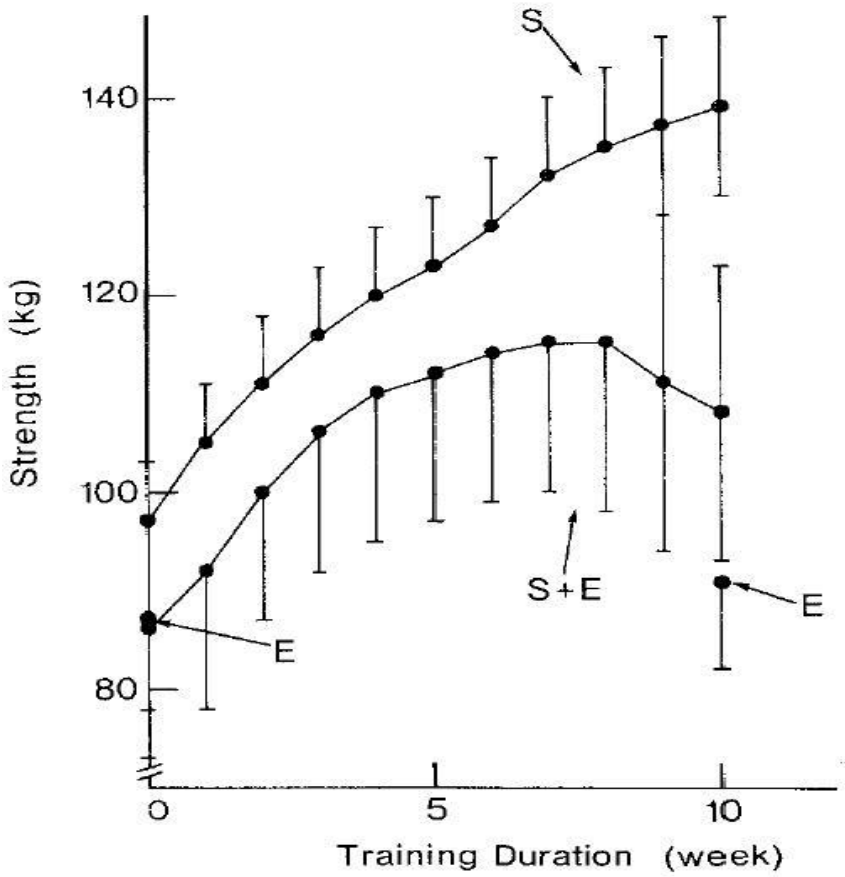

Figure 2.1. The first published data on strength interference as a result of concurrent training. Participants underwent 3 different 10 week training protocols involving 1) strength training alone (S), 2) endurance training alone (E) and 3) concurrent training (S + E) (Hickson, 1980).

These seminal data represented the first published article (Hickson, 1980) to report the muting effect of endurance exercise stimulus on strength responses.

Hickson referred to this attenuation as the “interference effect”; a phrase that is still commonly used in the concurrent training literature to this day. Since its original proposition in 1980 the interference effect has received considerable attention in scientific literature. Research ranges from investigations examining the effects of concurrent training regimens on strength performance and muscular growth responses to the underlying physiological mechanisms behind the phenomenon. Within this literature various mechanisms are proposed as contributors to the impairment of strength and hypertrophy. The most prominent of these include inhibited neural adaptation, changes in the endocrine anabolic:catabolic environment, and most recently position stands on the molecular inhibition of protein synthesis via divergent signalling pathways. This Literature Review will discuss and critically analyse the aforementioned relevant and published research relating to both strength and endurance training individually and concurrent training and the interference phenomenon.

2.2 Specificity of adaptive responses to exercise

It is essential that individuals have a clear objective when embarking on a training intervention, as different contractile and metabolic stressors elicit contrasting physiological and performance adaptations. Furthermore, research has indicated that certain training methods may actually be considered incompatible when considering the physiological adaptations to training (Rhea *et al.*, 2008). The specificity of training stimulus and the related performance and physiological responses is well documented (Hickson, 1980; Kraemer *et al.*, 1995; Bell *et al.*, 2000; Izquierdo *et al.*, 2005; Cadore *et al.*, 2010) as skeletal muscle is a highly malleable tissue that can adapt to a variety of exercise stimuli (Nader & Esser, 2001;

Coffey *et al.*, 2006; Flück, 2006). Repeated muscular contractions elicit a series of responses which over time alter the tissue characteristics in both untrained and trained muscle (Figure 2.2).

Exercise stimulus

Nerve stimulation

Primary messengers

Contractile activity

Secondary messengers

Regulatory genes

Functional genes

Fibre specific characteristics

Tissue characteristics (Phenotypes)

Figure 2.2. Individual steps by which contractile activity leads to skeletal muscle adaptation. Adapted from Williams & Neufer (1996).

The understanding of the complex processes of exercise-induced adaptation began in the 1960s (Holloszy, 1967; Goldberg, 1968). During this time the precise mechanisms behind adaptations to differing exercise stimuli were reported. Goldberg (1968) identified the role of increased amino acid-derived protein synthesis in the ability of skeletal muscle to augment its cross sectional area (CSA) following strength training. In turn, this was also shown to elicit potential increases in maximal contractile strength of the trained muscle. Holloszy (1967) reported that prolonged exercise (i.e. endurance exercise) performed on a regular basis differed in the physiological adaptations that are induced, with increased muscular mitochondrial content and enzyme activity apparent, which consequently resulted in an increased aerobic work capacity. Subsequent researched confirmed these adaptations to differing exercise stimuli (Goldberg, 1969; Goldberg & Goodman, 1969; Holloszy & Booth, 1976; Holloszy & Coyle, 1984). It is now apparent that the functional consequences of these adaptations are primarily determined by the intensity, frequency and volume of the contractile activity experienced (McCafferty & Horvath, 1977; Fernhall & Kohrt, 1990). These adaptations may also be dependent on mode of exercise performed (Izquierdo *et al.*, 2004).

Various sports and events require contrasting physical performance phenotypes for successful performance. Exercise and sport-specific conditioning has received substantial attention in scientific literature and applied sport science in the past decade, as result the understanding of the required stimuli to elicit specific adaptation has greatly improved. Training for sports and events at the extremes of the strength-endurance continuum such as Olympic lifting and ultra-endurance events (Figure 2.3) is relatively straight-forward compared with sports and events that require a combination of strength and endurance capabilities. In these situations

athletes and coaches are often forced to combine training methods which elicit contrasting and even antagonistic physiological and performance responses (García-Pallarés & Izquierdo, 2011). As previously stated, in the case of concurrent training the divergent stimuli of strength and endurance training can result in attenuated strength related adaptation when compared with conducting strength training in isolation (Hickson, 1980; Dudley & Djamil, 1985; Hennessy & Watson, 1994; Kraemer *et al.*, 1995; Horne *et al.*, 1997; Bell *et al.*, 2000; Häkkinen *et al.*, 2003; Izquierdo *et al.*, 2005).

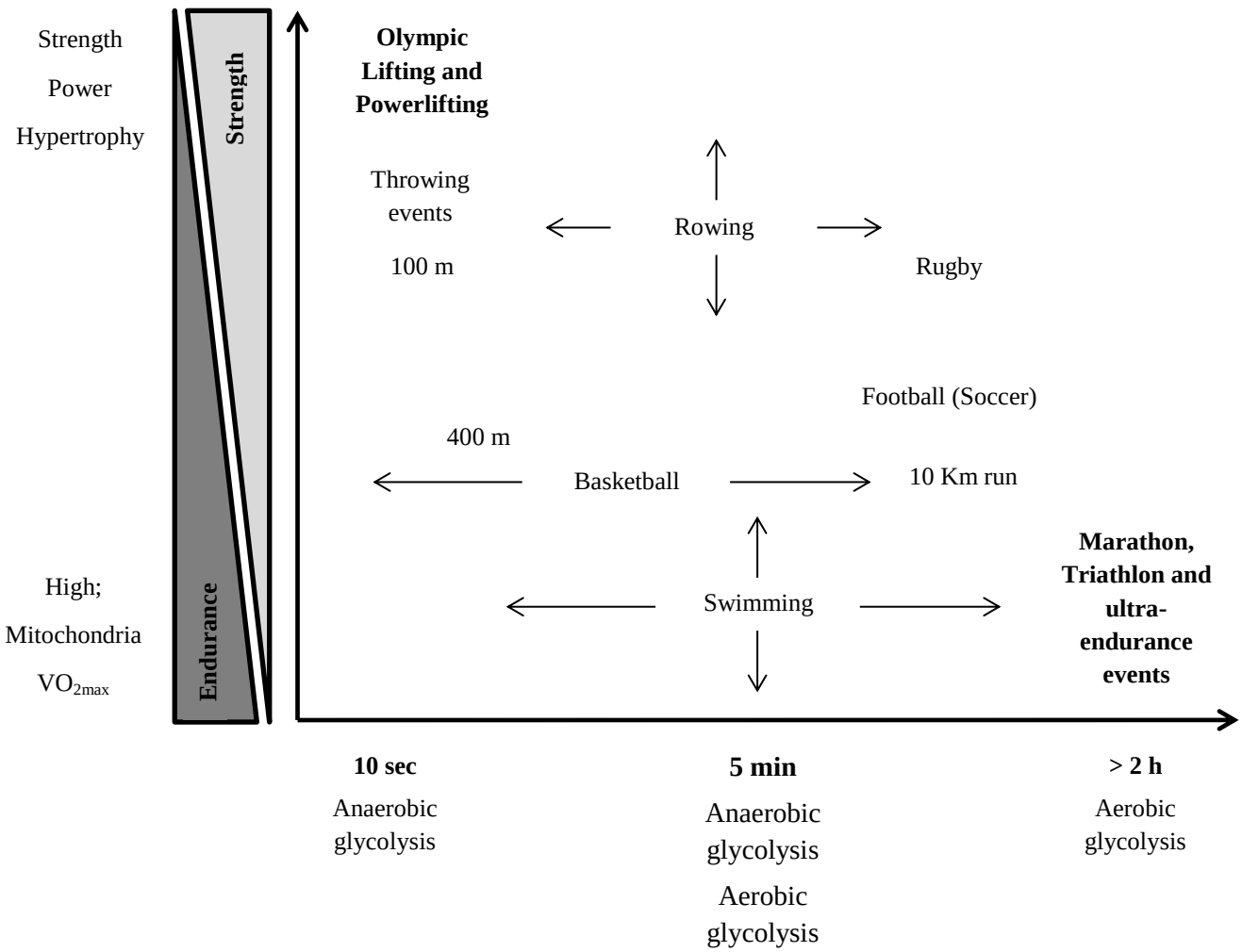

Figure 2.3. The strength-endurance continuum in relation to sport specific physical performance requirements, adapted from Nader (2006).

2.3 Strength training

Strength training can be used as a method of improving muscular strength by gradually increasing the ability of the neuromuscular system to generate and/or resist force through the use of free weights, machines, or the person's own body weight (Mosby, 2009). Characterised by work performed against high external loads for short durations (Fleck & Kraemer, 2004) strength training over time has been shown to result in a variety of physical and physiological adaptations, including muscle fibre hypertrophy, increased CSA, optimised neural recruitment patterns, and increased force generating capacity to name but a few (Häkkinen, 1989). These adaptations are a result of a cascade of physiological responses elicited by strength training as an exercise 'stressor' (Spiering *et al.*, 2008). The responses themselves are dependent on the 'acute strength training programme variables' previously defined (Kraemer, 1983). These key variables include; i) choice of exercise, ii) load, iii) volume (number of repetitions x number of set x load), iv) rest interval lengths between sets v) order of exercises performed, and vi) exercise modality to name but a few. The implementation of these acute programme variables ultimately determines the nature of performance, neuromuscular, biochemical and cell signalling responses to strength training (Spiering *et al.*, 2008) (Table 2.1).

Table 2.1. Appropriate manipulation of the acute programme variables to achieve various strength training related adaptations. Adapted from Baechle and Earle (2008).

Training goal	Load (% 1RM)	Goal repetitions	Sets*	Rest period length†
Strength	≥ 85	≤ 6	2 – 6	2 – 5 min
Power:				
Single-effort event	80 – 90	1 – 2	3 – 5	2 – 5 min
Multiple-effort event	75 – 85	3 – 5		
Hypertrophy	67 – 85	6 – 12	3 – 6	30s – 1 min 30 s
Muscular Endurance	≤ 67	≥ 12	2 – 3	≤30 s

*Assignments do not include warm-up sets.
† Between sets.

2.3.1 Neural adaptations to strength training

The increased muscular strength associated with strength training is dependent on numerous adaptations within the trained muscle and associated systems. Whilst fibre hypertrophy and increased CSA are important factors research has demonstrated an increased "neural drive" of the trained muscle fibres also contributes to the training induced increases in contractile strength (Moritani, 1979). This increased neural drive has also been reported to induce increases in muscular strength with little or no hypertrophic adaptation (Thorstensson *et al.*, 1976a; Komi *et al.*, 1978; Costill *et al.*, 1979). Strength increases in the early stages of a resistance training intervention (< 6 weeks) are primarily associated with neural adaptations via improved coordination and/or increased neural recruitment of muscle fibres before any hypertrophic adaptation has occurred (Rutherford & Jones, 1986; Sale, Martin & Moroz, 1992). Increased activation of the specific prime mover muscles involved in

the strength training intervention is a primary mechanism behind the neural induced strength increases (Moritani, 1979; Häkkinen & Komi, 1982).

In the majority of scientific literature examining the neuromuscular responses to strength training, electromyography (EMG) has been employed as the quantitative indicator of efferent neural drive (Aagaard *et al.*, 2002a; Aagaard *et al.*, 2002b). A number of researchers have successfully demonstrated increases in EMG activity following a strength training intervention (Moritani, 1979; Narici *et al.*, 1989; Aagaard *et al.*, 2000), whilst others report no integrated EMG increases as a result of strength training (Thorstensson *et al.*, 1976b; Cannon & Cafarelli, 1987). This disparity can make comparisons difficult, and it may be partly explained by the methodological limitations of recording surface EMG during maximal voluntary contractions (Aagaard *et al.*, 2002b); including electrode placement, surface preparation, prescribed range of motion of contraction and sampling frequency.

Acute and chronic neuromuscular responses to strength training appear to be regulated by two primary factors; i) the neural firing frequency and ii) the number of motor units recruited (Spiering *et al.*, 2008). The latter was first proposed by Henneman *et al.* (1965) and coined the "size principle". This states that neural recruitment begins with type I fibres and progresses to larger motor units and muscle fibres (type II) until force production is sufficient to overcome the resistance placed upon the working muscles. In a practical sense the size principle ensures that activities that require relatively low muscular force recruit type I fatigue resistant motor units. As the force requirements increase, as they would during heavy resistance exercise, higher threshold motor units are recruited. As such, it seems that resistance exercise using heavy to near maximal loads activates the full spectrum of motor units (Mikkola *et al.*, 2007). Neural firing frequency refers to the rate at which

the neuromuscular system is able to recruit muscle fibres in response to a resistance. Following strength training the larger motor units are recruited at a greater rate allowing more forceful contractions to be produced more quickly due to the increased firing frequency of the neuromuscular system (Aagaard, 2003). Explosive high velocity contractions such as Olympic lifting have been demonstrated to improve neural firing frequency and rate of force development to a greater extent than slower less forceful contractions. This is attributable to the fact that explosive type movements place a greater demand on the neuromuscular system as fast recruitment of high force motor units is necessary to effectively perform movements of high force and velocity (Behm, 1995).

2.3.2 Fibre type transformations in response to strength training

The muscle fibres in which the previously discussed neural factors elicit contractions are split into slow twitch I (slow-oxidative), fast twitch IIA (fast-oxidative glycolytic) and fast twitch IIX (fast glycolytic) (Wilson *et al.*, 2012). Slow twitch type I fibres have greater mitochondrial volume, densities and capillary-fibre content than both species of type II fibres (Sullivan & Pittman, 1987). As a result, these fibres have greater fatigue resistance and energy maintenance compared with type II fibres (Costill *et al.*, 1978). In contrast, contractions of type IIA and IIX fibres typically produce greater peak power and contractile velocities than type I fibres (Widrick *et al.*, 2002; Malisoux *et al.*, 2006). Research has also indicated that hypertrophic adaptation to strength training is greater in type II than type I fibres. Furthermore rates of ATP re synthesis following contractile activity are greater compared with slow type I fibres (Essén & Saltin, 1974; Schoenfeld, 2000; Karp, 2001).

Based on the phenotypes of the respective muscle fibres a high percentage of type II fibres seems to be the favourable muscle composition for strength training based adaptation and performance (Fry *et al.*, 2003). This relative composition of fibre type may however be altered by exercise stimulus (Gollnick *et al.*, 1972), with a recent review conducted by Wilson *et al*. (2012) concluding that exercise stimulus has the ability to transform fast IIA to IIX or *vice versa* depending of the nature of exercise. There is also research demonstrating the transformation of type I to type II fibres (or *vice versa* depending of the nature of exercise) (Simoneau *et al.*, 1985b; Esbjörnsson *et al.*, 1993; Kraemer *et al.*, 1995).

Strength training has been found to decrease the percentage of slow type I fibres with a concomitant increase in the percentage of IIA and IIX fibres. This morphological adaptation is typically coupled with increased contractile strength of the trained muscle (Paddon-Jones *et al.*, 2001; Liu *et al.*, 2003). However, there is also comparable literature which reports no fibre type transformation from slow to fast twitch or fast type IIA to IIX as a result of strength training (Adams *et al.*, 1993; Harridge *et al.*, 1996; Carroll *et al.*, 1998; McGuigan *et al.*, 2002). These variances in findings may be explained by the speed at which contractions in the respective exercise interventions were performed. Both Paddon-Jones *et al.* (2001) and Liu *et al.* (2003) employed fast isokinetic resistance exercise and observed significant slow to fast twitch fibre type transformations. Elsewhere, others employing interventions involving slower contractile speeds report no such transformations (Adams *et al.*, 1993; Harridge *et al.*, 1996; Carroll *et al.*, 1998). As such, it seems that direction of fibre type shifting may be dependent upon the intensity and/or velocity of contractile muscle actions performed during training.

2.3.3 Endocrine responses to strength training and mechanisms for adaptation

Correctly prescribed resistance training and the appropriate manipulation of the acute programme variables (Table 2.1) can result in neuroendocrine responses and adaptations to strength training (Kraemer & Ratamess, 2003a). As previously discussed in section 2.3.1, adaptations to strength training are predominantly neural in the initial phases of training. If strength training is progressively overloaded a greater volume of muscle fibres are recruited. This increased fibre recruitment not only results in increased contractile strength but also promotes a greater hormone-tissue interaction. This is proposed to be the consequence of increased muscle tissue activation promoting a greater hormonal response to strength training (Kraemer & Ratamess, 2005). These acute elevations in circulating blood hormone concentrations may enable greater stimulation of the nuclear and/or cytoplasmic receptors within the muscle tissue. Interaction between the circulating hormones and receptors initiates a series of biochemical responses which may place the muscle in an anabolic state conducive to fibre hypertrophy and strength adaptation (Spiering *et al.*, 2008; Basualto-Alarcón *et al.*, 2013).

The importance of the hormonal elevations in strength adaptation was simply and ingeniously demonstrated by Hansen *et al.* (2001). Two experimental conditions were employed; one group performed upper body strength training alone for 9 weeks, the other followed an identical upper body strength training regimen supplemented with lower body strength training designed to stimulate large muscle mass and hormone-tissue interactions. Following the respective interventions the group in which upper body training was combined with lower body training (thus experiencing greater circulating hormonal concentrations via an augmented

hormone-tissue interaction) experienced ~26% greater increase in upper body strength than those who performed identical upper body strength training in isolation. These data indicate strength training involving large muscle masses and the subsequent elevation of circulating hormones may augment strength gains following training.

The mechanisms underpinning strength and hypertrophic adaptation and the responses of the endocrine system are a contentious issue. It has been suggested that the increase in circulating hormonal concentrations alone do not influence the characteristics of the trained musculature but rather the subsequent milieu of events which occur when the elevated hormones interact with receptors within the muscle tissue (West & Phillips, 2012; Basualto-Alarcón *et al.*, 2013). These events and responses are specific to both the individual hormone and the specific receptor to which it binds.

The primary anabolic hormone associated with strength training and athletic performance is testosterone (Fry & Lohnes, 2010). As the principal androgen hormone testosterone can impact upon muscle tissue both directly and indirectly. Circulating testosterone can interact with motor neuron receptors and increase the volume of neurotransmitters augmenting the contractile strength of the trained muscle fibres (Bleisch *et al.*, 1984; Kelly *et al.*, 1985). Following strength training secreted testosterone binds to the nuclear androgen receptor which increases DNA transpiration (Figure 2.4), subsequent rates of protein synthesis are then increased (Vermeulen, 1988; Ratamess *et al.*, 2005; Spiering *et al.*, 2008; Basualto-Alarcón *et al.*, 2013) resulting in fibre hypertrophy and increased muscular strength (Kahn *et al.*, 2002). Indirectly testosterone can also promote growth hormone release via the pituitary glands.

Growth hormone (GH) is a generic term for a family of hormones thought to have >100 circulating variations (Baumann, 1991) with the 22kD GH molecule the most commonly researched in relation to strength training. Resistance training has also been demonstrated to increase binding of GH to its membrane bound receptor; namely the janus kinase 2 (JAK2) complex (Piwien-Pilipuk *et al.*, 2002). GH-induced JAK2 signalling then subsequently activates phosphoinositol 3-kinase (PI3k) (Spiering *et al.*, 2008) (Figure 2.4). This is of particular interest within the context of this thesis examining concurrent-training paradigms as phosphorylation of PI3k is an important aspect of the protein synthesis and growth-associated mammalian target of rapamycin (mTOR) signalling network (Richter & Sonenberg, 2005; Jastrzebski *et al.*, 2007). This is further discussed in section 2.3.4. GH may also influence anabolism via the production of insulin like growth factor-1 (IGF-1) in the liver (Baumann, 1991).

IGF-1 is secreted after GH stimulates liver cell DNA which synthesises the growth factors, secretion of testosterone is also involved in the regulation of IGF-1 (Yeoh & Baxter, 1988; Zorzano *et al.*, 1988). Like GH, IGF-1 interacts with the PI3k/PKB/mTOR/S6k1/4E-BP1signalling network and contributes to an increased rate of protein synthesis following strength training (Rommel *et al.*, 2001; Frost & Lang, 2007). This interaction is mediated by the binding of IGF-1 to the binding proteins. Elevated free IGF-1 following strength training enables increased binding to the receptors located in skeletal muscle which may promote protein synthesis (Forbes *et al.*, 1988; Clemmons, 1989). More recent research has indicated secretion of IGF-1 following strength training stimulates proliferation and differentiation of satellite cells located in the working muscle fibres (Hawke, 2005) (Figure 2.4). Stimulation of these satellite cells contribute to the formation of new nuclear

receptors located within the muscle, which allows increased intramuscular receptor binding with IGF-1 and other hormones associated with anabolism (Adams, 2002). This is thought to contribute to the longer term increases in CSA and strength associated with strength training.

All the hormones previously discussed in this review have been demonstrated to directly and/or indirectly contribute to strength development and fibre hypertrophy (Kraemer & Ratamess, 2005; Spiering *et al.*, 2008), however strength training also elicits increases in hormones associated with the inhibition of protein synthesis and catabolism (Kuoppasalmi & Adlercreutz, 1985; Kraemer *et al.*, 1995). These glucocorticoids primary function is to signal and regulate carbohydrate metabolism, they are also related to intramuscular glycogen stores. When these glycogen stores are depleted other substrates (such as protein) must be catabolised to maintain energy. It is by this mechanism that glucocorticoids may inhibit strength and hypertrophic development (MacDougall, 1986; Florini, 1987) (Figure 2.4). Cortisol accounts for ~95% of the glucocorticoid response to exercise stimulus and is released from the adrenal gland. As a result cortisol is the most researched catabolic hormone in the context of strength training and resultant endocrine and performance responses and adaptations (Kraemer & Ratamess, 2005).

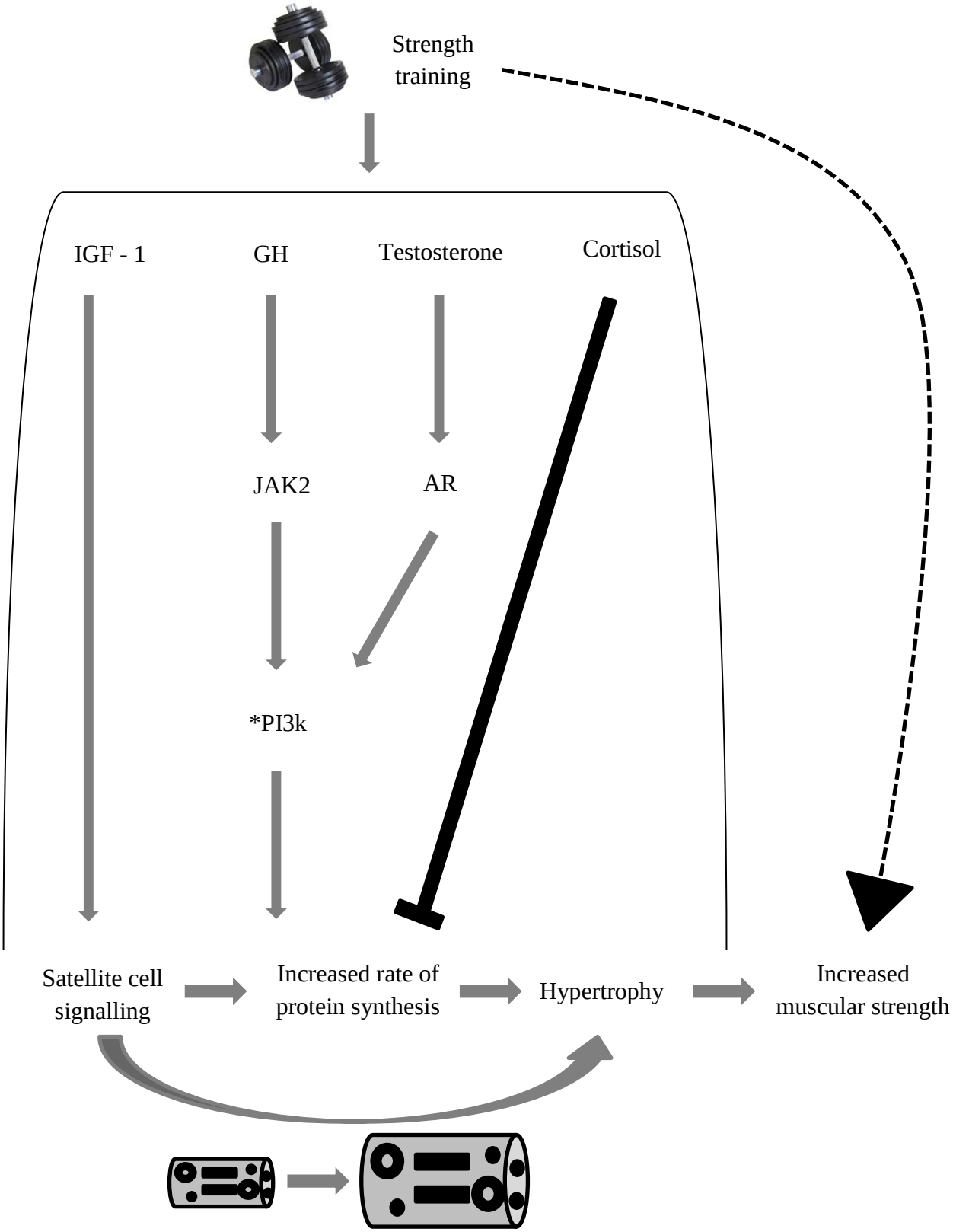

Figure 2.4. Primary endocrine and growth-associated network responses to strength training. Arrows indicate increased activation and horizontal crossed line indicates inhibition. * Initial phase of signalling network. AR =androgen receptors, GH = growth gormone, IGF - 1 = insulin like growth factor 1, JAK2 = janus kinase 2 and PI3k = phosphoinositol 3-kinase.

The responses of the endocrine system to strength training are not all encompassing and are dependent on both the responsive hormone(s) and the nature of the strength training stimulus (McCaulley *et al.*, 2009), these are discussed below;

2.3.3.1 Acute responses

Numerous articles have reported increased total (Weiss *et al.*, 1983; Chandler *et al.*, 1994; Hickson *et al.*, 1994; Kraemer *et al.*, 1998b; Kraemer *et al.*, 1999a; Ahtiainen *et al.*, 2003b; Tremblay *et al.*, 2004) and free testosterone (Ahtiainen *et al.*, 2003b; Durand *et al.*, 2003; Tremblay, Copeland & Van Helder, 2004) as strength training can acutely increase circulating testosterone. The magnitude of these increases can be influenced by exercise selection (Hansen *et al.*, 2001), intensity and volume (Kraemer *et al.*, 1990; Hakkinen & Pakarinen, 1993; Gotshalk *et al.*, 1997) and training status (Kraemer *et al.*, 1998a; Tremblay, Copeland & Van Helder, 2004). Exercises which stimulate large muscle masses including Olympic lifts, squats and deadlifts have been reported to increase testosterone to a greater extent than movements involving less muscle mass (Volek *et al.*, 1997; Kraemer *et al.*, 2008b). As the aforementioned lifts are all potent metabolic stressors, it may be suggested that metabolic components such as blood lactate concentrations (Lac^-) may stimulate testosterone release (Lu *et al.*, 1997). This hypothesis is also supported by the fact hypertrophy based programmes with short rest intervals result in greater testosterone increases than strength based programmes with longer recovery periods (Kraemer *et al.*, 1990).

The magnitude of GH increase in response to acute strength training appears to be dependent on the total work performed in the experimental protocol. The metabolic properties of the prescribed training may also be important as protocols

eliciting high Lac^- tend to produce the most substantial GH elevations (Kraemer *et al.*, 1990; Gotshalk *et al.*, 1997; Hoffman *et al.*, 2003; Kraemer *et al.*, 2003). As high correlations between Lac^- and GH have been reported (Hakkinen & Pakarinen, 1993) it may be suggested that Hydrogen (H^+) accumulation as a result of lactic acidosis may be a key factor influencing acute GH release (Kraemer *et al.*, 1993). This indicates high volume and intensity strength training is a prominent precursor to elevated levels of GH.

Programmes which elicit substantial GH and Lac^- also seem to elicit the greatest cortisol response (Ratamess *et al.*, 2005). This may indicate that like GH, cortisol responses are greater when the strength training protocol involves a high metabolic demand (high repetitions and short rest periods) (Hakkinen & Pakarinen, 1993; Kraemer *et al.*, 1993). These responses do not appear to be influenced by training status as both those accustomed and unaccustomed to strength training display similar elevations in cortisol (Kraemer *et al.*, 2008b).

The acute responses of IGF-1 to resistance exercise stimulus is a contentious area as some authors report no change in IGF-1 during or following (< 2 h) strength training (Chandler *et al.*, 1994; Kraemer *et al.*, 1998b; Kraemer *et al.*, 2008c), whereas others have observed acute elevations during and post (< 2 h) comparable strength training protocols (Kraemer *et al.*, 1990; Rubin *et al.*, 2005). The lack of acute IGF-1 elevation may be attributed to the fact peak IGF-1 release is delayed until GH stimulated mRNA synthesis and secretion from the liver can take place. As such, elevations in IGF-1 may not peak until 16-28 h post the initial strength training induced GH release (Chandler *et al.*, 1994) (Kraemer *et al.*, 1993). This may partly explain why various researchers have observed no acute increase in IGF-1, as few studies monitor levels >2 h post strength training.

2.3.3.2 Chronic adaptations

The long-term effect of strength training on testosterone appears less conclusive than the acute responses. Furthermore, there is much debate on whether testosterone plays a mechanistic role within strength training and subsequent hypertrophy and strength development or is simply a marker of adaptation. Research indicates that resting testosterone levels are a more accurate reflection of the current state of the muscle tissue than the global training status of the individual (Ahtiainen *et al.*, 2003a). It has been reported that basal testosterone levels may increase during chronic strength training (Kraemer *et al.*, 1999b; Marx *et al.*, 2001). However, other researchers have suggested that these increases only occur when volume and intensity of the programme are high (i.e. relatively high repetitions and short rest periods) (Ahtiainen *et al.*, 2003a). Both Raastad *et al.* (2001) and Ahtiainen *et al.* (2003a) reported increased resting testosterone concentrations during high volume strength training. However, when training volume decreased a concomitant reduction in resting testosterone levels was observed (~12%). As such, changes in volume and intensity of strength training performed may result in temporary adaptations in basal testosterone levels, these however may return to baseline when volume and intensity of strength training is reduced. Whilst the effects of prolonged strength training on basal testosterone levels are somewhat inconclusive, Tremblay, Copeland and Van Helder (2004) and Kraemer *et al.* (1999b) reported the testosterone response to strength training was greater in those who regularly performed resistance training. Although basal concentrations were not different these data indicate a heightened response of testosterone to resistance exercise stimulus as a result of prolonged strength training. This may be due to enhanced adrenergic sensitivity or secretory capacity of the Leydig cells (in males) (Fry & Kraemer, 1997).

The majority of research examining the influence of chronic strength training on resting GH concentrations has reported no significant affect in both men and women of various ages and training status (Kraemer *et al.*, 1999b; McCall *et al.*, 1999; Hakkinen *et al.*, 2000; Marx *et al.*, 2001; Ahtiainen *et al.*, 2003a). The lack of chronic change in basal GH concentrations may suggest that the acute GH response to strength training stimuli is the most prominent for tissue remodelling. This is supported by the fact McCall *et al.* (1999) reported strong correlations between fibre hypertrophy and strength training induced increases in GH (type I fibres: $r = 0.74$, type II fibres: $r = 0.71$, both $p < 0.05$). This was however observed in a relatively low sample (n = 11). Similar data were reported in a far greater sample (n = 56) by West and Phillips (2012) although correlations were notably weaker (type I fibres: $r = 0.36$, $p = 0.006$, type II fibres: $r = 0.28$, $p = 0.04$).

The chronic adaptations of IGF-1 in response to strength training appear somewhat more conclusive than acute responses. Although a small number of studies employing short term resistance training have reported no changes in basal IGF-1 (Kraemer *et al.*, 1999b; McCall *et al.*, 1999) the majority of published literature has observed some form of adaptation in circulating levels of IGF-1. Rubin *et al.* (2005) noted IGF-1 concentrations were higher in resistance-trained men than untrained counterparts. Significant elevations in resting IGF-1 concentrations have occurred following 13 weeks of strength training (Borst *et al.*, 2001) and similar increases were also demonstrated by Marx *et al.* (2001). The authors also observed the magnitude of increases were greater in participants who followed a high volume, multi-set programme. Similarly in female populations' high volume resistance training has elicited the greatest responses in resting IGF-1 levels (Koziris *et al.*,

1999). These findings indicate that adaptations in basal IGF-1 in response to prolonged strength training are dependent on overall training volume.

Various authors have reported no change in resting cortisol levels as a result of chronic strength training (Fry *et al.*, 1994; Potteiger *et al.*, 1995; Hakkinen *et al.*, 2000; Ahtiainen *et al.*, 2003a). Basal cortisol levels appear to be more representative of overall training induced physiological stress than strength training status (Bosco *et al.*, 2000). As such resting cortisol levels do not differ between trained and untrained individuals. However, in those of similar training status (e.g. highly strength trained athletes or recreationally trained non-athletes) individuals under elevated training induced physiological stress may display higher cortisol levels that those who are not (Kraemer & Ratamess, 2005).

It is evident that the endocrine responses to strength training influence muscle morphology and strength development. As such, strength training protocols eliciting high circulating concentrations of anabolic hormones may promote the greatest increases in muscular strength (Hansen *et al.*, 2001). Whether this is a direct result of increases in circulating anabolic hormones or receptor binding augmenting protein synthesis remains unclear. What is clear however is that increased rates of protein synthesis are essential for strength training to induce increased contractile strength and CSA.

2.3.4 Molecular and signalling responses to strength training

Protein synthesis is not only augmented by the aforementioned binding of anabolic hormones to nuclear receptors, strength training also stimulates cellular signalling pathways and satellite cells which result in increased rates of protein synthesis. This is thought to be a compensatory response to the physiological stress

experienced during strength training (Phillips *et al.*, 1997; Nader & Esser, 2001; Bolster *et al.*, 2003). This is illustrated by the fact strength training results in protein breakdown, this is coupled with a disproportionate increase in protein synthesis eliciting and overall increase in protein synthesis (Spiering *et al.*, 2008). MacDougall *et al.* (1995) reported strength training resulted in a 50% increase in protein synthesis 4 h post exercise and a 115% increase 24 h post cessation of strength training. It was also reported that rate of protein synthesis did not return to resting levels until 36 h post exercise. This acute increased rate of protein synthesis is not sufficient to alter muscle or performance phenotypes (Baar, 2006). However, overloaded strength training performed consistently over time results in increased muscle mass and strength as a result of continued increased intramuscular protein synthesis (Phillips *et al.*, 1997). There is also evidence to suggest that repeated strength training causes a change in the basal state of the muscle, resulting in a greater capacity for increased protein synthesis in response to exercise stimulus (Yan *et al.*, 1993; Winder & Hardie, 1996; Goldspink, 1999).

Although the precise mechano-sensory mechanisms by which strength training influences protein synthesis are yet to be fully elucidated, analysis techniques employed in biochemistry and molecular biology has allowed researchers to determine the signalling activities which ultimately result in increased protein synthesis as a result of resistance exercise. It has been demonstrated that strength training-induced increases in protein synthesis are primarily regulated by the mTOR signalling network (Richter & Sonenberg, 2005; Jastrzebski *et al.*, 2007) (Figure 2.5). This network acts as a key signalling hub and integrates nutritional, hypoxic, energy stress, endocrine and mechanical stimulus to regulate protein synthesis (Hamilton & Philp, 2013).

As a result of strength training stimulated satellite cell signalling and/or binding of anabolic hormones to the nuclear receptors PI3k is activated, this is the first signalling protein phosphorylated in the mTOR network (McManus *et al.*, 2004; Cuthbertson *et al.*, 2006). Subsequent phosphorylation of protein kinase B (PKB) results in activation of mTOR (Nader & Esser, 2001; Bolster *et al.*, 2003). mTOR's primary downstream targets have been defined as eukaryotic initiation factor 4E (eIF4E), 4E binding protein 1 (4E-BP1) and 70-kDa S6 protein kinase (S6k1) (Bolster *et al.*, 2004) and it is at this "initiation phase" rate of protein synthesis is regulated (Mendez *et al.*, 1997). It should also be noted that like all adaptations to strength training the responses of the PI3k/PKB/mTOR/S6k1/4E-BP1 growth signalling network are not all encompassing and are dependent on the application of the acute programme variables detailed in Table 2.1 and the nature of strength training performed (Newman, 2008).

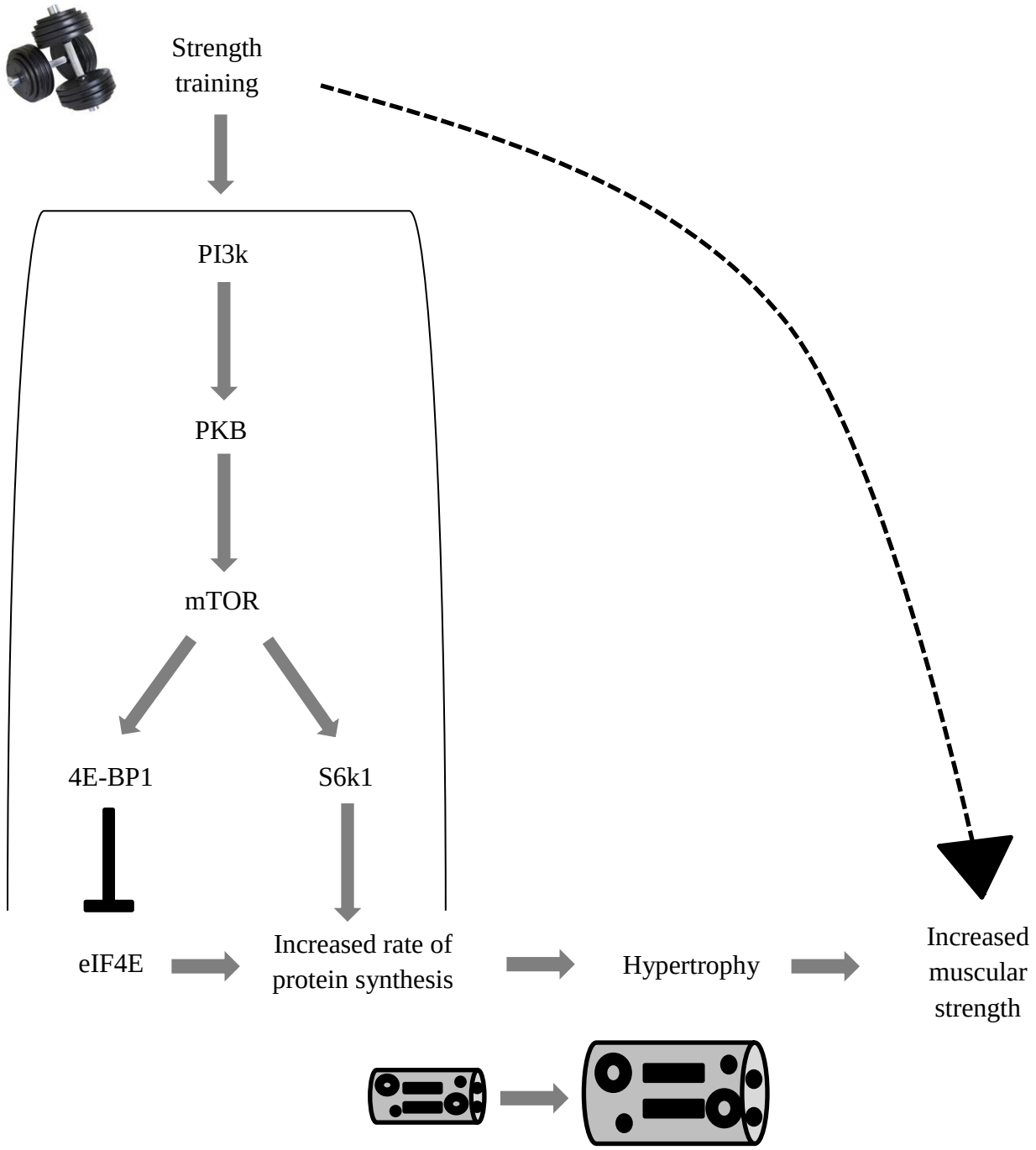

Figure 2.5. Schematic of the PI3k/PKB/mTOR/S6k1/4E-BP1 growth associated signalling network and its relationship with strength training related adaptation. Arrows indicate subsequent increased phosphorylation and horizontal crossed line indicates inhibition. Dashed line indicates primary result of strength training. 4E-BP1 = 4E binding protein 1; eIF4E = eukaryotic initiation factor 4E; mTOR = mammalian target of rapamycin; PI3k = phosphoinositol 3-kinase; PKB = protein kinase B; S6k1 = 70-kDa S6 protein kinase.

As previously discussed exercises and lifts which stimulate larger muscle masses including deadlifts, back squats and Olympic lifts promote greater anabolic hormone tissue interactions than small muscle group exercises (e.g. bicep curls) (Nindl *et al.*, 2003). As these hormones promote satellite cell signalling and activation of the mTOR network it is reasonable to suggest that the greatest increases in anabolic signalling and protein synthesis are elicited by exercises involving large muscle mass, although the has not yet been directly investigated. Research has however investigated the responses of the mTOR network to concentric and eccentric muscular contractions. Eliasson *et al.* (2006) reported maximal eccentric actions produce greater increases in phosphorylated S6k1 than maximal concentric contractions, due to the increased muscular tension associated with eccentric muscle actions. This may also be a compensatory response to the greater stress and muscle damage elicited by eccentric type strength training (Nosaka & Newton, 2002).

Whilst it appears the type of contractions performed during strength training influences phosphorylation of proteins within the mTOR network, there is limited data pertaining to the effect of strength training load on protein synthesis. However, studies employing high-frequency electrical stimulation (which stimulated high force contractions, like those associated with strength training with high loads) and low frequency electrical stimulation (which stimulated low force contractions) (Nader & Esser, 2001; Atherton *et al.*, 2005) have provided inferences which may allow us to hypothesize how training load may influence molecular signalling. The higher force contractions elicited increased phosphorylation of mTOR and its downstream targets which regulate protein synthesis, whereas the lower force contractions resulted in activation of the divergent adenosine monophosphate activated protein kinase (AMPK) signalling network, which is associated with energy maintenance (this

network will be discussed in detail in section 2.4.5). These data indicate that higher loads may stimulate greater activation of the mTOR signalling network and subsequent protein synthesis. Like training load there is also a dearth of research examining the molecular adaptations to differing volumes of strength training.

Training volume and its influence on strength and hypertrophic adaptation is somewhat paradoxical. From one perspective adequate volume of strength training is necessary for gains in muscular CSA and contractile strength (Borst *et al.*, 2001). However high volume strength training may also result in glycogen depletion, which is a prominent precursor to cortisol catabolising protein and phosphorylation of the previously mentioned AMPK network (Steinberg *et al.*, 2006). The AMPK network is also activated following endurance type exercise and research conducted in murine models has indicated it may directly inhibit phosphorylation of the mTOR network and protein synthesis (Inoki *et al.*, 2003; Nader, 2006) (this will be discussed in detail in sections 2.4.5 and 2.6.6).

Although there is limited published research on the manipulation of the acute programme and their influence on intramuscular protein synthesis it is clear that the mTOR network is an important mediator of strength and hypertrophic adaptation. This network and it's interaction with other signalling pathways is of particular importance in the context of this thesis as cross talk between the mTOR and AMPK networks may result in attenuated protein synthesis when concurrent training is performed.

2.4 Endurance training

Jones & Carter (2000) defined endurance as "the capacity to sustain a given velocity or power output for the longest possible time". As such the primary

requirement for endurance performance is the ability to sustain repeated muscular contractions at a given submaximal intensity (Hawley, 2002). For the purposes of this review and throughout this thesis, endurance training will be considered as continuous exercise lasting between 5 and 240 min at relative intensities between 30 – 90% heart rate max and $\dot{V}O_{2max}$. Exercise of shorter durations requires significant contributions from anaerobic and metabolic pathways and exercise of longer durations is heavily influenced by psychological and nutritional factors (Hill, 1999; Jones & Carter, 2000). Like strength training, endurance exercise involves a complex integration of physiological functions and responses which ultimately result in improved endurance performance (Hawley *et al.*, 1997).

2.4.1 $\dot{V}O_2$ kinetics and endurance training

The ability to sustain repeated muscular contractions relies heavily on the aerobic resynthesis of adenosine triphosphate (ATP). For efficient resynthesis adequate atmospheric oxygen delivery to the cytochrome oxidase in the mitochondrial electron transport chain is essential (Davies & Thompson, 1979; Léger *et al.*, 1986). As such oxygen delivery to the working muscles is a key factor in endurance training and performance. $\dot{V}O_{2max}$ has long been associated with endurance performance (Hermansen & Saltin, 1969; Costill *et al.*, 1973) and is largely dependent on the rate at which oxygen can be supplied to muscles (Saltin & Strange, 1992). Following an endurance training programme, research has demonstrated that adaptations to the working muscles require reduced blood flow at comparable submaximal intensities. This is due to increased arterio-venous oxygen differences (Paterson *et al.*, 1979). Coupled with increased stroke volume and reduced heart rate at submaximal intensities this results in an increased $\dot{V}O_{2max}$ and

subsequent improvements in endurance performance (Shephard, 1992; Spina *et al.*, 1993).

In addition to these adaptations, endurance training also improves the oxygen carrying and transport capacities of blood via increased total blood haemoglobin (Green *et al.*, 1990). As most studies report increased $\dot{V}O_{2max}$ and endurance performance following endurance training, it is difficult to ascertain if there is an optimal exercise volume and intensity for developing this phenotype. There is however evidence to suggest that regardless of overload during long-term training $\dot{V}O_{2max}$ will stabilise and further improvements in endurance performance are largely products of improved economy and lactate threshold (Jones, 1998; Pierce *et al.*, 2008).

2.4.2 Economy and endurance training

Exercise economy has been defined as "the steady state $\dot{V}O_2$ measured in ml·kg·min at a given absolute exercise intensity" (Costill, Thomason & Roberts, 1973; Storen *et al.*, 2008). Improvements in economy result in a utilisation of a lower percentage of $\dot{V}O_{2max}$ at the same given exercise intensity (Morgan *et al.*, 1995). Research has elucidated that overall training volume is the primary factor in improving endurance exercise economy, as the best economy levels are often observed in more experienced distance athletes who complete large weekly mileages (Pate *et al.*, 1992; Jones, 1998).

More recent research has indicated strength training may be an effective means of improving endurance exercise economy (Paavolainen *et al.*, 1999; Millet *et al.*, 2002; Storen *et al.*, 2008). Millet *et al.* (2002), Paavolainen *et al.* (1999) and Storen *et al.* (2008) all reported 5.0 – 7.8% improvements in running economy

following 8 – 9 weeks of strength training. These improvements in economy were coupled with improvements in time to exhaustion and/or time trial performance without any increases in $\dot{V}O_{2max}$. Similar data have also been reported in cross county skiers (Hoff *et al.*, 2002; Østerås *et al.*, 2002), although the improvements in economy were more pronounced (9.0 and 27.0% respectively). This may be due to the fact there is far greater contribution of the upper body in cross country skiing than running. As such it is unsurprising that whole body strength training had an enhanced effect on performance. The mechanism for this enhanced economy and endurance performance is likely that a lower percentage of maximal strength would be taxed per stride/revolution lowering the demands of motor units recruited (Hoff, Gran & Helgerud, 2002). Also, time to peak force achieved is lessened due to the increased rate of force development (RFD) associated with strength training. This in turn would increase the relaxation time in each stride/revolution and result in better circulatory flow through the working muscles and improved access to O_2 and other necessary substrates. All of these factors combined may contribute to improved time trial performance and/or time to exhaustion.

2.4.3 Fibre type transformations and endurance training

As previously discussed in section 2.3.2, slow type I muscle fibres have both greater mitochondrial volume densities and capillary-fibre content than both variations of type II fibres (Sullivan & Pittman, 1987). Slow oxidative fibres are also far more fatigue resistant than their type II counterparts (Costill, Daniels & Fink, 1978), and as such it is unsurprising that high proportions of type I fibres have been associated with high $\dot{V}O_{2max}$ values and endurance performance (Bergh *et al.*, 1978; Costill, Daniels & Fink, 1978).

Like strength training, endurance training can result in altered relative fibre type composition within trained muscle. Research has demonstrated both cycling and running based aerobic training protocols have increased the percentage of slow oxidative fibres coupled with a decreased percentage of fast oxidative and fast glycolytic fibres (Jansson *et al.*, 1978; Howald *et al.*, 1985; Simoneau *et al.*, 1985a; Sale *et al.*, 1990). There is also evidence to suggest that endurance training may cause increased expression of slow myosin in type II fibres which in turn reduces the contractile speed and results in diminished energy expenditure (Fitts *et al.*, 1989). This may not apply to all endurance exercise modalities however as the increased expression of slow myosin has primarily been reported in swimming.

Fibre type and relative composition shifting in favour of slow myosin and slow type I fibres is beneficial for steady state endurance performance. However, there are also implications for muscle force production. Endurance training-induced shifts from fast to slow type muscle fibres reduce the force generating capabilities of the muscle (Widrick *et al.*, 2002; Malisoux *et al.*, 2006). Consequently this adaptation is likely to negatively impact performance in events which require the working musculature to produce high forces rapidly. These may include sprint and power events or indeed middle distance races that have the potential requirement for a sprint finish (Figure 2.3).

2.4.4 Mitochondrial biogenesis and endurance training

Research has indicated that mitochondria are the primary subcellular structures that influence the oxidative capacity and fatigue resistance to repeated contractile activity of skeletal muscle (Hoppeler & Fluck, 2003). Mitochondrial biogenesis refers to the up regulation of mitochondrial mass and function and is one

of the primary and most important adaptations to endurance training (Yan *et al.*, 2011). Holloszy (1967) was the first to report that endurance training resulted in mitochondrial biogenesis in human skeletal muscle. This important and novel finding was subsequently confirmed by follow up research investigating the mitochondrial adaptations to endurance training (Holloszy & Booth, 1976; Saltin *et al.*, 1976). Further research has since suggested the increase in muscle mitochondria is meditated by contractile activity rather than external stimuli such as alteration in the metabolic and endocrine environment. This may be evidenced by observations that mitochondrial adaptations are limited to the specific fibres that are recruited during endurance training (Gollnick *et al.*, 1972; Saltin *et al.*, 1976; Henriksson, 1977).

2.4.5 Molecular and signalling factors and endurance training

Research indicates the two primary signalling responses to endurance exercise are i) the repetitive rise in free calcium in response to repeated muscular contractions, and ii) the activation of the energy-modulating AMPK signalling network (Winder *et al.*, 2006). This progressive increase in the Adenosine Monophosphate (AMP):ATP ratio and levels of free calcium are thought to be the primary signals responsible for muscular adaptation to endurance exercise stimulus (Holloszy, 2005; Baar, 2006) (Figure 2.6).

The endurance training induced rise in the AMP:ATP ratio increases the amount of AMP bound to AMPK. This reaction alters the conformation of AMPK and makes it a more effective substrate for upstream active kinase Liver Kinase B1 (LKB1). This increases AMPK phosphorylation during and after endurance exercise (Hardie & Sakamoto, 2006). Research has elucidated to the fact that AMPK's main

function is to monitor the energy status of muscle cells, or act as a “metabolic fuel gauge” (Winder, 2001) (Figure 2.6). This hypothesis is based on the fact that AMPK seems to be primarily activated in response to decreased energy levels associated with repeated muscular contractions (Hawley, 2009). It has also been reported that AMPK inhibits ATP-consuming pathways (such as mTOR and protein metabolism) and simultaneously activates pathways involving carbohydrate (CHO) and fatty acid catabolism to restore ATP levels (Hardie & Sakamoto, 2006).

In addition to the activation of AMPK endurance training also stimulates a rise in intracellular free calcium (Baar, 2006). This increase activates calcium-sensitive signalling molecules; including calcium-activated protein kinase (CamK). The active AMPK and CamK phosphorylate the enzyme histone deacetylases (HDAC) and the protein myocyte-enhancing factor 2(MEF 2), both of which regulate gene expression of peroxisome proliferator-activated receptor gamma, co activator 1 alpha (PGC-1α) (Czubryt *et al.*, 2003). This is an important gene which activates and regulates the expression of mitochondrial proteins (Lin *et al.*, 2005). Research has demonstrated an acute bout of aerobic exercise induces increases PGC-1α expression and mitochondrial protein content in skeletal muscle (Irrcher *et al.*, 2003). This leads to elevated mitochondrial biogenesis, which as previously discussed is key adaptation to endurance training.

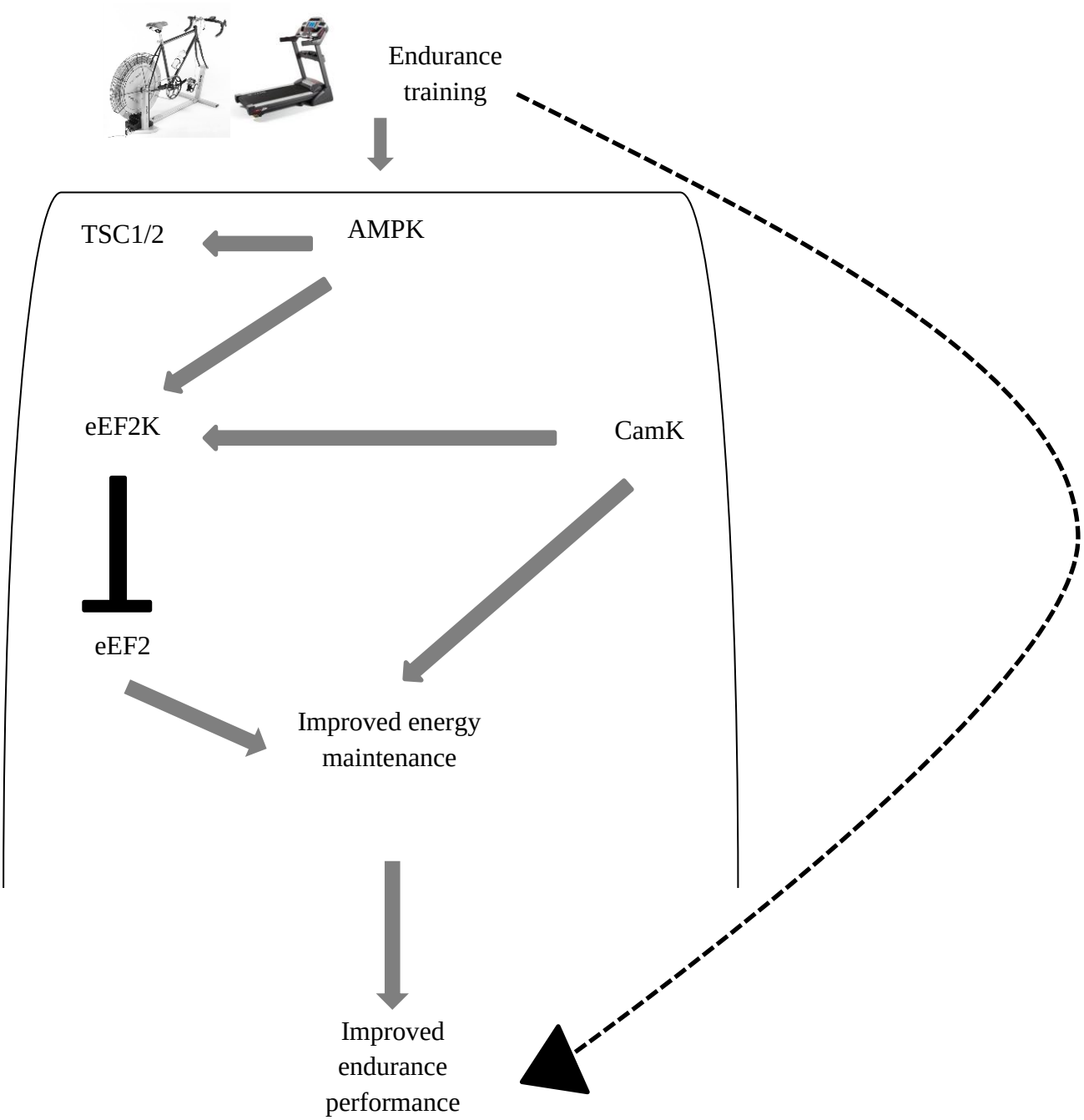

Figure 2.6. Schematic of the AMPK energy modulating signalling network and its relationship with endurance training related adaptation. Arrows indicate subsequent increased phosphorylation and horizontal crossed line indicates inhibition. Dashed line indicates primary result of endurance training. AMPK = adenosine monophosphate activated protein kinase; CamK = calcium-activated protein kinase; eEF2 = eukaryotic elongation factor 2; eEF2k = eukaryotic elongation factor 2 kinase; TSC1/2 = tuberous sclerosis complex 1/2.

2.5 The Interference Phenomenon

As previously discussed, strength and endurance training result in vastly differing physiological and performance responses (Goldberg, 1968; 1969; Holloszy & Booth, 1976; Holloszy & Coyle, 1984). This is due to the extremely malleable nature of human skeletal muscle and the specificity of physiological responses to exercise stimulus (Coffey & Hawley, 2007). Achieving improved strength and endurance phenotypes requires contrasting training methodologies and ultimately results in divergent biochemical, neural and performance adaptations. Despite this fact, concurrent strength and endurance training remains common practice in sports events which require both strength and endurance capabilities (as depicted in Figure 2.3 “the strength-endurance continuum”) and recreational exercise.

Numerous studies have investigated the effects of a variety of concurrent training regimens on strength, performance and muscular growth responses (Table 2.2). Additional research has also sought to examine the underlying physiological mechanisms behind the interference phenomenon. Initial research into concurrent training primarily focused on the effects of concurrent training regimens on physical performance measures. Prior to the mid 90’s no researchers assessed any potential physiological mechanisms for the observed interference. This however did not prevent hypothesis’ being formulated about why the inhibition of strength, power and hypertrophic responses may occur. The “chronic” and “acute” hypotheses were subsequently proposed.

Table 2.2. Summary of research investigating the effects of concurrent strength and endurance training programmes on strength and hypertrophic adaptations.

Author(s)	WK	Details of training intervention	Strength training protocol	Endurance training protocol	Strength and/or hypertrophic interference?
Marta *et al*. (2013)	8	**S** 2 d/wk **C** 2 d/wk **S** & **E** same session	Medicine ball throws and plyometric jumps	Repeated shuttle runs @ ~75% $\dot{V}O_{2max}$	**No**
Holviala *et al*. (2012)	21	**S** 2 d/wk **C S** 2 d/wk & **E** 2 d/wk separate days	Multi joint and periodized using fixed equipment	Cycle ergometry for 30 min under lactate threshold	**No**
Santos *et al*. (2012)	8	**S** 2 d/wk **C** 2 d/wk **S** & **E** same session	Medicine ball throws and plyometric jumps	Repeated shuttle runs @ ~75% $\dot{V}O_{2max}$	**No**
Silva *et al*. (2012)	11	**S** 2 d/wk **C** 2 d/wk **S** & **E** same session	Multi joint and periodized using fixed equipment and free weights	4 conditions; interval cycling, interval running, continuous cycling and interval running	**No**
Karavirta *et al*. (2011)	21	**S** 2 d/wk **C S** 2 d/wk & **E** 3 d/wk separate days	Multi joint and periodized using fixed equipment and free weights	Cycle ergometry for 30 min under lactate threshold	**Yes** – Impaired strength and hypertrophic responses
Hendrickson *et al*. (2010)	8	**S** 3 d/wk **C** 3 d/wk same session	Multi joint and periodized on fixed equipment	Interval and continuous running	**No**

Cadore *et al*. (2010)	12	**S** 3 d/wk **C** 3 d/wk same session	Multi joint and periodized using fixed equipment and free weights	Interval and continuous cycle ergometry	**Yes** – Impaired maximal isometric strength
Wong *et al*. (2010)	8	**S** 2 d/wk **C S** & **E** 2 d/wk same day	Multi joint using free weights, 4 sets of 6RM with 3 min rest intervals	Sprint (running) intervals	**No**
Sillanpaa *et al*. (2009)	21	**S** 2 d/wk **C S** 2 d/wk **E** 2 d/wk separate days	Multi joint and periodized using fixed equipment	Interval and continuous cycle ergometry	**No**
Gergely (2009)	9	**S** 2 d/wk **C S** & **E** 2 d/wk separate days	Lower body only and periodized on fixed equipment	2 conditions; continuous cycle ergometry or running both for 20 – 40 min @ 65% max HR	**Yes** – Impaired strength gains
Shaw *et al*. (2009)	16	**S** 3 d/wk **C S & E** 3 d/wk separate days	Multi joint using fixed equipment and free weights, 2 sets of 15 reps @ 60% 1RM	Combination of running, rowing, stepping and cycle ergometry for 22 min @ 60% max HR	**No**
Bell *et al*. (2008)	12	**S** 3 d/wk **C S** 3 d/wk & **E** 3 d/wk separate days	Multi joint and periodized using fixed equipment and free weights	Continuous running @ 70% $\dot{V}O_{2max}$	**No**

Chtara *et al*. (2008)	12	**S** 2 d/wk **E** 2 d/wk **C** (**S** – **E**) 2 d/wk same session **C** (**E** – **S**)	Mutli joint and periodized combined circuit type strength endurance and power training using body weight and free weights	Interval and continuous running	**No**
Izquierdo *et al*. (2005)	16	**S** 2 d/wk **E** 2 d/wk **C** 1 x **S** & 1 x **E** once weekly	3 conditions; 4 exercises to failure, 4 exercises not to failure and 2 exercises not to failure, all pull exercises using fixed equipment and free weights	Rowing training similar to that of "Olympic rowing"	**Yes** – Lower limb strength inhibited
Glowacki *et al*. (2004)	12	**S** 2 3 x wk **E** 2 – 3 wk **C** 5 x wk	Multi joint and periodized using fixed equipment and free weights	Interval and continuous cycle ergometry	**No**
Hakkinen *et al*. (2003)	21	**S** 2 d/wk **C** 2 x **S** & 2 x **E**	Lower body only and periodized on fixed equipment	Continuous cycle ergometry below and above lactate threshold	**Yes** – Attenuated explosive strength
Balabinis *et al*. (2003)	7	**S** 4 d/wk **E** 4 d/wk **C S** & **E** same day	Lower body only and periodized on fixed equipment	Continuous cycle ergometry @ ~70% $\dot{V}O_{2max}$	**No**

Millet *et al*. (2002)	14	**E** variable **C E & S**-2 x wk	Lower body only and periodized using fixed equipment and free weights	Triathlon "pre-condition phase"	**No**
McCarty *et al*. (2002)	10	**S** 3 d/wk **E** 3 d/wk **C** combined **S** & **E** in same session	Multi joint and periodized using fixed equipment and free weights	Continuous cycle ergometry 50 min @ 70% HRR	**No**
Bell *et al*. (2000)	12	**S** 3 d/wk **E** 3 d/wk **C S** & **E** alternate days	Multi joint and periodized using fixed equipment and free weights	Interval and continuous cycle ergometry	**Yes** – Impaired strength gains
Horne *et al*. (1997)	12	**S** 3 d/wk **E** 3 d/wk **C S** & **E** alternate days	Multi joint and periodized using fixed equipment	Interval and continuous running	**Yes** – Impaired strength gains
Kraemer *et al*. (1995)	12	**S** 4 d/wk **E** 4 d/wk **C S** & **E** same day	Multi joint and periodized using fixed equipment and free weights	Interval and continuous running	**Yes** – Impaired strength gains
McCarthy *et al* (1995)	10	**S** 3 d/wk **E** 3 d/wk **C** combined **S** & **E** in same session	Multi joint and periodized using fixed equipment and free weights	Continuous cycle ergometry 50 min @ 70% HRR	**No**

Hennessy & Watson (1994)	8	**S** 3 d/wk **E** 4 d/wk **C** random **S** & **E** combined & separate 5 d/wk	Multi joint and periodized using fixed equipment and free weights	Continuous running for 30 – 40 min @ 60% v$\dot{V}O_{2max}$	**Yes** – Impaired strength gains
Nelson *et al*. (1990)	20	**S** 4 d/wk **E** 4 d/wk **C S** & **E** same day	Unilateral knee extension and flexion performed on a dynamometer, 3 sets of 6 maximal efforts @ 0.52 rad·s^{-1}	Cycle ergometry for 30 – 60 min @ 75 – 85% max HR @ 83 RPM	**No**
Hunter *et al*. (1987)	12	**S** 4 d/wk **E** 4 d/wk **C S** & **E** same day	Multi joint and periodized using fixed equipment and free weights	Interval and continuous running	**Yes** – Reduced CMJ
Dudley & Djamil (1985)	7	**S** 3 x wk **E** 3 x wk **C S** & **E** alternate days	Unilateral leg extensions performed on a dynamometer, 2 sets of maximal voluntary efforts to failure @ 4.19 rad·s^{-1}	Interval cycle ergometry	**Yes** – Reduced peak torque at high velocities
Hickson (1980)	10	**S** 5 d/wk **E** 6 d/wk **C S** & **E** same day	Lower body only and periodized on fixed equipment and using free weights, 5 sets of 5 @ 80% 1RM with 3 min rest intervals	Interval and continuous running	**Yes** – Impaired strength gains

S = strength training, **E** = endurance training and **C** = concurrent training.

2.5.1 The chronic hypothesis

The chronic hypothesis suggests that the trained muscle is placed under a situation of conflict during a concurrent training programme as the muscle is attempting to adapt simultaneously to both forms of training (i.e. strength and endurance) (Leveritt *et al.*, 1999). As the nature of adaptations to strength and endurance training are so divergent (see sections 2.3 and 2.4 for more information) it is reasonable to suggest that the trained muscles are not able to optimally adapt to the strength training stimulus. Research has indicated that impaired strength as a result of combining strength and endurance training may be due to sub optimal neural (Häkkinen *et al.*, 2003), fibre type (Kraemer *et al.*, 1995), endocrine (Kraemer *et al.*, 1995) and molecular (Baar, 2006) adaptations. These mechanisms recognised as determinates of the 'chronic hypothesis' will be further discussed in section 2.6.

2.5.2 The acute hypothesis

The acute hypothesis was first proposed by Craig *et al.* (1991) who reported running immediately before weightlifting resulted in inhibition of lower body strength development. This hypothesis contends that simply performing strength and endurance training concurrently may not inhibit strength development. Rather that scheduling of strength and endurance training session's results in diminished quality and intensity of strength training due to residual fatigue. It was proposed that this residual fatigue as a result of previous endurance training may compromise the ability of the trained muscles to develop adequate muscular tension during strength training (Craig *et al.*, 1991). This suggestion is supported by the fact that the degree of tension developed during strength training is a key factor influencing strength development (Atha, 1981). As such, the acute hypothesis states that interference may

potentially be avoided via appropriate programme design. More recent research has indicated divergent anabolic signalling may be associated with diminished strength adaption (Nader, 2006; Baar, 2009; Coffey *et al.*, 2009a; Coffey *et al.*, 2009b) which may also play a role in the acute hypothesis. These variances in the anabolic:catabolic environment and sub optimal signalling as a result of poor scheduling of strength and endurance training are discussed in detail in sections 2.6.5 and 2.6.6.

2.5.3 Programme variables

Investigations into concurrent training and the interference phenomenon have employed a variety of strength and endurance training protocols in an effort to determine the underlying mechanisms that regulate physiological adaptation. These interventions differ in exercise modality, body parts targeted, intensity, frequency and the sequencing of exercise. Whilst these variations in experimental protocols provide information on various programme variables and their association with any interference it also makes comparisons between studies difficult.

2.5.3.1 Exercise modality

Research involving isoinertial strength training has reported strength inhibition when combined with endurance training. In the original study in which interference was assessed Hickson (1980) focused on the development of lower limb strength and employed exercises including back squats, seated leg extensions and seated leg press. Dudley and Djamil (1985) also examined lower limb only training but only included seated leg extensions performed on an isokinetic dynamometer. Hennessy and Watson (1994) and Kraemer *et al.* (1995) employed more functional

and multi-joint models and unlike Hickson (1980) and Dudley and Djamil (1985) assessed both lower and upper body strength adaptation. Power development also seems to be inhibited in studies utilising isoinertial strength training in a concurrent programme (Hunter *et al.*, 1987; Hennessy & Watson, 1994; Kraemer *et al.*, 1995; Häkkinen *et al.*, 2003). Elsewhere, separate research has indicated concurrent training does not attenuate the development of isokinetic strength at slow contractile speeds (<1.7 rad $\cdot$ s^{-1}), whereas at higher speeds maximal force production was inhibited in the same muscle groups (Dudley & Djamil, 1985; Nelson *et al.*, 1990; Craig *et al.*, 1991; Abernethy & Quigley, 1993). It may therefore be suggested that power and explosive strength phenotypes may be more susceptible to interference than maximal strength (Hunter, Demment & Miller, 1987; Häkkinen *et al.*, 2003).

In the body of published literature pertaining to concurrent training both cycling and running are the most frequently used endurance exercise modalities. When reviewing published articles examining the effects of running and/or cycling on interference it appears that running results in greater attenuation of strength and hypertrophic responses than cycling. A recent meta-analysis conducted by Wilson *et al.* (2011) revealed concurrent training with running, but not with cycling resulted in significant inhibition of lower body strength and hypertrophy. This is perhaps attributable to the fact cycling involves biomechanical movement patterns with greater similarity to many of the compound lifts employed as measures of lower body strength (Gregory *et al.*, 1991; Escamilla, 2001; Gergley, 2009). As such, it is possible there may be less competing stimuli within the trained muscles as the mechanics of the movements are at least similar. Furthermore the eccentric lower body muscle loading associated with running may result in more muscle damage than cycling. This suggestion is not unreasonable as eccentric contractions have been

shown to result in greater muscle damage than concentric muscle activity on numerous occasions (Hather *et al.*, 1991; Cleak & Eston, 1992; Nosaka & Newton, 2002). A potential third explanation is that cycling itself may result in increased strength and hypertrophy of the lower limb musculature (Macaluso *et al.*, 2003; Mascher *et al.*, 2011; Mikkola *et al.*, 2012). This suggests that the stimulus of cycling is more similar to that of strength training than running, and is supported by research demonstrating signalling pathways associated with strength training adaptation and protein synthesis are similarly activated by cycling and strength training (Mascher *et al.*, 2011).

As previously stated the variability in protocols employed in separate studies make direct comparisons within the literature difficult. It also seems possible that differences in both strength and endurance training protocols induce differing levels of interference as a result of the specificity of biomechanical and/or neuromuscular adaptation (Docherty & Sporer, 2000). It is therefore difficult to make general conclusions about the interference effect from the current body of published research.

2.5.3.2 Upper vs. lower body

It has been suggested that interference may be body part specific. This is largely due to the fact that the few studies which have employed upper body strength and endurance training reported no inhibited upper body strength gains (Abernethy & Quigley, 1993; Bell *et al.*, 1997). Conversely many studies employing lower body strength and endurance training have reported attenuated strength responses in the lower limbs (Hickson, 1980; Hunter, Demment & Miller, 1987; Izquierdo *et al.*, 2005; Karavirta *et al.*, 2011; Cadore *et al.*, 2012c). Bell *et al.* (1997) investigated the

effects of implementing strength training in rowers and observed that those who performed strength training alone obtained similar gains in upper body strength as those who performed strength training alongside rowing training. Similarly Abernethy and Quigley (1993) reported no muted development of arm extension strength as a result of arm ergometer endurance training. It may be argued that activities such as rowing and arm cranking sit further towards to the strength end of the strength-endurance continuum (Figure 2.3) than steady state running or cycling. As a result the stimuli of rowing and arm cranking may not be considered as divergent as running or cycling to strength training. Further investigations examining upper and lower body strength training may benefit from employing endurance training involving near equal contribution from the upper and lower body musculature, elliptical or cross type endurance training, for example.

2.5.3.3 Intensity of exercise

Although strength training modalities and frequencies differ in concurrent training literature, the intensities, repetition schemes and rest periods employed are found to be relatively consistent. These strength training protocols are designed to stimulate strength and muscular growth to determine if any concurrent endurance training performed may attenuate these responses. As such, researchers manipulate the acute programme variables to induce improvements in strength, and on certain occasions, hypertrophy (Docherty & Sporer, 2000; Wilson *et al.*, 2011). For further details on the acute programme variables please refer to Table 2.1.

Limited research has assessed the effects of varying endurance training intensities on interference. The majority of published literature pertaining to concurrent training employs steady state running and/or cycling protocols lasting

~30 min (Leveritt *et al.*, 1999; Wilson *et al.*, 2011). A small number of studies have assessed the effect of higher intensity sprint type exercise on strength, power and hypertrophic interference. Balabinis *et al.* (2003) observed that high-intensity interval sprinting did not inhibit strength or power development. Rhea *et al.* (2008) also reported short duration sprinting was a more effect method of improving power than low intensity prolonged exercise in a comparable population. A possible explanation for this may be the neuromuscular system is required to exert high forces over short durations during repeated sprints as opposed to low forces over time in steady state exercise. This indicates a greater commonality between repeated sprint activity and strength training than strength and prolonged endurance training. This is also illustrated in the theoretical Venn diagram (Figure 2.7).

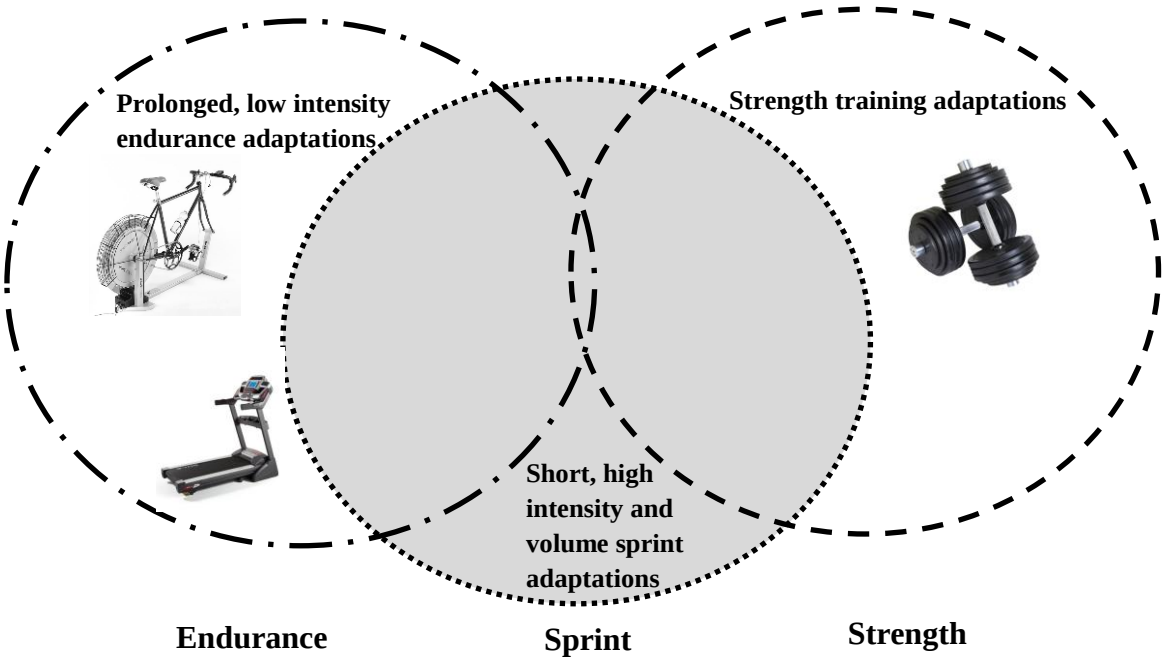

Figure 2.7. Competing training adaptations. Commonality of adaptations to strength, endurance and sprint type training. Adapted from Wilson *et al.* (2011).

2.5.3.4 Frequency of exercise

As detailed in Table 2.2 the interference phenomenon is neither conclusive nor exhaustive. Various authors have reported muted strength and/or hypertrophic responses as a result of concurrent training (Hickson, 1980; Kraemer *et al.*, 1995; Bell *et al.*, 2000; Izquierdo *et al.*, 2005; Gergley, 2009; Karavirta *et al.*, 2011), whereas others have observed no inhibited development of these phenotypes (Nelson *et al.*, 1990; McCarthy *et al.*, 1995; McCarthy, Pozniak & Agre, 2002; Millet *et al.*, 2002; Chtara *et al.*, 2008; Marta *et al.*, 2013). Many authors who have observed an absence of inhibition have employed a low training frequency (Millet *et al.*, 2002; Chtara *et al.*, 2008; Wong *et al.*, 2010; Marta *et al.*, 2013). This frequency typically equates to $< 3\ d \cdot wk^{-1}$. A number of researchers who have reported interference have employed greater training frequencies of $\geq 3\ d \cdot wk^{-1}$ (Craig *et al.*, 1991; Hennessy & Watson, 1994; Kraemer *et al.*, 1995). Based on these data it has been suggested that training frequency may be a key determinant for the presence of interference. It may also be hypothesised that if training frequency is too high, the overall training stress becomes too great and strength development plateaus regardless of the interference phenomenon itself (Häkkinen *et al.*, 2003; Mikkola *et al.*, 2007; Davis *et al.*, 2008). As a result some researchers have suggested the interference phenomenon may be a result of overtraining. This is further discussed in section 2.6.4.

It appears that greater frequencies of endurance training can result in muted strength, power and morphological responses (Craig *et al.*, 1991; Hennessy & Watson, 1994; Kraemer *et al.*, 1995) and lower frequencies do not (Sale *et al.*, 1990; Abernethy & Quigley, 1993; McCarthy *et al.*, 1995). These observations allow oneself to speculate that the magnitude of interference experienced may be dependent on the volume of endurance training performed, a question which has not

been appropriately addressed in scientific literature. The majority of studies investigating concurrent training and the interference effect tend to employ similar research designs and thus may be limited in their experimental value. These typically include a strength training condition, a concurrent training condition and an endurance or control condition (McCarthy, Pozniak & Agre, 2002; Häkkinen *et al.*, 2003; Shaw *et al.*, 2009). Data regarding differing frequencies of strength and endurance training is lacking, and represents a critical area for further understanding. As such it is currently unknown if the frequency and ratio of strength and endurance training performed may influence the degree of strength, power and hypertrophic interference experienced. Therefore, studies employing identical strength training regimens yet varying frequencies of endurance training would provide useful insights into whether the magnitude of interference experienced is proportional to the volume of endurance training performed.

2.5.3.5 Sequencing of exercise

Within the body of published research pertaining to concurrent training the order in which strength and endurance training are performed differs between individual studies, as does the time between the differing exercise stimuli (Table 2.3). The importance of sequencing of strength and endurance training to avoid interference has previously been highlighted (Craig *et al.*, 1991; Leveritt *et al.*, 1999; Leveritt *et al.*, 2000; Sporer & Wenger, 2003; García-Pallarés *et al.*, 2009) and it has been proposed that insufficient recovery from endurance training may limit strength training related adaptation (García-Pallarés & Izquierdo, 2011). This may be attributed to the compromised ability of the neuromuscular system to rapidly develop force due to residual fatigue (the acute hypothesis, section 2.5.2) (Craig *et al.*, 1991;

Leveritt & Abernethy, 1999). It may also be appropriate to speculate that subsequent strength training absolute volume and/or intensity may be decreased as a result of preceding endurance exercise.

Like most aspects of concurrent training and the interference phenomenon sequencing of strength and endurance training is a contentious issue. Research has reported no effect of inter session sequencing on strength related responses (Gravelle & Blessing, 2000; Chtara *et al.*, 2008; Schumann *et al.*, 2014) whereas others have reported an influence of training order on interference experienced (Sale *et al.*, 1990; Collins & Snow, 1993; García-Pallarés *et al.*, 2009). Collins and Snow (1993) reported maximal upper body strength responses were greater when endurance training was conducted immediately prior to strength training compared with strength then endurance training. This is contradictory to the acute hypothesis as Craig *et al.* (1991) reported running immediately before weightlifting resulted in inhibition of lower body strength development. This inhibition was attributed to endurance prior to strength training resulted in diminished quality and intensity of strength training due to residual fatigue. Although Sale *et al.* (1990) reported no differences in hypertrophy between same and separate day strength and endurance training, greater strength gains were observed when strength and endurance training were performed on separate days. It has also been reported that in well-trained individuals strength training ability is lessened for ≥ 8 h post endurance training (Sporer & Wenger, 2003). Both of these findings are contradictory to those of Collins and Snow (1993) and support the acute hypothesis. Elite Kayakers have been reported to separate strength and endurance training sessions by 6 – 8 h allow full glycogen restoration (García-Pallarés *et al.*, 2009). This 6 – 8 h gap between sessions also resulted in greater strength increases than participants who performed separate

strength and endurance training in closer proximity. Glycogen depletion as a potential cause of the interference phenomenon will be discussed in section 2.6.1.

Limited data exist detailing the physiological responses to varying sequencing of concurrent strength and endurance training (summary provided in Table 2.3). Coffey *et al*. (2009a and 2009b) as yet are the only researchers to have assessed the signalling pathways associated with interference and the order of strength and endurance training. This significance and applications of these molecular data will be discussed in section 2.6.6. Further research examining the neural and endocrine responses to varying sequencing protocols may enhance the current understanding of the interference phenomenon.

Table 2.3. Summary of research involving concurrent regimens performed on the same day and their findings.

Author(s)	**Sequence of exercise in concurrent regimen(s)**	**Time between sessions**	**Strength and/hypertrophic interference?**	**Anabolic endocrine and/or molecular signalling interference?**
Marta *et al*. (2013)	**S** then **E**	None	**No**	**-**
Cadore *et al*. (2012a)	**S** then **E** & **E** then **S**	None	**Yes** - Greater strength gains when **S** performed before **E**	**-**
Cadore *et al*. (2012b)	**S** then **E** & **E** then **S**	None	**-**	**Yes - E** then **S** promoted greater testosterone response
Santos *et al*. (2012)	**S** then **E**	None	**No**	**-**
Cadore *et al*. (2010)	**E** then **S**	None	**Yes** – Impaired maximal isometric strength	**-**
Hendrickson *et al*. (2010)	**E** then **S**	2 min	**No**	**-**
Wong *et al*. (2010)	**S** then **E**	5 h	**No**	**-**
Coffey *et al*. (2009a)	**S** then **E** & **E** then **S**	15 min	**-**	**Yes** - S6k1 phosphorylation inhibited when **E** precedes **S**
Coffey *et al*. (2009b)	**S** then **E** & **E** then **S**	15 min	**-**	**Yes** - IGF-1 mRNA signalling greater when **S** precedes **E**
Garcia-Pallares *et al*. (2009)	**S** then **E** (where possible)	6 – 8 h (where possible)	**No**	**-**
Chtara *et al*. (2008)	**S** then **E** & **E** then **S**	None	**No**	**-**

Goto *et al*. (2005)	**E** then **S**	15 min	**-**	**Yes** – GH response attenuated by prior **E** compared with **S** alone
Balabanis *et al*. (2003)	**E** then **S**	7 h	**No**	**-**
McCarty *et al*. (2002)	**E** then **S** & **S** then **E** **(**rotated each session)	10 – 20 min	**No**	**-**
Gravelle & Blessing (2000)	**S** then **E** & **E** then **S**	None	**No**	**-**
Dolezal & Potteiger (1998)	**S** then **E**	Not reported	**Yes**	**-**
Kraemer *et al*. (1995)	**E** then **S**	5 h	**Yes** – Impaired strength gains	**Yes** – increased anabolism associated with **C**
McCarthy *et al* (1995)	**S** then **E**	None	**No**	**-**
Collins & Snow (1993)	**S** then **E** & **E** then **S**	Not reported	**Yes** – Upper body strength development greater when **E** precedes **S**	**-**
Craig *et al*. (1991)	**S** then **E**	Not reported	**Yes** – impaired maximal lower body strength	**No**
Nelson *et al*. (1990)	**S** then **E**	10 min	**No**	**-**
Sale *et al*. (1990)	**E** then **S**	None	**Yes –** greater strength development when **S** and **E** performed on separate days	**No**
Hunter *et al*. (1987)	**E** then **S**	Not reported	**Yes** – Reduced CMJ	**-**
Hickson (1980)	**S** then **E**	Not reported	**Yes** – Impaired strength gains	**-**

S = strength training, **E** = endurance training and **C** = concurrent training.

2.5.4 A model for examining the interference phenomenon?

As previously stated, research examining the interference effect has employed a variety of strength and endurance training protocols which differ in intensity, frequency length and volume (Dudley & Fleck, 1987; Leveritt *et al.*, 1999; Wilson *et al.*, 2011), some of which resulting in attenuated strength development and others not (see Tables 2.2 and 2.3 for additional information). These variances present difficulties in comparing studies and drawing general conclusions about the interference effect. Based on these variances in findings and the lack of conclusive data on interference it is appropriate to conclude that presently researchers have not yet been able to construct experimental protocols which are likely to result in interference. If interference could be more accurately predicted it could also be more effectively avoided via appropriate programming. Furthermore if interference could be predicted studies investigating the unpinning mechanisms behind interference may yield more conclusive findings.

Docherty and Sporer (2000) noted the variability in concurrent research and sought to develop a model for examining the interference phenomenon (Figure 2.8). This model is designed to elicit optimal inhibition of both strength and maximal aerobic power (MAP). As the potential effects of concurrent training on endurance training responses and performance are not the focus of this thesis, MAP adaptations will not be discussed.

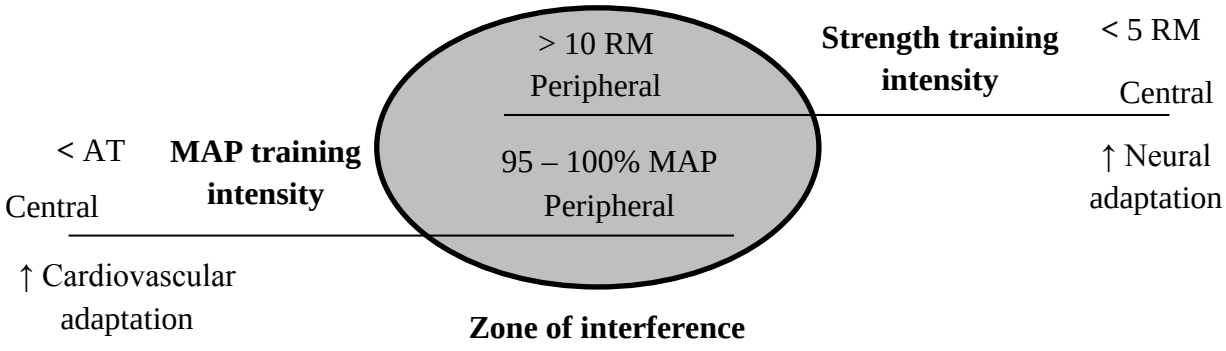

Figure 2.8. Intensity continuums and primary locations of adaptation for maximal aerobic power (MAP) and strength training and possible overlap when the two modes are combined. AT = anaerobic threshold; RM = repetition maximum. Adapted from Docherty and Sporer (2000).

A standardised model for examining the interference effect is an attractive prospect to researchers as it may remove the variability in concurrent research and allow more encompassing conclusions to be drawn. The proposed model suggests that inhibition of strength development (and attenuated improvements in MAP) may be optimised when high intensity interval training is employed as the endurance training element. It was also proposed that the aforementioned attenuation would be greatest when multiple set strength training was performed at a volume and intensity of 8 – 12 RM. The authors hypothesised that aerobic interval training would induce hypoxia in the muscle which would require an increased oxidative capacity. As Docherty and Sporer (2000) believed this environment would require the working muscles to adapt in distinctly different ways they suggested inhibition of strength (and MAP) would be at its greatest. The authors also proposed that combining aerobic interval training with higher intensity 3 – 6 RM strength training would result in diminished inhibition. It was speculated that at this intensity of strength training the working muscle could increase in oxidative capacity without significantly compromising neural adaptations to strength training (see section 2.3.1

for further details). As indicated by the Docherty and Sporer (2000) model, as endurance exercise intensity decreases and becomes more continuous the degree of attenuated strength, power and hypertrophic adaptations should be decreased. It was thought that adaptations to steady state continuous training would be centrally mediated and not compete with intra muscular adaptations to strength training.

Less than modest support is provided for the Docherty and Sporer (2000) model. Various research has reported contrasting effects of concurrent training to what is proposed in the model (Dudley & Djamil, 1985; Craig *et al.*, 1991; Bell *et al.*, 2000; Balabinis *et al.*, 2003; Izquierdo *et al.*, 2005; Rhea *et al.*, 2008; Gergley, 2009; Cadore *et al.*, 2010). As previously discussed in section 2.5.4 Balabinis *et al.* (2003), Rhea *et al.* (2008) and Wong *et al.* (2010) all observed high intensity sprint type exercise did not interfere with strength, power or hypertrophic adaptation. It has also been proposed that an increased commonality exists between high intensity sprint exercise and strength training (depicted in the theoretical Venn diagram, Figure 2.7).

Much of the research examining the interference phenomenon has observed strength and power responses to be inhibited when strength training is combined with prolonged steady state training (Hickson, 1980; Kraemer *et al.*, 1995; Häkkinen *et al.*, 2003; Izquierdo *et al.*, 2005; Karavirta *et al.*, 2011). As such it is perhaps unwise to use this model when designing a concurrent training protocol to induce interference. For consistency of research design it seems a model is required, however further work is needed to construct a model which will accurately predict interference.

From a research perspective it would be advantageous to have guidelines for exacerbating interference so the underlying physiological mechanisms may be

accurately analysed. However, from an applied perspective a model detailing how interference may be avoided would be of much more benefit as presently few if any guidelines on how to train concurrently without interference exist (Dudley & Fleck, 1987; Leveritt *et al.*, 1999). García-Pallarés *et al.* (2009) reported a 12 week periodized training programme was effective in inducing significant improvements in strength, power and endurance performance in elite canoeists and kayakers. Based on these data it seems an appropriately designed and implemented periodization scheme may be an effective means of developing various physical performance phenotypes without interference (Docherty & Sporer, 2000; Baker, 2001). This may be a novel research avenue to explore as further investigation is needed to determine the optimal periodization strategies for different populations.

2.6 Proposed mechanisms for the interference phenomenon

Despite considerable attention in published scientific literature, concurrent training and its influence on strength and hypertrophic adaptation remains a contentious issue. It is not only the effects of intensity, frequency, modes and sequencing of exercise which spark debate amongst researchers but also the underlying physiological mechanisms which may contribute to compromised strength and morphological adaptation.

2.6.1 Fatigue mechanisms

As proposed by the acute hypothesis (Craig *et al.*, 1991; Leveritt *et al.*, 1999) (section 2.5.2) interference may be caused by the compromised quality and quantity of strength training following endurance training. This hypothesis is supported by data previously detailed in section 2.5.6 (sequencing of exercise). Sale *et al.* (1990)

reported similar hypertrophic adaptations between strength and endurance training conducted on the same day and on separate days yet significantly greater strength gains were achieved when strength and endurance were performed on separate days. More recent research has also reported strength gains to be greater when strength training precedes endurance training (García-Pallarés *et al.*, 2009; Cadore *et al.*, 2012c).

García-Pallarés and Izquierdo (2011) published a series of recommendations on how to optimise simultaneous development of strength and aerobic fitness in Rowers and Canoeists. One of the principle recommendations was that strength sessions should be scheduled before endurance sessions or if this is not possible the respective sessions should be scheduled 8 h apart to avoid fatigue induced decrements in strength training performance. Separate research not investigating the interference effect has demonstrated endurance exercise modalities including prolonged running, cross-country skiing and cycling have induced acute reductions in maximal voluntary contractions (MVC) and dynamic strength by ~14% (Sahlin & Seger, 1995; Bentley *et al.*, 1998; Bentley *et al.*, 2000; Lepers *et al.*, 2000a; Lepers *et al.*, 2000b; Lepers *et al.*, 2001). Based on these data, it seems reasonable to suggest that strength performance and adaptations may be greater when sufficient recovery has been provided in an effort to allow strength training to be performed in a non-fatigued state.

There is currently limited research detailing the precise physiological mechanisms of residual fatigue which may contribute to interference. There is however limited data indicating this fatigue may be due to neural factors, as 6 h following a 30 min bout of intensive cycling significant reductions in strength performance have been coupled with a concomitant decrease in integrated EMG.

This may suggest fatigue may be attributed to neural factors (Bentley *et al.*, 2000). These data should perhaps be interpreted with caution as integrated EMG:force ratio which has previously been employed as an index of central fatigue (Avela *et al.*, 2001) was unaffected by endurance exercise. Another possible explanation is the endurance exercise induced build-up of metabolites such as inorganic phosphates, lactic acid and ammonia and depletion of energy substrates (Maclaren *et al.*, 1989). However Lac^- usually return to resting levels ~1 h post cessation of exercise (Francaux *et al.*, 1993) and strength performance can be reduced ~4 h following endurance exercise (Abernethy, 1993). As such it is perhaps unlikely that the build-up of inorganic phosphates is responsible for reduced strength training performance.

Perhaps the most widely accepted mechanism for the fatigue induced decrements in strength training quality and quantity following endurance training is glycogen depletion (Leveritt *et al.*, 1999; García-Pallarés *et al.*, 2009; García-Pallarés & Izquierdo, 2011). Although research investigating the interference effect has not yet directly analysed glycogen depletion there is support for this potential mechanism as strength performance is decremented in individuals who are glycogen depleted (Hepburn & Maughan, 1982). Furthermore strength training performance may be augmented by carbohydrate supplementation during strength training (Lambert *et al.*, 1991). Based on the aforementioned research findings it may be suggested that concurrent training may result in glycogen depletion which over time may contribute to attenuated strength responses. However, definitive statements cannot be made as this potential mechanism has not yet been directly investigated.

2.6.2 Neuromuscular factors

As the demands placed on the neuromuscular system by strength (see section 2.3.1 for more information) and endurance training are different it has been proposed that neural adaptations and changes in motor unit recruitment may contribute towards interference (Leveritt *et al.*, 1999). It has also been suggested that the neuromuscular mechanisms related to power production and explosive strength development may be the most effected by simultaneous strength and endurance training (Dudley & Djamil, 1985; Hunter, Demment & Miller, 1987; Chromiak & Mulvaney, 1990; Hennessy & Watson, 1994; Kraemer *et al.*, 1995; Häkkinen *et al.*, 2003). This suggestion is based on evidence that development of variables such as countermovement jump height (CMJ), RFD and peak torques at high velocities have been inhibited as a result of combining strength and endurance training (Dudley & Djamil, 1985; Hunter, Demment & Miller, 1987; Nelson *et al.*, 1990; Craig *et al.*, 1991; Abernethy & Quigley, 1993; Häkkinen *et al.*, 2003). This may be due to endurance training reducing the ability of the neuromuscular system to rapidly develop force (Ono *et al.*, 1976).

Häkkinen *et al.* (2003) reported notable increases rapid force production coupled with rapid neural activation of the trained muscles in participants who performed strength training alone for 21 weeks. No such improvements were observed in those who performed concurrent strength and endurance training. Similar data were reported by Cadore *et al.* (2012c) who reported greater improvements in neuromuscular economy in those who performed strength training with no preceding endurance training. Differing neural adaptations between concurrent training and strength training alone may support the acute hypothesis and provide a quantifiable mechanism for the competing stimuli of strength and

endurance training. However, the proposition of differing neuromuscular adaptations as a mechanism for inhibited strength and power responses is not supported by all relevant published literature. Indeed McCarthy, Pozniak and Agre (2002) reported no differences in strength and neural adaptation following strength or concurrent training, although training duration was notably shorter than that employed by Hakkinen *et al*. (2003) (10 vs. 21 weeks). Mikkola *et al.* (2007) also reported improvements in both strength and neuromuscular characteristics when strength training was combined with high volumes of endurance training. The data provided by Mikkola *et al.* (2007) should perhaps be interpreted with caution, as they are taken from a group of elite cross country skiers, making comparisons with research in non-elite or strength trained populations difficult.

Presently research examining the neuromuscular adaptations to concurrent training in active individuals is limited. Furthermore the studies which are available have employed variable strength training protocols. It has therefore been suggested that any observed antagonism may also be dependent on the type of strength training performed e.g. maximal strength, explosive strength or hypertrophy based programmes as these elicit differing responses and adaptations in the neuromuscular system (Häkkinen *et al.*, 2003). It seems future research in this area should ensure the strength training protocol employed is appropriate to stimulate adaptations in the neuromuscular system. In addition, to date the effects of varying volumes of endurance training on the neuromuscular responses to concurrent training remains unknown. This may prove an important avenue for future research as volume and frequency of training seems to be a key predictor of interference (Sale *et al.*, 1990; Craig *et al.*, 1991; Abernethy & Quigley, 1993; Volpe *et al.*, 1993; McCarthy *et al.*,

1995; Gravelle & Blessing, 2000; McCarthy, Pozniak & Agre, 2002; Häkkinen *et al.*, 2003).

2.6.3 Fibre type transformations

The intensity of training is the primary determinant for fibre type recruitment. Low to moderate intensities result in preferential recruitment of slow type I fibres whereas strength training characterised by near maximal force production recruits all fibre types (Leveritt *et al.*, 1999). The fibre type transformations in response to strength and endurance exercise stimulus individually have been previously discussed in this review (sections 2.3.2 and 2.4.3 respectively). It appears that the morphological responses are may be divergent based on the exercise stimulus (Simoneau *et al.*, 1985b; Esbjörnsson *et al.*, 1993; Kraemer *et al.*, 1995). It may also be feasible that these divergent responses may impair fibre hypertrophic adaptations and in turn strength development when strength and endurance training are conducted concurrently.

Although there is limited research specifically detailing the muscle fibre type transformations following concurrent training certain researchers have reported varying fibre type distributions in response to strength and concurrent training (Nelson *et al.*, 1990; Kraemer *et al.*, 1995; Bell *et al.*, 2000; Putman *et al.*, 2004). In contrast others report similar fibre type adaptations (McCarthy, Pozniak & Agre, 2002; Häkkinen *et al.*, 2003). Both Bell *et al.* (2000) and Kraemer *et al.* (1995) reported impairment of strength development and implicate inhibition of type I fibre hypertrophy as a mechanism. It has been proposed that impaired strength development associated with concurrent training may be due to increase in type I fibre composition with a concomitant decrease in fast type II fibre percentage

(Dudley & Fleck, 1987; Chromiak & Mulvaney, 1990). This suggestion is supported by the findings of Putman *et al.* (2004) who noted concurrent training resulted in greater fast to slow fibre type transformations and attenuated hypertrophy of slow type I fibres when compared with strength training alone. This muted type I fibre hypertrophy was also coupled with inhibited strength development in those participants who performed a combination of strength and endurance training. Nelson *et al.* (1990) also reported a percentage decrease in fast type IIa fibres with a concomitant increase in slow type I fibre percentage. This however was not coupled with any differences in strength development between concurrent and strength training conditions following a 20 week intervention.

Sale *et al.* (1990), McCarthy, Pozniak and Agre (2002) and Häkkinen *et al.* (2003) reported no change in fibre type ratio as a result of concurrent training nor any variance in individual fibre type hypertrophy. Strength development between concurrent and strength alone conditions were also similar. Research has indicated that hypertrophy of individual type I and II fibres is similar following strength and concurrent training when overall training frequency and volume remains low (< 3 $d \cdot wk^{-1}$) (Häkkinen *et al.*, 2003). This however was not observed by Sale *et al.* (1990) or McCarthy, Pozniak and Agre (2002) who both employed training frequencies of ≥ 3 $d \cdot wk^{-1}$ and reported no variance in individual fibre adaptation.

Research into individual fibre type hypertrophy and transformations in response to combined strength and endurance training is largely inconclusive. Adaptations may be dependent on the frequency and duration of the designated training programme. It is therefore difficult to draw any definitive conclusions based on the available research. It should perhaps also be noted that histochemical techniques were predominantly used to detect differences in fibre type hypertrophy

and transformations. As a result it is possible that more subtle changes in the myosin-heavy chain may have been undetected (Putman *et al.*, 2004).

2.6.4 Overtraining

Overtraining syndrome (OTS) is characterised by decremented physical performance, disturbances in mood state and a plateau or reduction in training induced adaptation (Urhausen & Kindermann, 2002). This generally occurs when training volume and intensity is too high and/or there is insufficient recovery. The majority of studies investigating concurrent training and the interference effect employ 3 experimental conditions; strength training, endurance training and concurrent training (on occasions a control condition is also included). Those following the concurrent training condition will typically perform the same amount of strength training as the strength group and the same amount of endurance training as endurance group. This design results in the concurrent training group effectively performing double the training volume and total work of those performing strength or endurance training in isolation (Dudley & Fleck, 1987). It has been hypothesised when overall training frequency, volume and duration becomes too great interference may occur. Therefore concurrent training may be associated with similar strength gains over a short period with responses plateauing in the latter weeks of the training intervention. This suggestion is supported by the findings of both Hickson (1980) and Häkkinen *et al.* (2003). These data may also suggest an over trained state results in the training stimuli exceeding the maximal adaptive responses of the respective physiological systems (Kraemer & Nindl, 1998). This however may be somewhat of an over simplification due to the inconsistent presence and magnitude of interference reported in the literature.

The fact frequency and volume of training seems to be a key indicator of interference also supports the suggestion that overtraining might play a role in muted strength adaptation to combining strength and endurance training (Nelson *et al.*, 1990; Hennessy & Watson, 1994; Häkkinen *et al.*, 2003; Gergley, 2009). Training history and current training status of participants is a common variant in concurrent training research (McCarthy, Pozniak & Agre, 2002; Shaw, Shaw & Brown, 2009). It seems that athletes and highly trained populations may be more susceptible to interference than untrained individuals (Baker, 2001; Baker & Newton, 2006; Rønnestad *et al.*, 2011). It is possible this may be due to overtraining as highly trained athletes experience a far greater training load and volume than those who are recreationally trained. This is supported by the fact many studies which have reported no interference when training frequency remains low (< 3 $d \cdot wk^{-1}$) recruited untrained individuals (Sale *et al.*, 1990; Craig *et al.*, 1991; Abernethy & Quigley, 1993; Volpe *et al.*, 1993; McCarthy *et al.*, 1995).

Dudley and Djamil (1985) contend overtraining cannot be solely responsible for impaired strength and power development associated with concurrent training regardless of training status. The volume of endurance training was 5 x 5 min sessions performed over 3 $d \cdot wk^{-1}$ and strength training volume was similarly low as participants were only required to perform 2 x 30 s sessions on 3 alternate $d \cdot wk^{-1}$. Despite this low training volume and relatively short programme duration (7 weeks) concurrent training resulted in a reduced magnitude of increase in maximal torques at high velocities when compared with strength training alone. It highly unlikely that a programme of this frequency, volume and duration would result in an over trained state, even in those who performed both strength and endurance sessions.

There is insufficient evidence for overtraining as a mechanism for interference and as yet no study has directly investigated overtraining within a concurrent training intervention. This dearth of research highlights the need for future studies to investigate the effect of varying frequencies and volumes of combined strength and endurance training.

2.6.5 Endocrine factors

Although it is not clear whether overtraining is responsible for interference the increased catabolic endocrine environment associated with overtraining (Kraemer & Ratamess, 2005) has been implicated in the inhibition of strength and hypertrophic development. Kraemer *et al.* (1995) were the first to investigate the interaction between anabolic (testosterone) and catabolic (cortisol) hormones in response to concurrent training. The authors hypothesised that as the endocrine responses to strength training (see section 2.3.3 for more information) and endurance exercise result in differing anabolic:catabolic responses (Galbo, 1983; Kraemer & Ratamess, 2005) the addition of endurance training to a strength training programme would promote a greater catabolic environment and attenuate strength and morphological adaptations. This was subsequently demonstrated as concurrent strength and endurance training resulted in attenuated hypertrophy and an increased catabolic environment demonstrated by increased cortisol and an absence of any increase in testosterone. In contrast, testosterone levels were increased in the strength alone group with concomitant reductions in cortisol indicating increased anabolism.

Similar findings were reported by Bell *et al.* (1997) who observed concurrent training resulted in greater urinary free cortisol concentrations compared with strength training alone in women. These data were reproduced in both males and

females as concurrent training was again demonstrated to result in an elevated catabolic state indicated by higher concentrations of cortisol combined with no change in the anabolic hormones testosterone and GH (Bell *et al.*, 2000). More recent research has examined the effect of the sequencing of strength and endurance training on the anabolic:catabolic responses. Cadore *et al.* (2012b) reported concurrent training with endurance performed before strength training resulted in greater testosterone increases than *vice versa*. The observed negative correlations between testosterone and cortisol could also indicate cortisol had an inhibitory effect on testosterone release. The growth hormone response to strength training may be inhibited by a preceding bout of endurance training (Goto *et al.*, 2005). However, the strength training protocol in this study elicited no increase in testosterone or cortisol regardless of any prior endurance training.

As Kraemer *et al.* (1995) observed increased catabolism at week 8 of a 12 week intervention it was proposed the decrease in testosterone:cortisol ratio may be due to an overtraining effect. This suggestion was supported by the further decrease in testosterone:cortisol ratio from weeks 8 to 12. Bell *et al.* (1997) and Bell *et al.* (2000) also reported no increase in catabolism indicated by increased cortisol until the end of the respective 12 week training interventions. It is not unreasonable to suggest overtraining may have played a role in the attenuation of type I fibre hypertrophy and increased catabolism as participants in the concurrent groups performed both strength and endurance aspects of the individual interventions. This as previously stated in section 2.6.4 results the concurrent training group having effectively double the training volume of those performing strength or endurance training in isolation to contend with (Dudley & Fleck, 1987). Furthermore the authors speculated a reduction in training volume would have created an

environment where an anabolic rebound in muscle size, strength and power could continue to increase over time and avoid any over training effects (Kraemer *et al.*, 1995).

The fact an acute bout of concurrent training (endurance preceding strength) results in greater testosterone increases than strength preceding endurance (Cadore *et al.*, 2012b) is a novel finding in itself as little data on the physiological responses to the sequencing of strength and endurance exercise exist. It was proposed that aerobic exercise following strength training was of insufficient intensity to maintain or further stimulate testosterone increases (75% of max heart rate for 30 min). Lactate accumulation during strength training and its role as an energy substrate during subsequent endurance training was also implicated in the return to resting levels of testosterone during endurance training. Although Lac^- were not measured in this study it is not unreasonable to suggest this as lactate as an energy substrate during endurance training may reduce the stimulus for testosterone increase (Gastin, 2001). The role of lactate in the endocrine responses to concurrent training may be an interesting avenue which warrants further investigation.

As previously discussed in this chapter, training status of participants is a common variant in concurrent training research. This is a problem when investigating the endocrine responses to concurrent training as individuals of differing training statuses have varying endocrine responses to specific training stimulus (Ahtiainen *et al.*, 2003a; Tremblay, Copeland & Van Helder, 2004; Cadore *et al.*, 2008). Strength trained individuals seem to display a greater anabolic hormone response to strength training than non-strength trained individuals (Tremblay, Copeland & Van Helder, 2004). The authors also reported that endocrine responses

to endurance type training are greater in endurance trained individuals than those who are classed as strength trained.

Although somewhat limited, data are available detailing the endocrine responses to both chronic and acute concurrent training the available research indicates endocrine factors may at least play a role in the inhibition of strength and hypertrophic responses. The most likely mechanism for this is the shift in the testosterone:cortisol ratio in favour of catabolism and subsequent inhibition of protein synthesis (Baar, 2006). Although it seems a series of further studies employing a consistent model and training status of participant is needed to clarify this.

2.6.6 Signalling and molecular factors

The signalling responses to individual strength and endurance training stimulus are detailed in sections 2.3.4 and 2.4.5 respectively. The two exercise types are associated with differing signalling pathways; strength training and its activation of the growth and protein synthesis associated mTOR network and endurance training activating the energy modulating AMPK network (Nader & Esser, 2001; Baar, 2006; Nader, 2006; Coffey & Hawley, 2007; Baar, 2009; Vissing *et al.*, 2011). The increased availability of molecular analysis techniques to sport and exercise scientists has allowed more research into the signalling responses to various exercise stimuli to be conducted.

It has been proposed that the increased catabolic environment associated with concurrent training may result in attenuated protein synthesis (Kraemer *et al.*, 1995). As such it is possible that signalling pathways associated with endurance training may also have a direct inhibitory effect on protein synthesis (Coffey & Hawley,

2007; Baar, 2009). This suggestion is also supported by the fact that as an energy sensor one of AMPKs key roles is to switch off energy consuming pathways and switch on energy producing pathways in responses to energy stress (like that experienced in exercise) (Hardie *et al.*, 2006; Hardie & Sakamoto, 2006). Protein synthesis requires a high energy demand and as a result may be supressed by AMPK (Inoki, Zhu & Guan, 2003; Gwinn *et al.*, 2008).

Inoki, Zhu and Guan (2003) were the first to report the inhibition of mTOR via AMPK in response to exercise stress and energy deficit. More specifically inhibition of mTOR phosphorylation occurs as a result of increased phosphorylation of Tuberous Sclerosis Complex 2 (TSC2) (Inoki, Zhu & Guan, 2003). Inhibition of TSC2 occurs as a result of phosphorylation of PKB (Potter *et al.*, 2003) which is an upstream activator of mTOR. Whereas, phosphorylation of AMPK results in increased phosphorylation of TSC2 and subsequent repression of mTOR (Inoki, Zhu & Guan, 2003) (Figure 2.9).

It seems in murine models endogenous AMPK can mediate a suppressive effect on mTOR (Atherton *et al.*, 2005; Thomson *et al.*, 2008; Mounier *et al.*, 2011). However, in human skeletal muscle the interactions between AMPK and rates of protein synthesis are yet to be fully elucidated. Various research has demonstrated no suppression of protein synthesis (as indicated by activity of the mTOR network) as a result of endurance exercise and increased AMPK phosphorylation (Coffey *et al.*, 2006; Wilkinson *et al.*, 2008; Camera *et al.*, 2010; Vissing *et al.*, 2011; Apró *et al.*, 2013). There are potential confounding factors which may have resulted in this non-inhibition. Coffey *et al.* (2006) recruited only highly trained athletes who may have a reduced sensitivity to exercise induced signalling. Unlike other comparable research Wilkinson *et al.* (2008) employed a unilateral model with opposite legs performing

strength and endurance training one after the other. It is possible that this approach may have resulted in a systemic response which influenced signalling in both limbs (Vissing *et al.*, 2011). Also none of the studies analysed the responses of TSC2. These data may have provided insights in to whether the endurance protocols employed were of sufficient time and intensity for AMPK to phosphorylate TSC2 and thus inhibit mTOR.

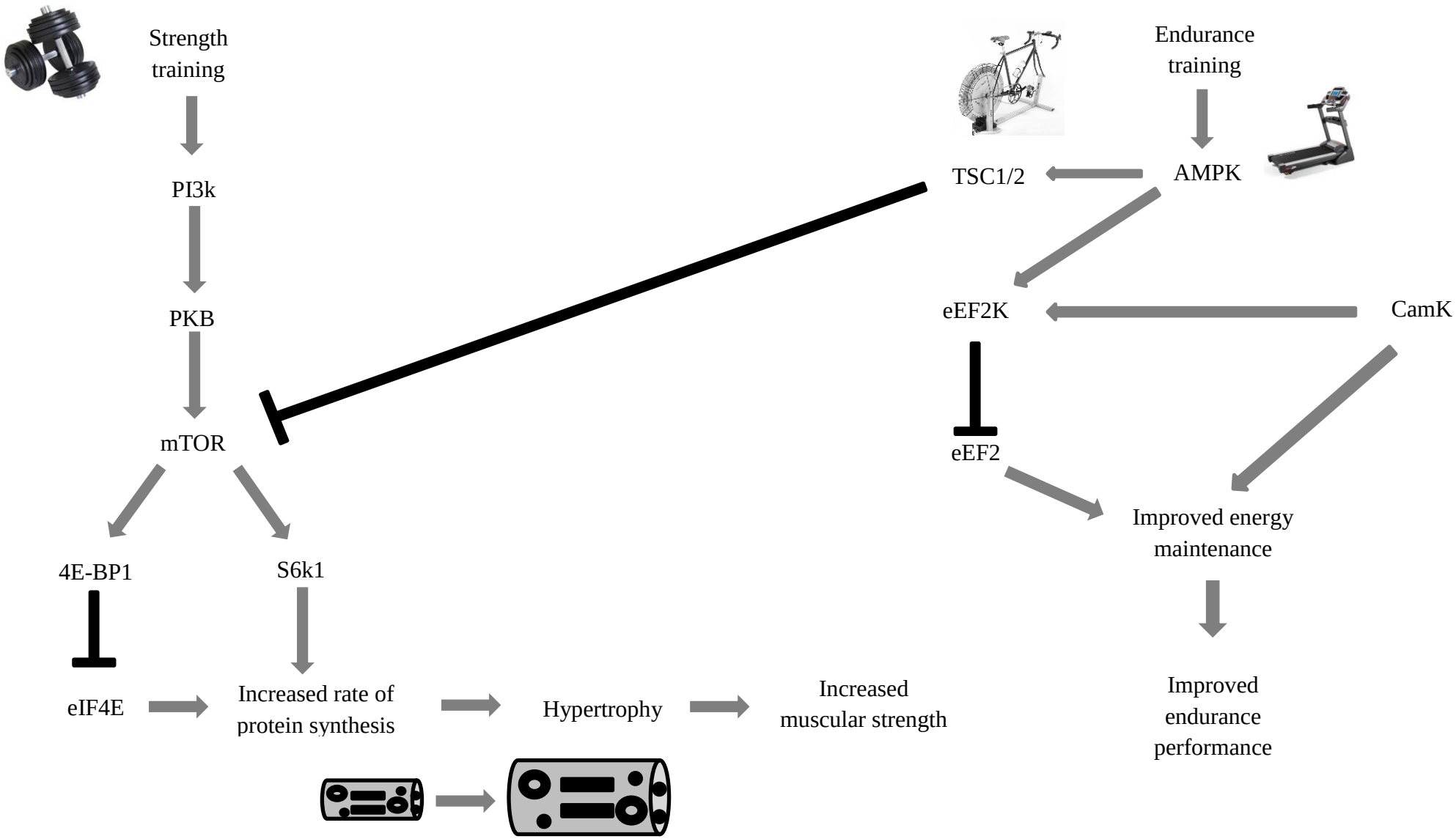

Figure 2.9. Schematic of the PI3k/PKB/mTOR/S6k1/4E-BP1 growth associated signalling network and AMPK energy modulating signalling network. Arrows indicate subsequent increased phosphorylation and horizontal crossed line indicates inhibition. 4E-BP1 = 4E binding protein 1; AMPK = adenosine monophosphate activated protein kinase; CamK = calcium-activated protein kinase; eEF2 = eukaryotic elongation factor 2; eEF2K = eukaryotic elongation factor 2 kinase; eIF4E = eukaryotic initiation factor 4E; mTOR = mammalian target of rapamycin; PI3k = phosphoinositol 3-kinase; PKB = protein kinase B; S6k1 = 70-kDa S6 protein kinase; TSC 1/2 = tuberous sclerosis complex 2.

Replicating the cross talk between the mTOR and AMPK signalling networks observed in rodent and in vitro models has proved difficult in human trials. This may be due to differences between electrically stimulated contractions (in rodents) and functional strength and endurance training. Also in humans both strength and endurance training switch on AMPK signalling (Vissing *et al.*, 2011), which is unsurprising as signalling is initiated ATP turnover. This may result in variances in signalling between strength and combined strength and endurance being difficult to detect, particularly due to the semi quantitative nature of molecular techniques such as Western Blotting (Aldridge *et al.*, 2008). Much of the research reporting no interaction between the mTOR and AMPK networks has employed cycling as the endurance training modality (Camera *et al.*, 2010; Vissing *et al.*, 2011; Apró *et al.*, 2013). 1 h of unilateral cycling at 65 – 70% $\dot{V}O_{2\max}$ has been demonstrated to increase both mTOR phosphorylation and protein synthesis (Mascher *et al.*, 2011). There is also evidence to suggest that cycling is as effective as strength training alone in eliciting hypertrophy in untrained participants (Mikkola *et al.*, 2012). These findings may in part account for the similar molecular responses to strength and concurrent training when cycling is employed as the endurance exercise modality.

There are limited data available relating to the physiological responses to varying sequencing of strength and endurance training. To date only 2 studies have investigated the molecular responses to differing sequencing of acute concurrent training (Coffey *et al.*, 2009a; Coffey *et al.*, 2009b). Initially Coffey *et al.* (2009b) investigated the effects of an acute concurrent training session (strength followed by 30 min cycling at 70% $\dot{V}O_{2\max}$ or *vice versa*) on protein synthesis and mRNA signalling responses. The authors noted phosphorylation of AMPK was greater 3 h

after strength training was conducted prior to endurance type exercise. This may indicate greater metabolic stress when endurance training takes place in close proximity to a preceding strength session. Although "sub optimal" anabolic signalling and protein synthesis occurred as a result of concurrent training it is difficult to conclude which sequence of exercise resulted in more favourable strength training responses. It was proposed whilst strength preceding endurance training resulted in increased inflammation and protein degradation endurance preceding strength training resulted in diminished anabolic responses as indicated by IGF-1 mRNA signalling. In a follow up study Coffey *et al.* (2009a) examined the same sequencing protocols but employed repeated sprints (on a cycle ergometer) as the endurance aspect of the experimental protocol. It was suggested that strength training performed after repeated sprints was undertaken in the presence of greater metabolic acidosis when compared with the initial exercise bout. This may partly explain the suppression of the protein synthesis marker S6k1 (Figure 2.9) as metabolic acidosis has been demonstrated to decrease protein synthesis in humans and rodents (Kleger *et al.*, 2001; Caso *et al.*, 2004). This is contrary to other data as high intensity intermittent exercise is thought to have a greater commonality with strength training than steady state endurance training (Balabinis *et al.*, 2003; Rhea *et al.*, 2008; Wong *et al.*, 2010), although these studies did not include any molecular measures. The findings of Coffey *et al.* (2009a) and Coffey *et al.* (2009b) should perhaps be interpreted with caution. Both propose acute concurrent training resulted in "sub optimal" protein synthesis and anabolic responses yet neither study included a strength training alone condition. As such it cannot be ascertained whether the concurrent condition elicited different responses to strength training in isolation. The real world applications of this research may be lacking as all protocols were

performed after an overnight fast. Very few individuals training to improve strength, power or muscular CSA train in a fasted state.

Despite the aforementioned confounding factors and misjudgements in research design the roles of the mTOR and AMPK axis' in interference are unclear. Currently it seems that a great deal of effort and research funding is being placed into assessing the potential molecular mechanisms behind the interference phenomenon. Based on the current body of research it may be naïve to attribute any interference to molecular factors, at least until further research has directly observed TSC2 elevation coupled with mTOR suppression in humans. Whilst the AMPK induced inhibition of mTOR is the most popular and contested mechanism related to the interference effect research in this area is presently inconclusive. Like most areas of concurrent training it seems further research is needed to clarify the roles of molecular signalling pathways in interference. Perhaps the most important of which is the effects of differing sequencing of strength and endurance training. However, it is essential that a strength alone condition is included to accurately determine whether either sequence of exercise has an inhibitory effect on protein synthesis when compared with strength training alone.

2.7 Summary

Whilst the existing body of literature examining concurrent training and the interference phenomenon provides intriguing findings, it is clear there are areas which necessitate further investigation. i) the influence of differing ratios of strength and endurance training on the presence and magnitude of interference. Numerous studies elude to the avoidance of inference when training frequency remains low (Sale *et al.*, 1990; Craig *et al.*, 1991; Abernethy & Quigley, 1993; Volpe *et al.*, 1993;

McCarthy *et al.*, 1995; Gravelle & Blessing, 2000; McCarthy, Pozniak & Agre, 2002; Häkkinen *et al.*, 2003) yet there are no published data on comparable strength training regimens with differing frequencies of endurance training performed concurrently. It seems reasonable to suggest that an increased volume of endurance training may result in more pronounced interference whereas lower volumes may not inhibit strength development. To test this hypothesis this thesis will initially assess the effects of differing ratios of strength and endurance training performed in a concurrent regimen on strength, anthropometric and neuroendocrine adaptations.

ii) the influence of strength and endurance training order on anabolic signalling associated with strength training adaptation. As previously stated there remains limited research on the effects of differing training order in a concurrent training regimen on strength development. Furthermore only 4 studies have examined the endocrine and/or molecular responses to varying sequencing of strength and endurance training. Additionally, although an increasing number of researchers are investigating the roles of the mTOR and AMPK signalling networks and protein synthesis inhibition, it is still unclear whether TSC2 can mediate any suppressive effect on mTOR in humans. The latter studies conducted within this thesis will examine endocrine and molecular anabolic factors contributing to strength development following concurrent training protocols with differing orders of strength and endurance training.

3. General methods

3.1 General methods

Many of the methodologies utilised within the individual research studies conducted as part of this thesis were consistent and/or repeated throughout. Details of all these assessment and analysis procedures employed are presented in this overarching chapter on methodology. In some instances the methodologies utilised were specific to the requirements of the individual investigations conducted as part of this thesis. Full details of these methodologies are presented in the relevant individual experimental chapters.

3.2 Ethical approval

All experimental procedures were first ratified by the academic Faculty's Research Ethics Committee in accordance with the Declaration of Helsinki (1964). In all cases, after being informed of the benefits and potential risks of the relevant investigations included in this thesis, all participants completed a standardised health-screening questionnaire and gave their written informed consent by signing a document that was approved by Northumbria University Institutional Review Board prior to participation in any study.

3.3 Participants

For all experimental investigations, each participant had completed > 2 years of strength training activities prior to the start of a study, and were therefore considered recreationally "resistance trained"; however none were involved in a specific or structured training programme. All participants were non-smokers, free from any endocrine or metabolic contraindications, and were not following any specialized dietary interventions. In all cases participants were asked to refrain from

nutritional supplementation or pharmacological interventions for 30 days prior to and throughout the duration of any experimental intervention. Descriptive statistics representing the participant characteristics are presented in each experimental chapter of this thesis.

3.4 Performance measures

A battery of performance measures was established to assess changes in participant physical and physiological standards. Based on each respective study design, these procedures were adopted prior to, during, and upon completion of experimental protocols in order to;

1. Determine and standardise the relative training intensities in the training interventions.
2. Assess the influence of any experimental intervention employed in this thesis on physical performance phenotypes and physiological changes.

Regardless of the study requirements, the protocols for performance measures were standardised in all cases; these are discussed below.

3.5 Whole body strength

For each exercised used in the determination of maximal force production characteristics, participants completed a standardised warm-up consisting of three submaximal sets with increasing load (40, 75 and 85% of predicted 1RM) and decreasing number of repetitions (10, 7 and 3, respectively). Each maximal 1RM attempt was ~5% lower load that the predicted 1RM, and the load was then increased

2 – 5% until the participant was unable to complete the respective lift with appropriate form (Rønnestad, Hansen & Raastad, 2011). Participants were given a maximum of five attempts per exercise to achieve their individual 1RM, with 3 min rest intervals between attempts. If participants failed twice with the same experimental load, the test was terminated and the previous successful lift was recorded as the participants 1RM. The exercises in which 1RM was assessed are described in greater detail in the respective experimental Chapters (5, 6 and 7).

The reliability of 1RM determination in the exercises employed within this thesis was assessed during pilot testing. Fifteen healthy recreationally resistance-trained men (age: 26 ± 4 y; body mass: 87.1 ± 13.4 kg; height: 185 ± 8 cm) attempted to achieved their 1RM in the required exercises on 2 separate occasions at the same time of day (± 1 h) with a 4 d interval between assessments to determine intra assessment session reliability. All participants were required to abstain from exercise for 24 h prior to assessments and repeat their nutritional intake the evening before and on day of assessments. Participants also performed the required exercises 2 times (with a 5 min recovery period) within the same assessment session to determine inter assessment session reliability. All assessments were conducted by the same investigator. Data pertaining to the intra and inter assessment session are presented in Table 3.1.

Table 3.1. Reliability of maximal strength assessment within this thesis

Maximal strength			
	ICC	*R*	CV (%)
Intra assessment	0.99	0.99	1.9
Inter assessment	0.97	0.96	2.1

intra-class correlation coefficients (ICC), Pearson's correlation coefficient (*r*) and coefficients of variation (CV).

3.6 Maximal aerobic capacity ($\dot{V}O_{2max}$)

Owing to separate investigational requirements, two modalities of determining participant $\dot{V}O_{2max}$ were utilised. Firstly, an incremental step test protocol conducted on a motorised treadmill (hp Cosmos, Pulsar, Nussdorf-Traunstein, Germany) was employed (see Chapters 5 and 6), while elsewhere a cycle ergometer (Velotron CS, RacerMate Inc., Seattle, WA, USA) protocol was adopted (Chapter 7). The rationale for adopting these differing methodologies is discussed further in the respective experimental chapters.

It was considered that a maximal effort was suitably obtained if participants met any of two of the following criteria: i) a change in $\dot{V}O_2 < 2$ ml·kg^{-1} ·min^{-1} across the two stages of the incremental test; ii) a respiratory exchange ratio of 1.15 or greater, or iii) ≥ 90% age predicted maximum heart rate (220-age) (Winter *et al.*, 2006). Expired air was measured via online breath by breath analysis (treadmill protocol: Cortex meta analyser 3B, Leipzig, Germany. Cycle ergometry: Oxycon Pro, CareFusion, Rolle, Switzerland) and heart rate was measured via short range telemetry (Polar RS400, Finland).

The reliability of $\dot{V}O_{2max}$ determination was assessed during pilot testing. Fifteen healthy recreationally resistance-trained men (age: 26 ± 4 y; body mass: 87.1

± 13.4 kg; height: 185 ± 8 cm) attempted to achieved their $\dot{V}O_{2max}$ during the protocols detailed below (sections 3.6.1 and 3.6.2) on 2 separate occasions at the same time of day (± 1 h) with a 4 d interval between assessments to determine intra assessment session reliability. All participants were required to abstain from exercise for 24 h prior to assessments and repeat their nutritional intake the evening before and on day of assessments. All assessments were conducted by the same investigator. Data pertaining to the intra assessment session reliability are presented in Table 3.2.

3.6.1 Determination of $\dot{V}O_{2max}$ via Treadmill

The treadmill gradient was set at 1% throughout (Jones & Doust, 1996). The speed was initially set at 10 km·h^{-1} and increased by 1 km·h^{-1} every 3 min until volitional exhaustion. This protocol is based on the methodology previously described by Walshe *et al.* (2010).

3.6.2 Determination of $\dot{V}O_{2max}$ via Cycle ergometer

Participants first performed an incremental lactate threshold assessment prior to the $\dot{V}O_{2max}$ test. The initial intensity was set at 150 W and was increased by 25 W at 4 min intervals until blood lactate concentrations (Lac^-) reached ≥ 4 mmol L^{-1}. Capillary puncture samples were taken from the fingertip and were obtained during the final 30 s of each 4 min stage. Lac^- was analysed immediately following capillary blood collection (for information regarding Lac^- analysis see section 3.10.1). After a ~10 min recovery period participants commenced the incremental $\dot{V}O_{2max}$ protocol which began at an intensity of 100 W. This intensity increased at a rate of 1 W every

3 s (20 W per min) until volitional exhaustion. This protocol is based on the methodology previously described by Bell *et al.* (2014).

Table 3.2. Reliability of endurance and work capacity assessed within this thesis.

Endurance and work capacity measures			
	ICC	*R*	CV (%)
$\dot{V}O_{2max}$ – treadmill protocol	0.99	0.98	2.9
$\dot{V}O_{2max}$ – cycle ergometer protocol	0.92	0.87	9.3

intra-class correlation coefficients (ICC), Pearson's correlation coefficient (*r*) and coefficients of variation (CV).

3.7 Perceptual feelings of effort – rate of perceived exertion

To examine fatigue and perception of physical exertion in response to the training interventions, rate of perceived exertion (RPE) was recorded during strength training (in Chapters 5, 6 and 7). Briefly, participants were required to select a number from 6 to 20 on the Borg Scale, corresponding to a statement which best described their level of exertion at that particular moment (Borg, 1970; Day *et al.*, 2004; Sweet *et al.*, 2004). Data pertaining to the reliability of this assessment method is presented in Day *et al*. (2004) and Sweet *et al.* (2004).

3.8 Venous blood sampling and storage

Venous blood samples were collected from the antecubital fossa in a branch of the basilica vein into vacutainer tubes (BD Vacutainer, NJ, USA) coated with Ethylenediaminetetraacetic acid (EDTA) to negate clotting (in Chapters 5 and 6). Whole blood was subsequently centrifuged (accuSpin 3R, Fisher Scientific, Loughborough, UK) at 4°C and 1509 g for 10 min, after which the resultant plasma

from each sample was then transferred to individual eppendorf containers for subsequent storage at -80°c.

3.9 Biochemical analysis

Biochemical analyses were performed on metabolic, endocrine, and signalling variables to provide mechanistic information relating to any observed biological adaptations and responses to the respective training interventions (employed in Chapters 5 and 6).

3.9.1 Blood glucose and lactate analysis

Capillary blood samples (20 ąL) were taken for analysis of glucose and blood lactate using a desk top device (Biosen C_Line Sport (2 channel)) glucose and lactate analyser (EKF Diagnostic, Barleben, Germany), which has detection limits of 0.5 – 40.0 mmol/L^{-1}. The analyser self-calibrated, the process was initiated when the unit was switch on and was repeated during every hour of use.

3.9.2 Testosterone and cortisol analysis

Plasma testosterone and cortisol were measured in duplicate via commercially available enzyme-linked immunosorbent assay (ELISA) kits (IBL International, Hamburg, Germany). In all cases procedures were followed according to the manufacturer's instructions. For both variables, 25 ąL of each standard, control and sample were pipetted into the respective wells of the mircotire plate, after which 2000 ąL of enzyme conjugate was then pipetted into each well and the plate was covered and left to incubate at room temperature (18 - 25°c) for 60 min. After this period the incubation solution was discarded and the microplate was

washed 3 times with wash buffer and distilled water solution diluted at a ratio of 1:10. 100 ąL of Tetramethylbenzidine (TMB) substrate solution was then pipetted into each well prior to a 15 min incubation period. Immediately following this incubation 100 ąL of TMB stop solution was pipetted into each well and the contents were briefly mixed by gently agitating the plate. The optical density was measured at 450 nm within 10 min of the stop solution being added using an Anthos 2010 mircoplate reader (DAZDAQ LTD, Brighton, UK (reference-wavelength 600 – 650 nm)). For testosterone there was a minimum detection limit of 0.2 $nmol \cdot L^{-1}$, inter-assay and intra-assay variation of 4.2 – 7.4 and 3.1 – 5.4 and the calibration curve revealed Pearson's correlation coefficients (r) = 0.99. For cortisol there was a minimum detection limit of 6.8 $nmol \cdot L^{-1}$ with an inter-assay and intra-assay variation of 2.1 – 5.0 and 2.6 – 3.5, the calibration curve revealed r = 0.99, respectively.

The reliability of the measurement of metabolic and endocrine variables was assessed during pilot testing, as were the responses of the aforementioned variables to the experimental exercise protocols employed in chapters 5 and 6. Fifteen healthy recreationally resistance-trained men (age: 26 ± 4 y; body mass: 87.1 ± 13.4 kg; height: 185 ± 8 cm) had blood samples draw at rest at following the experimental exercise protocol (full details presented in section 5.3.3.1) on 2 separate occasions at the same time of day (± 1 h) with a 4 d interval between assessments to determine intra assessment session reliability. Samples were analysed in duplicate to determine inter assessment reliability. All participants were required to abstain from exercise for 24 h prior to assessments and repeat their nutritional intake the evening before and on day of assessments. All assessments were conducted by the same

investigator. Data pertaining to the intra inter assessment session reliability are presented in Table 3.3.

Table 3.3. Reliability of metabolic and endocrine variables assessed within this thesis.

Biochemical variables						
Basal levels						
	ICC		*R*		CV (%)	
	Inter assessment	Intra assessment	Inter assessment	Intra assessment	Inter assessment	Intra assessment
Glucose	0.95	0.94	0.91	0.89	4.2	8.6
Lactate	0.96	0.97	0.94	0.92	3.7	4.6
Testosterone	0.89	0.85	0.89	0.86	4.0	9.4
Cortisol	0.92	0.96	0.94	0.92	4.7	11.1
Following experimental exercise protocol						
	ICC		*R*		CV (%)	
	Inter assessment	Intra assessment	Inter assessment	Intra assessment	Inter assessment	Intra assessment
Glucose	0.94	0.81	0.92	0.78	5.4	10.1
Lactate	0.91	0.79	0.90	0.81	4.8	6.9
Testosterone	0.87	0.74	0.84	0.78	3.4	12.2
Cortisol	0.93	0.81	0.91	0.77	5.1	14.8

intra-class correlation coefficients (ICC), Pearson's correlation coefficient (*r*) and coefficients of variation (CV).

3.10 Statistical analysis

3.10.1 p value based null hypothesis testing

Owing to the variations in individual study designs and differing number of experimental conditions, comparisons and time points for analysis, different

statistical analysis strategies were employed between investigations. These are discussed in detail in each experimental chapter of this thesis.

A criticism of this method is that is does not deal with the 'real world' meaningfulness of an outcome (Batterham & Hopkins, 2006). As such, inferential statistical analysis methods were also utilised to examine the practical effect of the separate training interventions on physical performance measures. This analysis method allowed the emphasis of magnitudes of effects and precision of estimates, rather than the traditional *p* value based null hypothesis testing which focuses on absolute effect instead of non-effect interpretation (Rowlands *et al.*, 2007). The aforementioned method defines the smallest practical effect allowing qualification of the probably of a worthwhile effect with inferential descriptors to aid interpretation (Rowlands *et al.*, 2007). Magnitude inferences recognise sample variability (Rowlands *et al.*, 2007), and provide athletes, applied practitioners and scientists with the practical meaningfulness of the results. The methods were consistent throughout the separate investigations and are detailed below.

3.10.2 Magnitude based inferences

Statistical analysis which reports uncertainty of outcomes as 90% confidence intervals (CI), generating probabilistic magnitude-based inferences about the true value of outcomes were employed (Batterham & Hopkins, 2006). Dependant variables were analysed using a published spread sheet (Hopkins, 2003) to determine the effect of the designated training interventions as the difference in change within each group.

To calculate the possibility of benefit, the smallest worthwhile effect for each dependant variable was the smallest standardized change in the mean – 0.2 times the

between-subject SD for baseline values of all participants (Batterham & Hopkins, 2006). This analysis method has previously been employed in similar investigations (Cockburn *et al.*, 2010; Gee *et al.*, 2011; Gee *et al.*, 2012). This method allows practical inferences to be drawn using the approach identified by Batterham and Hopkins (2006). Quantitative chances of benefit were assessed qualitatively: <1% indicated almost certainly none; 1% to 5% indicated very unlikely; 5% to 25% indicated unlikely; 25% to 75% indicated possibly; 75% to 95% indicated likely; 95% to 99% indicated very likely; and >99% indicated almost certainly (Hopkins, 2002). These inferences are also free from type I and II errors as they are probabilistic rather than definitive statements (Batterham & Hopkins, 2006).

4. Performance and neuromuscular adaptations following differing ratios of concurrent strength and endurance training

4.1 Abstract

Purpose: The present study examined the strength, morphological and neuromuscular adaptations to varying ratios of strength and endurance training and total work performed in a concurrent training regimen.

Methods: 24 resistance trained males completed 6 weeks of 3 $d \cdot wk^{-1}$ of either i) strength training (ST), ii) concurrent strength and endurance training ratio 3:1 (CT3), iii) concurrent strength and endurance training ratio 1:1 (CT1) or iv) no training (CON). All strength and endurance training consisted of unilateral leg extensions. Assessments of maximal voluntary contraction (MVC), limb girth, neuromuscular responses via electromyography (EMG) and muscular endurance were conducted at baseline and following 3 and 6 weeks of training.

Results: Post training ST and CT3 elicited greater MVC increases than CT1 and CON (both $p < 0.05$). ST resulted in greater increases in limb girth than both CT1 and CON ($p = 0.05$ and 0.004). CT3 induced greater structural adaptations than CON ($p = 0.04$). EMG increased similarly in all training conditions (all $p < 0.05$). Following 6 weeks of training both concurrent training conditions elicited improvements in muscular endurance (both $p < 0.05$).

Conclusions: It was concluded that both the ratio and frequency of concurrent strength and endurance training influenced the magnitude of strength and morphological development and degree of interference experienced in response to 6 weeks of 3 $d \cdot wk^{-1}$ of training. As neuromuscular responses were similarly affected by respective training interventions, the muted strength responses may be attributed to attenuated structural adaptation in the concurrent training conditions. These data suggest that if strength type adaptations are the primary focus of a training intervention, then frequency of endurance training should remain low (< 3 $d \cdot wk^{-1}$).

4.2 Introduction

Many sporting events, including invasion games (e.g. basketball, rugby union and football), sprint kayaking, and rowing, require the expression of high levels of muscular strength, yet at the same time they also demand endurance-type capabilities in order to optimize performance. As such it is inevitable that concurrent training will be performed at particular stages during an athlete's training cycle (García-Pallarés *et al.*, 2009; Argus *et al.*, 2010; García-Pallarés & Izquierdo, 2011). A greater understanding of the interactions between strength and endurance training would provide essential insight for applied practitioners involved in sporting activities that have recognised divergent physiological requirements.

The incompatibility of strength and endurance training has been investigated extensively within the literature, with the majority of studies employing similar research designs. These methodological designs typically include strength training, concurrent training and on occasion, endurance or control conditions (McCarthy, Pozniak & Agre, 2002; Häkkinen *et al.*, 2003; Shaw, Shaw & Brown, 2009). More recently, research has also investigated the effects of implementing strength training within specific populations; most notably groups of endurance trained athletes (Mikkola *et al.*, 2007; Rønnestad *et al.*, 2010; Rønnestad, Hansen & Raastad, 2011). However, what remains to be fully understood is whether the frequency and/or ratio of strength and endurance training performed within a holistic training programme can further influence the nature of any interference experienced. Indeed, as acute training variables central to the construct of any training programme, understanding how frequency and the distribution of training parameters impacts physiological adaptations is critical in developing effective training strategies.

The so called “interference effect” (Hickson, 1980) is neither conclusive nor exhaustive, as various investigators have reported no inhibiting effects of endurance training on the desired physiological adaptations to strength training (Nelson *et al.*, 1990; Sale *et al.*, 1990; Abernethy & Quigley, 1993; Volpe *et al.*, 1993; McCarthy *et al.*, 1995; Gravelle & Blessing, 2000; McCarthy, Pozniak & Agre, 2002; Häkkinen *et al.*, 2003). However when interrogating the literature in greater detail, this non inhibition tends to occur when training frequency remains low (typically < 3 $d \cdot wk^{-1}$) (Sale *et al.*, 1990; Craig *et al.*, 1991; Abernethy & Quigley, 1993; Volpe *et al.*, 1993; McCarthy *et al.*, 1995; Gravelle & Blessing, 2000; McCarthy, Pozniak & Agre, 2002; Häkkinen *et al.*, 2003). As such it may be prudent to ask if the ratio of strength and endurance training performed may influence the magnitude of any interference expressed.

It appears that an increased frequency of endurance training can result in attenuated strength and power responses (Craig *et al.*, 1991; Hennessy & Watson, 1994; Kraemer *et al.*, 1995) whereas lower frequencies do not (Sale *et al.*, 1990; Abernethy & Quigley, 1993; McCarthy *et al.*, 1995). Consequently, it makes the expectation tenable that magnitude of interference experienced is dependent on the volume of endurance training performed, a question which has not been addressed in scientific literature. Therefore, the purpose of this study was to investigate the effects of variation in concurrent strength and endurance training ratios and frequency on neuromuscular and anthropometric adaptations using an isolated limb model.

4.3 Methods

4.3.1 Experimental approach to the problem

A balanced, randomized, between-group study design was employed. Participants were randomly assigned to one of four experimental conditions; i) strength training (ST), ii) concurrent strength and endurance training at a ratio of 3:1 (CT3), iii) concurrent strength and endurance training at a ratio of 1:1 (CT1) or iv) no training (CON). The total duration of the study was 9 weeks including the 6 week training intervention, baseline, mid- and post-intervention measures. To reduce variation, allow greater standardisation and ensure the prescribed training stimulus affected the assessed musculature (Uh *et al.*, 2000) all training and performance assessments were conducted by adopting a unilateral, isolated limb model.

Participants in the ST group performed strength training alone on all scheduled training sessions. The CT3 group completed strength training on every scheduled session with every third session immediately followed by an endurance training protocol. Participants designated CT1 completed strength training immediately followed by endurance training at every scheduled session. Those participants assigned to CON performed no strength or endurance training during the 9 week experimental period. All participants were instructed to refrain from any strength or endurance training other than that prescribed by the investigator throughout the experimental period. Due to the requirements of the separate training protocols it was not possible to match total work performed in the respective experimental conditions.

Participants completed their respective intervention 3 times per week with ~48 h between sessions for 6 weeks resulting in a total of 18 separate training sessions. In order to assess whether the frequency and ratio of strength and

endurance training performed may influence the degree of strength development and/or structural adaptation experienced during experimental conditions, assessments of maximal voluntary contraction (MVC) and limb girth of the trained leg were assed prior to training, following 3 weeks of training, and upon completion of the respective training interventions. In order to determine the influence of neural and neuromuscular factors on any strength-related responses, neuromuscular activity was assessed by electromyography (EMG) during MVC determination. Elsewhere, in an effort to understand the impact on endurance-based parameters a muscular endurance testing protocol was employed at the aforementioned stages of the training intervention.

4.3.2 Participants

Twenty four healthy recreationally resistance-trained men (age: 25 ± 3 y; body mass: 82.3 ± 10.0 kg; height: 179 ± 7 cm; MVC: 311.2 ± 42.3 Nm) volunteered to participate in the study. Participants were matched at baseline for age, body mass and pre-training MVC (all $p > 0.05$). Additional information relating to study participants training status, nutritional restrictions and health status is presented in section 3.3.

4.3.3 Procedures

4.3.3.1 Strength and endurance training protocols

All training and assessments consisted of unilateral leg extensions of the dominant leg. Participants performed unilateral extension of the knee through a range of motion of 135° of flexion and extension at a speed $60°\cdot s^{-1}/1.05\ rads\cdot s^{-1}$. (Cybex Norm, Cybex International, New York, N.Y.). The experimental set up of the

dynamometer was consistent with the manufacturer's guidelines, with the axis of rotation of the knee set central to the lever arm of the dynamometer. The strength training protocol required participants to perform 5 sets of 6 repetitions at 80 ± 5% of their individual isokinetic MVC with 3 min rest intervals between sets. This training intensity was adopted as it has been reported to be appropriate for eliciting adaptations in strength and hypertrophy in recreationally trained non-athletes (Peterson *et al.*, 2004; 2005). Training intensity was progressively increased based on determination of MVC at the start of each training session.

The endurance training protocol consisted of 30 min of repeated isokinetic unilateral leg extensions at 30 ± 5% individual MVC for that session. Frequency was set at 1 s per muscle action. Tempo was standardized via electronic metronome throughout the trial (KDM 2, Korg, Tokyo, Japan). All training and testing was conducted at the same time of day (± 1 h) for each participant in order to avoid any diurnal performance variations. In order to standardize across all trial, participants were required to repeat their dietary intake the evening before and day of each training session and trial. Compliance was excellent and all participants completed all required training sessions.

4.3.3.2 Muscle strength measurements - maximal voluntary contraction

Assessments of participant's maximal unilateral strength were conducted at baseline and following 3 and 6 weeks of the respective training interventions. Unilateral leg extensions of the dominant leg and were performed on an isokinetic dynamometer (Cybex Norm, Cybex International, New York, N.Y) as an approach to determining maximal force production during voluntary muscle contraction. The experimental set up of the dynamometer was consistent with the manufacturer's

guidelines. Briefly (Figure 4.1), the axis of rotation of the knee was set central to the power head axis of rotation of the dynamometer. The ankle of the dominant leg was then firmly strapped to the limb adapter and stabiliser pad while the thigh was secured to prevent extraneous movement of the upper leg. The ankle non-dominant leg was placed behind a stop to prevent unwanted movement of the non-dominant limb and hips during contractions. Participant's upper body was firmly strapped into the dynamometer chair and during leg extensions they were required to grip the handles at the side to prevent any unwanted movement of the upper body.

Participants performed unilateral extension of the knee through a range of motion of 135° of flexion and extension at a speed $60°\cdot s^{-1}/1.05\ rads\cdot s^{-1}$. Participant's dominant limb was determined using methods consistent with those described by Hebbal and Mysorekar (2006) in which basic tasks including kicking a football; pushing an object with the foot and stamping on the ground were designated as the participant's dominant limb.

In all cases, participants were habituated with testing procedures of voluntary force production of the muscle groups tested. Participants first performed ten warm up repetitions at ~50% MVC, followed by two maximal repetitions. Upon completion of trial attempts and following a 3 min recovery period, participants were given 3 individual attempts to achieve their individual maximal torque. If participants peaked on their third attempt, following 3 min rest two further attempts (with a 3 min recovery period between attempts) were given to ensure maximum isokinetic torque for that visit was defined.

The reliability of MVC determination was assessed during pilot testing. Fifteen healthy recreationally resistance-trained men (age: 26 ± 4 y; body mass: 87.1 ± 13.4 kg; height: 185 ± 8 cm) attempted to achieved their MVC 2 separate

occasions at the same time of day (± 1 h) with a 4 d interval between assessments to determine intra assessment session reliability. All participants were required to abstain from exercise for 24 h prior to assessments and repeat their nutritional intake the evening before and on day of assessments. Participants also performed the required exercises 2 times (with a 5 min recovery period) within the same assessment session to determine inter assessment session reliability. All assessments were conducted by the same investigator. Data pertaining to the intra and inter assessment session are presented in Table 4.1.

Table 4.1. Reliability of unilateral maximal strength assessed within this thesis.

Unilateral maximal strength			
	ICC	*R*	CV (%)
Intra assessment	0.99	0.99	2.3
Inter assessment	0.99	0.99	1.6

intra-class correlation coefficients (ICC), Pearson's correlation coefficient (*r*) and coefficients of variation (CV).

Figure 4.1. Dynamometer set up for determination of MVC and muscular endurance.

4.3.3.3 Muscular endurance assessment

To assess the influence of the separate training interventions with differing volumes of strength and endurance training on localised muscular endurance characteristics, participants performed a standardised protocol designed to determine unilateral muscular endurance capabilities. All assessments consisted of a unilateral leg extension of the dominant leg and were performed using the aforementioned dynamometer and experimental set up detailed in section 4.3.3.2. Participants performed repeated unilateral isokinetic leg extensions at the knee joint through a range of motion of 135° at a speed $60°\cdot s^{-1}/1.05\ rads\cdot s^{-1}$. Intensity was set at 60 ± 5% of participant's individual MVC established in that session. Participants were required to perform 1 muscle action per s^{-1} until 60 ± 5% of initial MVC could no longer be maintained. The criteria for failure were set as i) an inability to complete repetitions at 60 ± 5% of initial MVC and/or ii) 1 muscle action per s^{-1}. Two consecutive failures to maintain the required performance standards were considered appropriate reason for cessation of the test. Tempo was standardised throughout all local muscular endurance tests via digital metronome (KDM-2, Korg, Inagi, Tokyo, Japan). Time to exhaustion (TTE) was recorded upon cessation of the protocol and used for data analysis.

The reliability of unilateral muscular endurance assessment was determined during pilot testing. Thirty males (25 ± 5 y; 79.5 ± 5.4 kg; 180.5 ± 6.5 cm) completed the experimental protocol on 2 separate occasions at the same time of day (± 1 h) with a 4 d interval between assessments to determine intra assessment session reliability. All participants were required to abstain from exercise for 24 h prior to assessments and repeat their nutritional intake the evening before and on day of

assessments. All assessments were conducted by the same investigator. Data pertaining to the intra assessment session reliability are presented in Table 4.2.

Table 4.2. Reliability of endurance and work capacity measures assessed within this thesis.

Unilateral muscular endurance			
	ICC	*r*	CV (%)
Intra assessment	0.99	0.99	6.9

intra-class correlation coefficients (ICC), Pearson's correlation coefficient (*r*) and coefficients of variation (CV).

4.3.3.4 Limb girth measurements

Measurements of participant's limb girth were conducted to assess the effect of the respective interventions on the morphological adaptations of the trained musculature. These assessments were conducted pre, following 3 and 6 weeks of training. Due to investigational requirements limb girth of the dominant thigh was chosen as a suitable proxy of morphological adaptation. In all cases, girth was assessed using an anthropometric tape measure (MyoTape, Body Tape Measure, Accufitness, CO, USA). The tape was placed horizontally around the around the mid-thigh. This position was accurately determined in all cases as the mid-way point between the inguinal crease and proximal border of the patella. The proximal border of the patella was marked while the participant extended the knee whilst in the standing position. All assessments were conducted in accordance with standardised procedures (Lohman *et al.*, 1988).

The reliability of limb girth assessment was determined during pilot testing. Fifteen healthy recreationally resistance-trained men (age: 26 ± 4 y; body mass: 87.1 ± 13.4 kg; height: 185 ± 8 cm) had the girth of the their mid-thigh (of the dominant

limb) measured on 2 separate occasions at the same time of day (± 1 h) with a 4 d interval between assessments to determine intra assessment session reliability. All participants were required to abstain from exercise for 24 h prior to assessments and repeat their nutritional intake the evening before and on day of assessments. Participants also had the girth of their dominant limb measured 2 times (with a 5 min interval) within the same assessment session to determine inter assessment session reliability. All assessments were conducted by the same investigator. Data pertaining to the intra and inter assessment session are presented in Table 4.3.

Table 4.3. Reliability of limb girth measures employed within this thesis.

Limb girth			
	ICC	*r*	CV (%)
Intra assessment	0.99	0.99	1.4
Inter assessment	0.99	0.99	1.1

intra-class correlation coefficients (ICC), Pearson's correlation coefficient (*r*) and coefficients of variation (CV).

4.3.3.5 Electromyography

Surface electromyography (EMG) was utilised as a proxy of the neural activation during maximal contractions and like other outcome measures was assessed pre, at the mid-point and following the respective training interventions. Surface EMG was recorded over *vastus lateralis* (VL) and *bicep femoris* (BF) muscles using paired electrodes (22 mm diameter, model; Kendall, Tyco Healthcare Group, Mansfield, MA, USA) 2 cm apart. VL electrodes were placed at a position ⅔ on the line from the anterior superior spina iliaca superior to the lateral side of the patella (Hermens *et al.*, 2000). Electrodes for the BF were placed at 50% on the line between the ischial tuberosity and the lateral epicondyle of the tibia. A reference

electrode was placed over the patella (Hermens *et al.*, 2000) (Figure 4.2). Prior to application of electrodes, all sites were first shaved, abraded, and then wiped clean with a sterile swab and marked with indelible ink to ensure a consistent placement of electrodes could be assured during subsequent experimental procedures. EMG signals were amplified (1000x), band pass filtered at 10-1,000Hz (D360, Digitimer, Hertfordshire, UK) and sampled at 5,000Hz (CED Power 1401, Cambridge Electronics Design, Cambridge, UK). Raw EMG recordings were normalised to individual EMG activity during sessional MVC (Tallent *et al.*, 2012).

The reliability of electromyographic assessment employed within this thesis was determined during pilot testing. Fifteen healthy recreationally resistance-trained men (age: 26 ± 4 y; body mass: 87.1 ± 13.4 kg; height: 185 ± 8 cm) attempted to achieved their unilateral MVC whilst surface EMG was recorded on 2 separate occasions at the same time of day (± 1 h) with a 4 d interval between assessments to determine intra assessment session reliability. All participants were required to abstain from exercise for 24 h prior to assessments and repeat their nutritional intake the evening before and on day of assessments. Participants also performed the attempts to achieve their unilateral MVC whilst surface EMG was recorded (with a 5 min recovery period) twice within the same assessment session to determine inter assessment session reliability. All assessments were conducted by the same investigator. Data pertaining to the intra and inter assessment session are presented in Table 4.4.

Table 4.4. Reliability of electromyographic measures assessed within this thesis.

Neuromuscular variables			
	ICC	*R*	CV (%)
Intra assessment			
EMG – VL	0.81	0.87	12.6
EMG – BF	0.86	0.89	9.4
Inter assessment			
EMG – VL	0.85	0.93	9.7
EMG – BF	0.91	0.92	7.8

intra-class correlation coefficients (ICC), Pearson's correlation coefficient (*r*), coefficients of variation (CV), *vastus lateralis* (VL) and *bicep femoris* (BF).

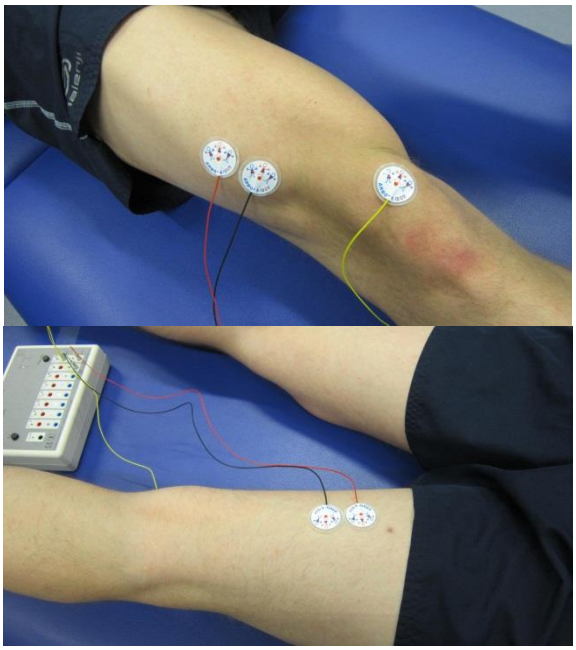

Figure 4.2. Placement of surface electrodes.

4.3.3.6 Statistical analysis

Data are presented as mean ± standard deviation. Values of MVC, TTE and limb girth were 'normalised' by transforming them to percentage (%) change from baseline and used for analysis. Initial pilot work indicated that the aforementioned

measures demonstrated good test-retest reliability for measures of MVC, TTE, EMG and limb girth. EMG data was normalised using MVC values from each individual training/assessment session. All subsequent statistical analysis was conducted on converted data. Prior to analysis the dependant variables were verified as meeting required assumptions of parametric statistics and changes in all assessed measures were analysed using mixed model repeated measures ANOVA tests. ANOVA analysed differences between 4 conditions (ST, CT3, CT1 and CON) and 3 time points (baseline, mid-intervention and post-intervention). The alpha level of 0.05 was set prior to data analysis. Assumptions of sphericity were assessed using Mauchly's test, and if the assumption of sphericity was violated a Greenhouse Gessier correction was employed. If significant effects between conditions or over time were observed *post-hoc* differences were analysed with the use of Bonferroni correction. Statistical power of the study was calculated post-hoc using G*Power statistical software (v3.1.3, Düsseldorf, Germany) using the effect size, group mean, SD and sample size of the primary outcome measures, in this case being MVC and limb girth. Power was calculated as between 0.8 and 1 indicating sufficient statistical power (Cohen, 1992).

Elsewhere statistical analysis which reports uncertainty of outcomes as 90% confidence intervals (CI), generating probabilistic magnitude-based inferences about the true value of outcomes were also employed (Batterham & Hopkins, 2006). These methods are discussed in detail in section 3.10.2.

4.4 Results

4.4.1 Performance measures

4.4.1.1 Maximal unilateral strength

A significant time x group interaction ($F_{(6, 40)} = 7.71$, $p < 0.001$) and an a time effect ($F_{(2, 40)} = 15.15$, $p < 0.001$) were observed for changes in participants maximal unilateral strength. After 3 weeks, participants who completed training interventions (ST, CT3 and CT1) experienced a mean increase in MVC of 8.1 ± 3.8%, with further increases of 20.9 ± 11.9% observed post-training training. There was a significant effect across time from baseline to mid training (12.4 ± 3.9%) for MVC values in the ST group ($p = 0.016$). Increases were present from baseline to post-intervention in both ST and CT3 conditions ($p < 0.001$), while no time effects were observed from baseline to post intervention in CT1 and CON conditions ($p = 0.152$ and 0.58 respectively).

At the mid-training point MVC in ST condition increased 19.0 ± 2.4% more than CON condition ($p = 0.01$). No other significant differences were observed at this time point. Post-training ST resulted in 22.7 ± 5.9% and 41.0 ± 2.4% greater increases in MVC than CT1 and CON conditions ($p = 0.005$ and < 0.001 respectively; Figure 4.3). CT3 condition also resulted in significantly greater increases in MVC than CT1 and CON conditions post intervention ($p = 0.024$ and < 0.001 respectively). Inferential analyses of the respective training interventions effects on unilateral lower body strength are presented in table 4.5.

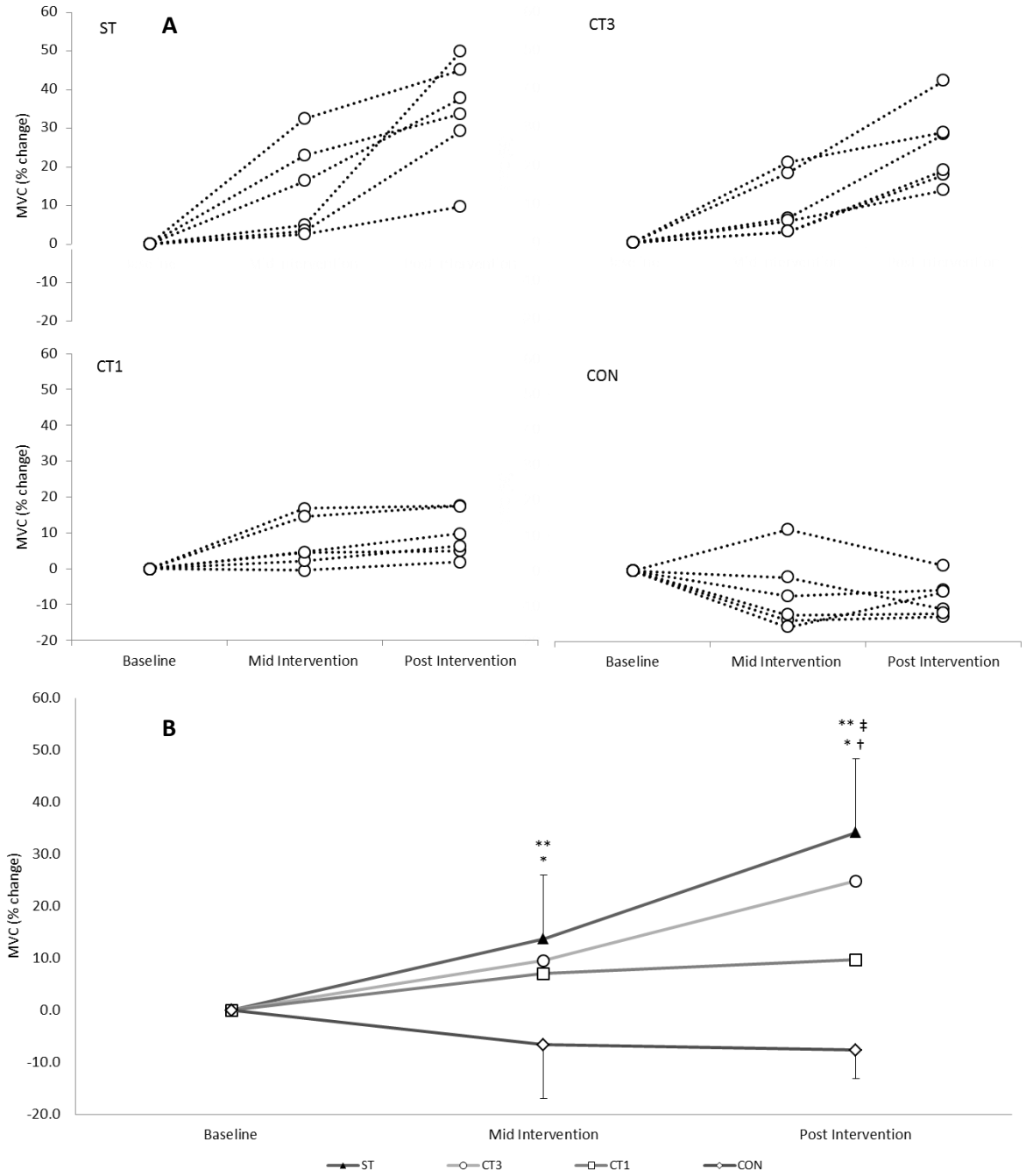

Figure 4.3. Individual (Panel A) and mean (Panel B) relative peak torque in unilateral leg extensions of the right leg in response to respective training interventions in the ST (n = 6), CT3 (n = 6), CT1 (n = 6) and CON (n = 6) conditions. ST, strength training alone performed every session; CT3, strength performed every session, strength and endurance training performed every third session; CT1, strength and endurance training performed every session; CON, no strength or endurance training performed during experimental period. * Significantly greater than baseline in ST condition ($p < 0.05$). ** ST significantly greater than CON ($p < 0.05$). † ST and CT3 significantly greater than baseline ($p < 0.05$). ‡ ST and CT3 significantly greater than CT1 and CON ($p < 0.05$).

Table 4.5. Effect of respective training interventions on increases in MVC.

Condition	Mean effect±90% CI	Qualitative inference
Change from baseline to mid intervention		
ST	12.3 ± 10.9	Likely beneficial
CT3	7.1 ± 11.3	Unclear
CT1	4.9 ± 6.8	Unclear
CON	-6.9 ± 9.3	Unlikely beneficial
Change from baseline to post intervention		
ST	30.4 ± 13.2	Most likely beneficial
CT3	24.6 ± 8.5	Most likely beneficial
CT1	7.2 ± 6.1	Likely beneficial
CON	-10.6 ± 10.9	Very unlikely beneficial

Note: Mean effect refers to the first named stage of intervention minus the second named stage of intervention. For the ±90%CI, add and subtract this number to the mean effect to obtain the 90% confidence intervals for the true difference. ST, strength training alone performed every session; CT3, strength performed every session, strength and endurance training performed every third session; CT1, strength and endurance training performed every session; CON, no strength or endurance training performed during experimental period.

4.4.1.2 Muscular endurance

A significant time effect was observed for muscular endurance responses ($F_{(2, 31)} = 10.23$, $p < 0.001$). CT3 elicited improvements of 21.1 ± 4.2% in TTE mid-training ($p = 0.008$). Post training intervention CT3 also resulted in TTE improvements of 26.1 ± 6.7% ($p = 0.048$). CT1 condition increased TTE post-training by 35.5 ± 11.1% ($p = 0.014$). Inferential analyses of the respective training interventions effects on unilateral muscular endurance are detailed in Table 4.6.

Table 4.6. Effect of respective training interventions on increases in TTE.

Condition	Mean effect±90% CI	Qualitative inference
Change from baseline to mid intervention		
ST	43.7 ± 55.2	Unclear
CT3	21.3 ± 14.4	Very likely beneficial
CT1	17.6 ± 10.5	Very likely beneficial
CON	19.3 ± 17.4	Unclear
Change from baseline to post intervention		
ST	27.6 ± 39.8	Unclear
CT3	26.1 ± 16.2	Very likely beneficial
CT1	35.6 ± 19.5	Very likely beneficial
CON	6.1 ± 25.3	Unclear

Note: Mean effect refers to the first named stage of intervention minus the second named stage of intervention. For the ±90% CI, add and subtract this number to the mean effect to obtain the 90% confidence intervals for the true difference. ST, strength training alone performed every session; CT3, strength performed every session, strength and endurance training performed every third session; CT1, strength and endurance training performed every session; CON, no strength or endurance training performed during experimental period.

4.4.2 Structural adaptation

A significant time x group interaction ($F_{(6,40)}$ = 2.78, p = 0.024) and a time effect ($F_{(2, 40)}$ = 17.38, p < 0.001) were observed for muscular growth responses. ST and CT3 conditions induced significant increases of 1.7 ± 0.4% and 1.7 ± 0.9% in limb girth at mid intervention, respectively. Post training further increases of 3.7 ± 2.3% and 2.5 ± 1.2% were observed (all p < 0.05).

Limb girth adaptions from baseline to post intervention were 2.3 ± 0.5% (p = 0.04) and 3.6 ± 0.1% (p = 0.004) greater in ST compared to CT1 and CON respectively (Figure 4.4). It was also observed that CT3 elicited a 2.4 ± 1.7% greater increases in limb girth than CON when assessed post training (p = 0.04). Inferential analyses of the respective training interventions effects on limb girth are detailed in table 4.7.

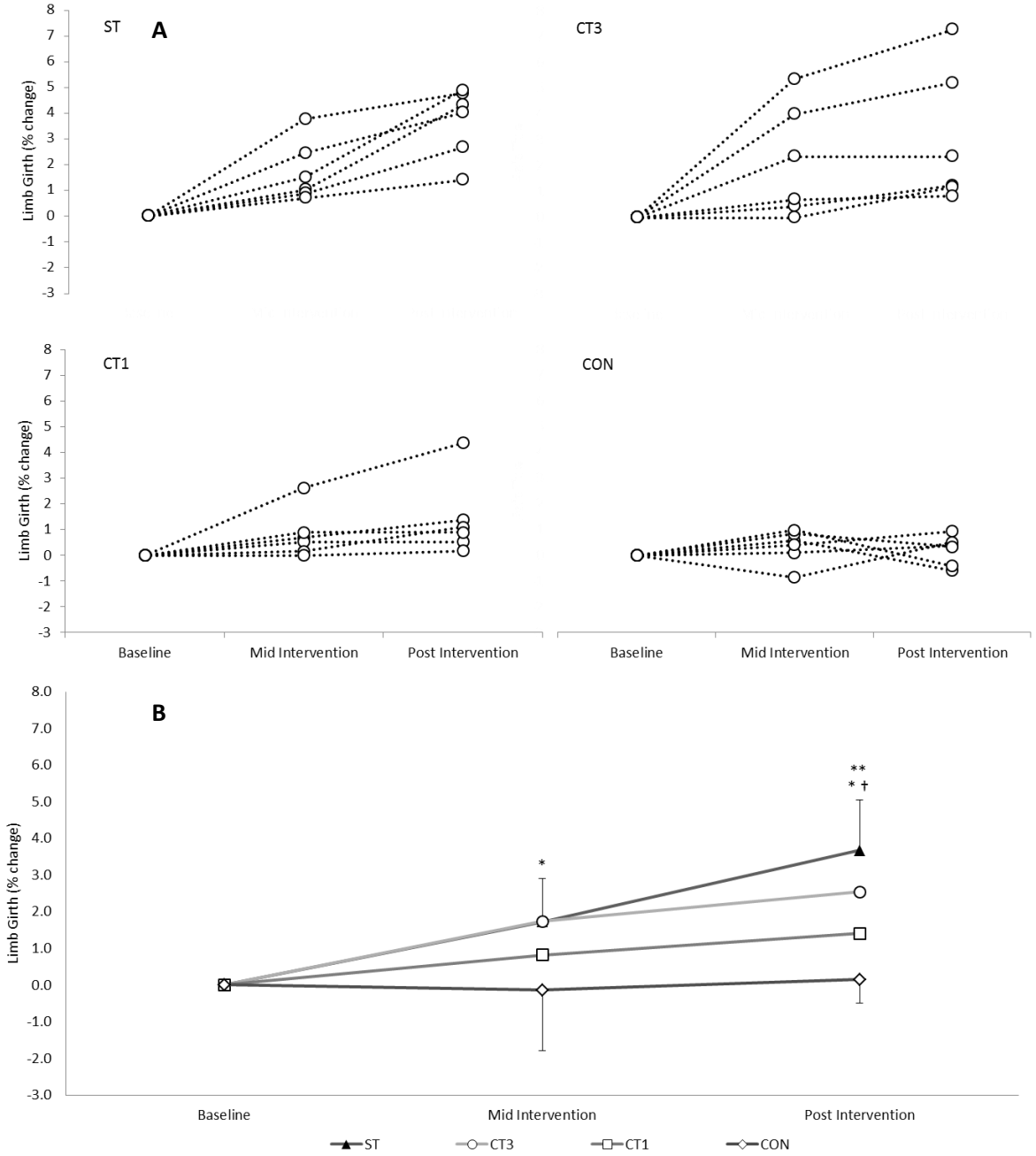

Figure 4.4. Individual (Panel A) and mean (Panel B) relative changes in right mid-thigh limb girth in response to respective training interventions in the ST (*n = 6*), CT3 (*n = 6*), CT1 (*n = 6*) and CON (*n = 6*) conditions. ST, strength training alone performed every session; CT3, strength performed every session, strength and endurance training performed every third session; CT1, strength and endurance training performed every session; CON, no strength or endurance training performed during experimental period. * ST and CT3 significantly greater than baseline ($p < 0.05$). ** ST greater than CT1 and CON ($p < 0.05$). † CT3 greater than CON ($p < 0.05$).

Table 4.7. Effect of respective training interventions on increases in limb girth.

Condition	Mean effect±90% CI	Qualitative inference
Change from baseline to mid intervention		
ST	2.0 ± 1.2	Likely beneficial
CT3	2.0 ± 2.5	Likely beneficial
CT1	1.2 ± 0.9	Possibly beneficial
CON	1.1 ± 9.5	Unclear
Change from baseline to post intervention		
ST	4.3 ± 1.2	Most likely beneficial
CT3	2.8 ± 3.1	Likely beneficial
CT1	1.0 ± 0.9	Possibly beneficial
CON	1.2 ± 3.7	Unclear

Note: Mean effect refers to the first named stage of intervention minus the second named stage of intervention. For the ±90% CI, add and subtract this number to the mean effect to obtain the 90% confidence intervals for the true difference. ST, strength training alone performed every session; CT3, strength performed every session, strength and endurance training performed every third session; CT1, strength and endurance training performed every session; CON, no strength or endurance training performed during experimental period.

4.4.3 Neuromuscular factors

A significant time x group interaction was observed for neuromuscular responses during MVC ($F_{(6, 28)} = 3.113$, $p = 0.018$). Neuromuscular responses during MVC increased significantly over time for all conditions with the exception of CON (all $F_{(1, 17)} = 12.45$, $p < 0.05$). No effect of training intervention was observed (Figure 4.5).

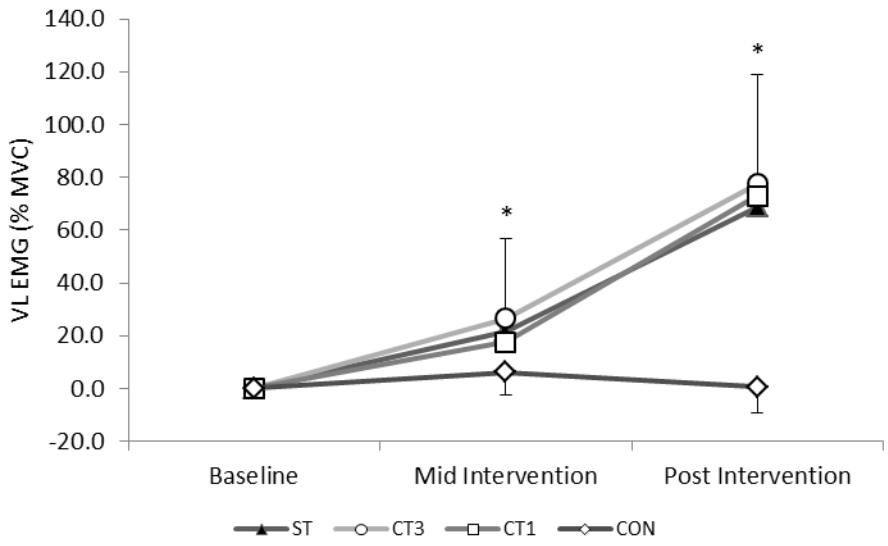

Figure 4.5. Relative increases in neuromuscular activity during MVC as assessed by EMG in the VL in response to respective training interventions in the ST (*n* = *6*), CT3 (*n* = *6*), CT1 (*n* = *6*) and CON (*n* = *6*) conditions. ST, strength training alone performed every session; CT3, strength performed every session, strength and endurance training performed every third session; CT1, strength and endurance training performed every session; CON, no strength or endurance training performed during experimental period. * significantly higher than baseline in training groups ($p < 0.05$).

4.5 Discussion

The focus of the present research was to examine the impact of differing ratios of strength and endurance training in a concurrent training regimen on strength and muscle morphology. The study sought to prioritise muscular strength development as a primary objective, and to examine the impact of concurrent endurance components upon it. The results of this study demonstrate that 6 weeks of 3 $d \cdot wk^{-1}$ strength training was successful in eliciting improvements in both strength and limb girth. It was also observed that concurrent training with both low and high frequencies of endurance training improves muscular endurance. When an endurance element was added to training the degree of strength and muscular growth responses were blunted in proportion to the frequency of endurance training. As such, our

findings may indicate that frequency of endurance training performed during a concurrent training strategy may influence the degree of interference and/or adaptation experienced.

In the present study training was conducted in an isolated limb, employing the same biomechanical movement pattern for both strength and endurance training. It has been proposed that if the primary objective of a training programme is developing strength in a specific muscle group then endurance training should be avoided in that muscle group as specificity of movement pattern may amplify interference (Gergley, 2009). As such, this may explain why in the present study clear interference was reported whereas other studies which have employed similar training frequencies but using multi-joint resistance training and cycling or running endurance protocols observed no interference (Sale *et al.*, 1990; Craig *et al.*, 1991; Abernethy & Quigley, 1993; Volpe *et al.*, 1993; McCarthy *et al.*, 1995; Gravelle & Blessing, 2000; McCarthy, Pozniak & Agre, 2002; Häkkinen *et al.*, 2003).

Both concurrent conditions resulted in muted strength adaptation. This is consistent with previous research (Hickson, 1980; Dudley & Djamil, 1985; Craig *et al.*, 1991; Hennessy & Watson, 1994; Kraemer *et al.*, 1995), however many of the studies which have reported interference characteristics employed training interventions with greater frequencies than employed in the present study. This attenuation of strength development was greater when increased volumes of endurance training were performed and may be attributable to overall training stress becoming too great and strength development then plateaus and hence a contributing factor to interference (Häkkinen *et al.*, 2003; Mikkola *et al.*, 2007; Davis *et al.*, 2008). Strength development was however similar following 6 weeks of strength and concurrent training with low volumes of endurance training (1 $d \cdot wk^{-1}$, CT3).

previous research has also demonstrated interference may be avoided when frequency of endurance training remains low (< 3 d·wk^{-1}) (Hickson, 1980; Dudley & Djamil, 1985; Häkkinen *et al.*, 1985; Leveritt *et al.*, 1999; McCarthy, Pozniak & Agre, 2002; Mikkola *et al.*, 2007; Davis *et al.*, 2008). Elsewhere, Gergley (2009) reported that 9 weeks of concurrent training (2 d·wk^{-1}) resulted in compromised strength development. Like the findings of the present study, this demonstrates that interference may still occur when training duration remains low and may be dependent on the relative doses of strength and endurance training performed. At mid intervention limb girth had increased by 1.7 ± 0.4% in the ST and 1.7 ± 0.9% in CT3 conditions. In addition, following 3 weeks (i.e. mid intervention) of training strength development was similar between both concurrent conditions and strength training alone. Other authors have also suggested that concurrent training may be beneficial for developing strength and muscular growth in the early phases of training (Balabinis *et al.*, 2003; Häkkinen *et al.*, 2003). This supports the hypothesis that concurrent training with high frequencies of endurance training results in elevated overall training stress and the plateau of strength development.

Recreationally resistance trained individuals were recruited to participate in the present study in which clear interference was observed through both attenuated strength and limb girths. Training history and current training status of participants is a common variant in concurrent training research (McCarthy, Pozniak & Agre, 2002; Shaw, Shaw & Brown, 2009). All participants who completed the present study had prior experience of strength training, although none could be described as 'highly trained'. Many studies that have reported no interference when training frequency remains low (< 3 d·wk^{-1}) recruited untrained individuals (Sale *et al.*, 1990; Craig *et al.*, 1991; Abernethy & Quigley, 1993; Volpe *et al.*, 1993; McCarthy *et al.*, 1995).

Based on these findings it appears that athletes and highly trained populations may be more susceptible to interference than untrained individuals (Baker, 2001; Baker & Newton, 2006; Rønnestad, Hansen & Raastad, 2011). It is possible this may be due to overtraining, as highly trained individuals experience a far greater training load and volume than those who are recreationally trained. This may partly explain why interference was observed.

As frequency and volume of training seems to be a key indicator of interference, various researchers have suggested the muted strength and hypertrophic responses may be due to overtraining (Nelson *et al.*, 1990; Hennessy & Watson, 1994; Häkkinen *et al.*, 2003; Gergley, 2009). As training frequency and duration remained relatively low in the present study (6 weeks of 3 $d \cdot wk^{-1}$) it is unlikely that the attenuated strength and muscular growth can be attributed to overtraining. Dudley & Djamil (1985) also reported inhibited strength responses were unlikely to be due to overtraining in a short duration low frequency programme.

Inferential statistical analysis indicated only the ST and CT3 conditions were "most likely beneficial" for improving strength following training. Furthermore ST was the only condition which was "most likely beneficial" for improving limb girth. CT1 was only deemed "possibly beneficial" for improving limb girth, this may indicate the attenuated strength responses were due to lack of morphological adaptation. No differences in neuromuscular responses were observed between training interventions during the present study; this is in agreement with previous research stating neuromuscular characteristics are not fully inhibited by concurrent training (Paavolainen *et al.*, 1999; McCarthy, Pozniak & Agre, 2002; Mikkola *et al.*, 2007). However, neuromuscular factors including altered patterns in neural recruitment (Dudley & Fleck, 1987; Chromiak & Mulvaney, 1990; Kraemer *et al.*,

1995; Gergley, 2009), neuromuscular fatigue (Leveritt & Abernethy, 1999; Leveritt *et al.*, 1999; Davis *et al.*, 2008) and the inability to develop adequate force due to endurance training (Dudley & Fleck, 1987; Rhea *et al.*, 2008; Rønnestad, Hansen & Raastad, 2011) have previously been proposed as mechanisms for interference. The relatively short duration of training employed here may account for the similar neural responses between groups. More longitudinal studies have reported greater variance in neuromuscular responses (Häkkinen, Alen & Komi, 1985; McCarthy *et al.*, 1995).

Neuromuscular responses were similar between the prescribed training interventions (evident from EMG data), therefore it may be suggested that the attenuated improvements in strength were primarily due to lack of hypertrophic adaptation. CT3 and CT1 conditions resulted in 1.2 ± 0.8% and 2.3 ± 1.6% lower limb girth increases than ST alone, this was coupled with 5.4 ± 3.7% and 22.7 ± 16.1% lower increases in MVC. This indicates that in the present study the inclusion of endurance training may have impaired muscular growth which in turn resulted in attenuated strength responses. This concurs with other conclusions that the muted strength responses associated with concurrent training can be attributed to lack of hypertrophy (Dudley & Fleck, 1987; Chromiak & Mulvaney, 1990; Kraemer *et al.*, 1995; Leveritt *et al.*, 1999; Bell *et al.*, 2000; Gergley, 2009; Rønnestad, Hansen & Raastad, 2011).

As strength and endurance training initiate various contrasting biochemical, endocrine and molecular responses there are potential mechanisms for the interference effect that have not been analysed here. The interference phenomenon may be attributed to an increased catabolic hormonal state caused by increased training frequency and volume of endurance training (Kraemer *et al.*, 1995; Bell *et*

al., 2000). More recent research has indicated endurance training induced low muscle glycogen and may impair intracellular signalling pathways responsible for hypertrophy (Hawley, 2009; Rønnestad, Hansen & Raastad, 2011). It has also been suggested that the molecular signalling pathways responsible for endurance-based adaptations inhibit the activation of pathways responsible for protein synthesis, and thus strength and hypertrophic adaptations (Baar, 2006; Nader, 2006; Baar, 2009).

Concurrent training is typically associated with impaired strength and hypertrophy, however various researchers have indicated concurrent training is an effective means of improving muscular endurance (Davis *et al.*, 2008; Rønnestad, Hansen & Raastad, 2010; 2011). This was also observed in the present study, as concurrent training conditions were shown to improve muscular endurance. Concurrent training conducted 3 times weekly (CT1) resulted in 7.6 ± 2.3% greater increases in TTE than strength training alone. Davis *et al*. (2008) reported similar findings; concurrent training increased TTE by 8.1% more than strength training alone. This was further illustrated as following 3 and 6 weeks of training it was only the concurrent conditions that were deemed "very likely beneficial" for improving muscular endurance. The benefit of ST and CON on TTE was deemed "unclear".

The aims of this thesis were to investigate and draw conclusions regarding the potential underlying physiological mechanisms relating to concurrent training strategies and the interference phenomenon, and further elucidate the effects of manipulating programme variables within concurrent training regimens on strength related adaptation. Moreover, the initial focus of this thesis was to examine the impact of differing ratios of strength and endurance training on performance, anthropometric and neuroendocrine responses and adaptations. Although concurrent training was observed to be an effective means of improving muscular endurance,

data presented in this chapter demonstrates that when strength and endurance training are performed concurrently greater volumes of endurance training expressed in a potential incremental fashion result in an amplified inhibition of strength and muscular growth. Lower volumes of endurance exercise did not result in a noteworthy inhibition of strength or muscular growth. As such, it is suggested that frequency and volume of endurance training performed have the potential to be key determinants of the interference effect.

4.6 Practical applications

In the current study, short term, high frequency isolated limb concurrent strength and endurance training resulted in attenuated strength and morphological responses. However these data also indicated that the ratio of strength and endurance training performed influences the degree of interference experienced. As all prescribed training interventions had similar effects on neuromuscular adaptations, improvements in strength in the present study appear to be attributable to structural adaptation.

The findings of this chapter have implications for the programming of concurrent training strategies. Higher volumes of endurance training in a concurrent programme resulted in amplified inhibition of strength development. As such the data presented indicate that if strength development and/or hypertrophic adaptation is/are the primary objective(s) of a training intervention volume of endurance training should remain low ($\leq 1\ d \cdot wk^{-1}$). Furthermore those programming for sports and events which require both strength and endurance capabilities yet prioritise strength type performance phenotypes should carefully monitor the volume of endurance training prescribed if interference is to be avoided.

As previously stated the study was conducted in an isolated limb model, which allowed greater standardisation, ensured training stimulus affected the assessed musculature and limited confounding factors which may have influenced outcome measures (Uh *et al.*, 2000). However the real world applications of these data are limited as isolated limb training results in little improvement in functional physical performance.

Whilst this chapter presents novel performance data the underlying mechanisms behind interference are yet to be fully elucidated. It is also unclear whether the strength responses observed in this chapter can be replicated following a functional multi joint training intervention. As such the next research avenue of this thesis will examine differing ratios of multi joint strength and endurance training on strength related performance and proposed endocrine indicators of anabolism and catabolism.

5. Differing ratios of concurrent strength and endurance training: Physiological stress and impaired strength development

5.1 Abstract

Purpose: The present study examined the strength and endocrine responses to varying ratios of strength and endurance training and total work performed in a concurrent training regimen.

Methods: 30 resistance-trained men completed 6 weeks of 3 $d \cdot wk^{-1}$ of strength training (ST), concurrent strength and endurance training ratio 3:1 (CT3), concurrent strength and endurance training ratio 1:1 (CT1) or no training (CON). Strength training was conducted using multi-joint training strategy, while endurance training consisted of treadmill running. Assessments of maximal strength, lower body power, body composition and endocrine factors were conducted pre training and following 3 and 6 weeks of the intervention.

Results: Following 6 weeks of training, ST and CT3 elicited similar increases in lower body strength; furthermore, ST resulted in greater increases than CT1 and CON (all $p < 0.05$). All training conditions resulted in similar increases in upper body strength following training. The ST group observed greater increases in lower body power than all other conditions (all $p < 0.05$). CT1 was the only condition to elicit increases in resting cortisol levels following of training ($p = 0.008$).

Conclusions: When implemented as part of a concurrent training regimen, higher volumes of endurance training result in the inhibition of lower body strength, whereas low volumes do not. Lower body power was attenuated by high and low frequencies of endurance training. It was also observed that higher frequencies of endurance training result in increased resting cortisol levels following training. These data suggest that if strength development is the primary focus of a training intervention, frequency of endurance training should remain low.

5.2 Introduction

Research has indicated that any interference experienced during a concurrent strength and endurance training regimen may be dependent in part on the volume of training performed (Sale *et al.*, 1990; Craig *et al.*, 1991; Abernethy & Quigley, 1993; Volpe *et al.*, 1993; McCarthy *et al.*, 1995; Gravelle & Blessing, 2000; McCarthy, Pozniak & Agre, 2002; Häkkinen *et al.*, 2003). Despite this, no study has specifically examined the effects of multi joint concurrent training inventions with varying training volumes on strength development. Data presented in Chapter 4 demonstrate that the magnitude of interference experienced may be proportional to the frequency of endurance training performed; indicating overall training volume and stress may indeed regulate the presence of any interference experienced.

Elevated training stress has previously been proposed as a mechanism for interference (Dudley & Fleck, 1987), and is perhaps attributable to the experimental design of many published studies investigating concurrent training and the interference phenomenon. This design involves the concurrent group performing identical volumes of strength training to those conducting strength training alone. The concurrent condition is also required to perform endurance training (of equal frequency to strength training) in the same regimen, resulting in the concurrent condition incorporating double the training volume and total workload of the strength training condition. The greater total work performed in concurrent training regimens may then explain why protocols involving higher concurrent training frequencies ($\geq$ 3 $d \cdot wk^{-1}$) result in interference (Craig *et al.*, 1991; Hennessy & Watson, 1994; Kraemer *et al.*, 1995) (Chapter 4 of this thesis) whereas lower frequencies (and total workloads) do not (McCarthy *et al.*, 1995; McCarthy, Pozniak & Agre, 2002). These data support the hypothesis that total work performed in a

concurrent programme influences both the presence and magnitude of any interference experienced, although the underlying mechanisms are yet to be fully elucidated.

The attenuated strength development as a result of greater training volumes observed in Chapter 4 was not due to impaired neural adaptation, and is demonstrated by the similar neural responses to the individual training interventions (Figure 4.5). As a result it should be considered that there is value in exploring other physiological mechanisms that might contribute to interference. There is presently limited published data pertaining to the hormonal responses to concurrent training protocols. Endocrine responses to exercise stress have been widely studied as a means of gaining insight into the physiological responses and adaptations potentially taking place in response to various training paradigms (Häkkinen & Pakarinen, 2007; Crewther *et al.*, 2008; Fry & Lohnes, 2010; West & Phillips, 2012).

In a somewhat seminal publication, the role of elevated endocrine responses and catabolism has been previously implicated in the interference phenomenon (Kraemer *et al.*, 1995). The authors reported a decreased testosterone:cortisol ratio following concurrent training with no such decrease in participants who performed strength training alone. Subsequent research replicated these findings, as Bell *et al*. (1997) and Bell *et al*. (2000) reported concurrent but not strength training in isolation increased cortisol following a training intervention. In addition to elevated cortisol, Bell *et al.* (2000) reported no elevations in resting testosterone or growth hormone following concurrent training; both were however increased by strength training conducted in isolation. Elevated cortisol is associated with the inhibition of protein synthesis, subsequent fibre hypertrophy and increases in contractile strength of the trained musculature (Kuoppasalmi & Adlercreutz, 1985; Kraemer *et al.*,

1995); furthermore, research has also indicated basal cortisol levels are representative of overall training induced physiological stress (Bosco *et al.*, 2000; Kraemer & Ratamess, 2005). As such, it may be hypothesised that the high training volumes experienced in concurrent training regimens can result in elevated physiological stress, which is reflected in the responses of anabolic and catabolic hormones. This shift in the endocrine milieu in favour of catabolism may contribute to attenuated strength and hypertrophic adaptation associated with concurrent training.

The influence of varying ratios of strength and endurance training on the magnitude of interference reported in an isolated limb model illustrates the value in exploring the role of training frequency in a systematic fashion assessing whole body strength development. Furthermore, having reviewed the body of literature, it is apparent that there is no research (other than Chapter 4 of this this thesis), focusing on the frequency and ratio of strength and endurance training performed. Additionally no research has assessed if differing ratios of strength and endurance training can influence the degree of interference experienced as a result of adaptations in the anabolic:catabolic environment. Therefore, the research conducted as part of this chapter investigated the strength, anthropometric and endocrine responses to a variety of concurrent strength and endurance training ratios, with incremental loads in a functional multi joint model.

5.3 Method

5.3.1 Experimental approach to the problem

A balanced, randomized, between-group study design was employed to examine the effect of differing ratios of strength and endurance training in a

concurrent regimen on strength, anthropometric, and endocrine variables. The experimental investigation was 10 weeks in duration, during which participants were randomly assigned to one of four experimental conditions: either i) strength training alone (ST), ii) concurrent strength and endurance training at a ratio of 3:1 (CT3), iii) concurrent strength and endurance training at a ratio of 1:1 (CT1), or iv) no training (CON). Participants in the ST group were required to perform strength training alone on all scheduled training sessions. In comparison, the CT3 group completed strength training on every scheduled session with every third session immediately followed by an endurance training protocol. Elsewhere, participants designated CT1 completed an identical strength training protocol immediately followed by endurance training at every scheduled session, while those participants in the CON group performed no strength or endurance training during the experimental period. Due to the requirements of the separate training protocols it was not possible to match total work performed in the respective experimental conditions. All participants were instructed to abstain from any other strength or endurance training throughout the experimental period beyond that prescribed by the investigator.

Participants completed their respective intervention 3 $d \cdot wk^{-1}$ with ~48 h between sessions for 6 weeks resulting in a total of 18 separate training sessions. In order to assess whether the frequency and ratio of strength and endurance training performed influenced strength, physical performance, and changes in body composition, assessments of 1 repetition maximums (1RM), countermovement jump height (CMJ), and body composition were assed pre, mid and post-intervention. To assess the effect of the designated training interventions on endocrine factors related to strength and morphological adaptation, venous blood samples were taken and subsequently analysed for circulating testosterone and cortisol concentrations.

During the investigation, venous blood samples were collected immediately before (pre) and following the cessation of exercise (post) in the initial, mid and final compound training sessions of the 18 sessions performed.

5.3.2 Participants

Thirty healthy, recreationally resistance-trained men (age: 23 ± 4 y; body mass: 79.2 ± 6.7 kg; height: 179.2 ± 6.7 cm; % body fat: 16.2 ± 5.4 %; sum of assessed 1RMs: 506.0 ± 11.4 kg; CMJ: 52.5 ± 7.3 cm; $\dot{V}O_{2max:}$ 50.2 ± 5.8 ml·kg·min) volunteered to participate in the study. Prior to the study commencing, participants were matched for age, body mass, body fat % and 1RM load (all $p > 0.05$), and then randomly assigned to one of the four experimental conditions. Additional information on study participants training status, nutritional restrictions and health status is presented in section 3.3.

5.3.3 Procedures

5.3.3.1 Strength training protocol

Prior to the intervention all participants completed a familiarisation week involving all training sessions in order to habituate them with the resistance training techniques employed. The strength training intervention was comprised of 3 sessions, and each was performed on separate days with ~48 h between sessions. Each session was composed of differing exercises; as such each of the sessions were designated “compound”, “pull” and “push” respectively, to best describe the nature of exercises performed. Full details of each session are presented in Table 5.1. The respective sessions were performed in the same order each week (compound, push

then pull), furthermore the order of exercises within each session was consistent throughout the intervention.

During the familiarisation period training intensity was set at 70% 1RM for 3 sets of 10 repetitions. The first 3 weeks of the training intervention required participants to complete all sessions and exercises at 80% 1RM for 4 sets of 8 repetitions. The following and final 3 weeks of the intervention were completed at an intensity of 85% 1RM for 5 sets of 6 repetitions. These loads, volumes and rest intervals were selected as they are appropriate for eliciting adaptations in strength and hypertrophy in recreationally trained non-athletes (Peterson *et al.*, 2004; 2005). Additionally, strength training programmes of this nature involving exercises which stimulate large muscle masses and shorter rest periods elicit large increases in the endocrine factors assessed within this study (Volek *et al.*, 1997; Kraemer *et al.*, 2008b). Full details of the intervention are presented in Table 5.1. All strength and/or endurance-based exercise commenced at the same time of day (1000 h ± 1 h) to avoid any diurnal performance or endocrine variations (Hayes *et al.*, 2010). When blood samples were collected, participants arrived at the lab having refrained from consuming food or caffeine for 2 h prior to assessment. Participants were also advised to abstain from exercise for 24 h prior to a visit. Training load was modified accordingly for each exercise if a participant's 1RMs were observed to change at the mid-intervention assessments. Compliance was excellent and all participants completed all required training sessions.

Table 5.1. Programme variables within periodized resistance training intervention.

	Week 1	Pre-intervention assessments	
	Week 2	Familiarisation	
	Sets	3	
	Repetitions	10	
	% 1RM	70	
	Rest (s)	90	
	Weeks 3 – 5	Training	
	Sets	4	
	Repetitions	8	
	% 1RM	80	
	Rest (s)	120	
	Week 6	Mid-intervention assessments	
	Week 7 – 9	Training	
	Sets	5	
	Repetitions	6	
	% 1RM	85	
	Rest (s)	120	
	Week 10	Post-intervention assessments	
Sessions	Compound	Pull	Push
	back squat, bench press, bent over row, dead lift and military press	high pull, lat pull down, seated row, standing dumbbell reverse fly and seated hamstring curls	incline bench press, front squat, push press, seated leg press and dumbbell chest flys

5.3.3.2 Endurance training protocol

Frequency of endurance training was dependant on the experimental condition participants were randomly assigned to. ST and CON involved no endurance training during the experimental period, CT3 required participants to perform endurance training once per week immediately following the "compound" sessions of the strength training intervention (details presented in Table 5.1) and CT1 required participants to perform the endurance training protocol 3 times per week immediately following each session of the strength training intervention. In all instances endurance training was conducted immediately following strength training.

The endurance training protocol required participants to run on a treadmill (hp Cosmos, Pulsar, Nussdorf-Traunstein, Germany) at 1% incline at 70% of their pre-determined running velocity at $\dot{V}O_{2max}$ (v$\dot{V}O_{2max}$). Running velocity was modified if participant's v$\dot{V}O_{2max}$ was observed to change at the mid-intervention assessments.

5.3.3.3 Whole body strength assessments - 1 repetition maximum (1RM)

1 repetition maximum (1RM) loads were established for all strength-training exercises prior to the experimental intervention and following 3 and 6 weeks of training. For analysis purposes lower body strength was assessed via the total of 1RMs in the back squat and deadlift (Figures 5.1 and 5.2). To examine strength development in the upper body musculature, the sum of 1RMs in the bench press, bent over row and military press (Figures 5.3 – 5.5) were analysed. These exercises were chosen as they are considered gross motor movements that require all the major joints and muscle groups involved in the strength training intervention. All assessments were conducted in line with standardised procedures (Rønnestad,

Hansen & Raastad, 2011) and were consistent between investigations. Further details of 1RM determination are presented in section 3.5.

Figure 5.1. Back squat.

Figure 5.2. Deadlift.

Figure 5.3. Bench press.

Figure 5.4. Bent over row.

Figure 5.5. Military press.

5.3.3.4 Maximal aerobic capacity - $\dot{V}O_{2max}$

Assessments of participant's maximal oxygen uptake and running velocity at $\dot{V}O_{2\text{max}}$ were conducted at baseline, after 3 weeks of training and following the 6 week training intervention. All assessments were conducted in line with standardised procedures (Walshe *et al.*, 2010) and were consistent between investigations. Details of $\dot{V}O_{2\text{max}}$ determination were presented in the General Methods in section 3.6.1.

5.3.3.5 Lower body power - countermovement jump assessment

Assessment of participant's lower body power via maximal countermovement jump height (CMJ) was conducted prior to their designated training intervention and following 3 and 6 weeks of training. Maximal CMJ was adopted as a proxy of lower body power, and was assessed using a contact mat (Just Jump, Probotics, Huntsville, AL, USA). CMJs have previously been employed to monitor power in various athletic events and populations (Bret *et al.*, 2002; Apostolidis *et al.*, 2004; Requena *et al.*, 2009). Prior to assessment, all participants were fully habituated with the procedure. Following familiarization, independent

trials of CMJs were then conducted with 3 min between each individual jump; the highest jump being recorded for data analysis. When performing the test, participants positioned themselves in the centre of the contact mat and place their hands on the iliac crest where they were to remain throughout. CMJs began from an erect standing position. When ready participants squatted to a self-selected depth perceived as their individual optimal depth, and immediately ascended to jump vertically for maximal height (Figure 5.6).

The reliability of CMJ determination was assessed during pilot testing. Fifteen healthy recreationally resistance-trained men (age: 26 ± 4 y; body mass: 87.1 ± 13.4 kg; height: 185 ± 8 cm) attempted to achieved their maximal CMJ on 2 separate occasions at the same time of day (± 1 h) with a 4 d interval between assessments to determine intra assessment session reliability. All participants were required to abstain from exercise for 24 h prior to assessments and repeat their nutritional intake the evening before and on day of assessments. Participants also attempted to achieve their maximal CMJ 2 times (with a 5 min recovery period) within the same assessment session to determine inter assessment session reliability. All assessments were conducted by the same investigator. Data pertaining to the intra and inter assessment session are presented in Table 5.2.

Table 5.2. Reliability of muscular force and power measures assessed within this thesis.

Lower body power			
	ICC	*R*	CV (%)
Intra assessment	0.91	0.95	3.5
Inter assessment	0.94	0.92	2.9

intra-class correlation coefficients (ICC), Pearson's correlation coefficient (*r*) and coefficients of variation (CV).

Figure 5.6. Countermovement jump assessment.

5.3.3.6 Body composition - air displacement plethysmography

All participants lean mass and % body fat was assessed prior to and following 3 and 6 weeks of training. Lean mass and % body fat were assessed using air displacement plethysmography (BodPod, Life Measurements Instruments, CA, USA) (Siri, 1961; McCrory *et al.*, 1995; Fields *et al.*, 2002). Initially the devise was calibrated using a metal cylinder of known and standardised composition. Participants were asked to disrobe to minimal clothing and place a tight fitting cap over their hair (Figure 5.7). Participants were then weighed on a calibrated scale to a resolution of 5 g to ensure body composition was relative to participant's accurate body mass. Participants then entered the empty chamber and sat down for the initial measurement of body volume, the door was subsequently closed for the measurement of body composition. Once two consistent measures of body

composition were obtained the participant exited the chamber and % body fat and lean mass were recorded using associated software (Dempster & Aitkens, 1995).

The reliability of body composition as assessed via air displacement plethysmography was assessed during pilot testing. Fifteen healthy recreationally resistance-trained men (age: 26 ± 4 y; body mass: 87.1 ± 13.4 kg; height: 185 ± 8 cm) had their body composition assessed on 2 separate occasions at the same time of day (± 1 h) with a 4 d interval between assessments to determine intra assessment session reliability. All participants were required to abstain from exercise for 24 h prior to assessments and repeat their nutritional intake the evening before and on day of assessments. Participants also had their body composition measures 2 times (with a 10 min interval between assessments) within the same assessment session to determine inter assessment session reliability. All assessments were conducted by the same investigator. Data pertaining to the intra and inter assessment session are presented in Table 5.3.

Table 5.3. Reliability of measurement of body composition via air displacement plethysmography.

Air displacement plethysmography			
	ICC	*r*	CV (%)
Intra assessment			
Lean mass	0.99	0.98	2.7
% body fat	0.98	0.98	2.5
Inter assessment			
Lean mass	0.99	0.99	1.7
% body fat	0.99	0.99	2.0

intra-class correlation coefficients (ICC), Pearson's correlation coefficient (*r*) and coefficients of variation (CV).

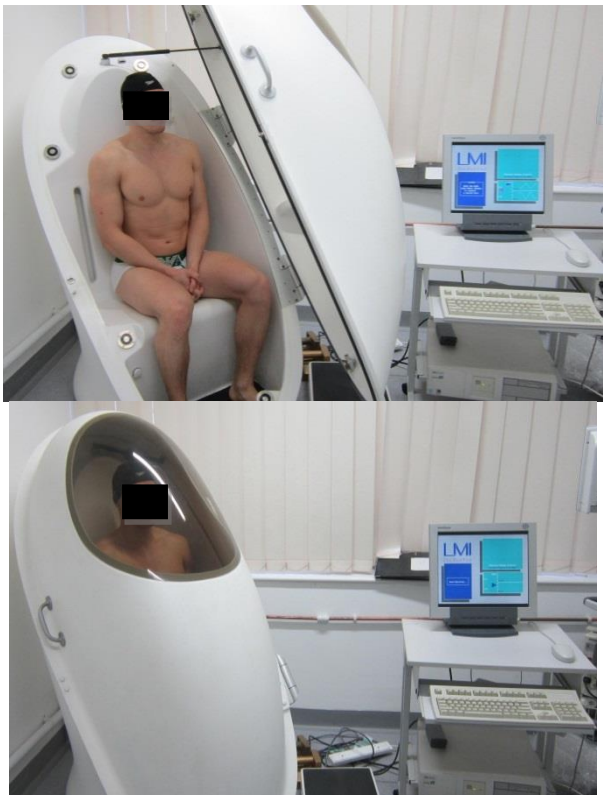

Figure 5.7. Body composition assessment via air displacement plethysmography.

5.3.3.7 Rate of perceived exertion

RPE was assessed immediately following the completion of each set in all training sessions (additional information presented in Table 5.1). Further details of RPE assessment are presented in 3.7.

5.3.3.8 Blood sampling and storage

Venous blood samples were collected immediately before (pre) and following the cessation of exercise (post) in the initial, mid and final compound training sessions (additional information presented in Table 5.1) of the 18 sessions performed. Further details of blood sampling are presented in 3.8.

5.3.3.9 Biochemical analysis

Blood samples were analysed for testosterone, cortisol, lactate (Lac^-) and glucose concentrations. Full details of biochemical analysis can be found in sections 3.9.1 and 3.9.2.

5.3.3.10 Statistical analysis

Data are presented as mean ± standard deviation. Values of RMs, CMJ and lean mass were transformed to percentage (%) change from baseline and used for analysis, all other variables were analysed as raw data. Prior to analysis dependant variables were verified as meeting required assumptions of parametric statistics and changes in all assessed measures were analysed using mixed model repeated measures ANOVA tests. ANOVA analysed differences between 4 conditions (ST, CT3, CT1 and CON) and 3 time points (baseline, mid-intervention and post-intervention). The alpha level of 0.05 was set prior to data analysis. Assumptions of sphericity were assessed using Mauchly's test of sphericity, if the assumption of sphericity was violated Greenhouse Gessier correction was employed. If significant effects between conditions or over time were observed *post-hoc* differences were analysed with the use of Bonferroni correction. Statistical power of the study was calculated post-hoc using G*Power statistical software (v3.1.3, Düsseldorf, Germany) using the effect size, group mean, SD and sample size of the primary outcome measures, in this case being lower and upper body maximal strength and endocrine factors. Power was calculated as between 0.8 and 1 indicating sufficient statistical power (Cohen, 1992).

Elsewhere statistical analysis which reports uncertainty of outcomes as 90% confidence intervals (CI), generating probabilistic magnitude-based inferences about

the true value of outcomes were also employed (Batterham & Hopkins, 2006). Further details can be found in section 3.10.2.

5.4 Results

5.4.1 Physical performance measures

Participant's baseline strength and endurance physical performance capabilities were similar between experimental conditions, these data are presented in Table 5.4.

Table 5.4. Participant's baseline maximal strength, lower body power and maximal aerobic capacity.

Lower body maximal strength – 1RMs (kg)				
	ST	CT3	CT1	CON
Back squat	117.8 ± 7.7	120.3 ± 11.8	122.4 ± 8.9	118.5 ± 12.5
Deadlift	136.3 ± 7.9	142.6 ± 12.4	139.7 ± 6.7	136.9 ± 9.5
Total	254.1 ± 11.5	262.9 ± 14.2	262.1 ± 10.6	255.4 ± 11.4
Upper body maximal strength – 1RMs (kg)				
	ST	CT3	CT1	CON
Bench press	99.1 ± 9.2	105.9 ± 7.1	107.4 ± 12.4	101.6 ± 8.8
Bent over row	80.0 ± 5.3	77.5 ± 6.6	82.5 ± 5.8	80.5 ± 7.4
Military press	61.6 ± 6.1	67.5 ± 5.8	65.5 ± 7.9	60.3 ± 5.1
Total	240.6 ± 11.9	250.9 ± 12.8	255.4 ± 14.0	242.4 ± 13.6
Lower body power – CMJ (cm)				
	ST	CT3	CT1	CON
	52.7 ± 10.3	52.8 ± 7.7	50.7 ± 7.5	53.9 ± 5.1
Maximal aerobic capacity – $\dot{V}O_{2max}$ (ml·kg·min)				
	ST	CT3	CT1	CON
	52.1 ± 7.0	47.4 ± 4.9	49.5 ± 6.3	51.9 ± 7.8

Note: ST, strength training alone performed every session; CT3, strength performed every session, strength and endurance training performed every third session; CT1, strength and endurance training performed every session; CON, no strength or endurance training performed during experimental period

5.4.1.1 Upper and lower body maximal strength

A significant time x group interaction was observed ($F_{(4,\ 36)}$ = 4.940, p = 0.003) for lower body strength development, as was an effect of time ($F_{(1,\ 36)}$ = 45.042, p < 0.001). All training conditions elicited increases in lower body strength

at the mid-intervention time point following 3 weeks of training (ST; 9.0 ± 4.5%, $p < 0.001$. CT3; 9.8 ± 11.0%, $p = 0.024$. CT1; 5.8 ± 3.2%, $p < 0.001$). Similarly lower body strength improved in all training conditions from baseline to post-intervention (ST; 17.2 ± 7.2%, $p < 0.001$. CT3; 15.0 ± 11.8%, $p = 0.003$. CT1; 10.1 ± 4.9%, $p < 0.001$). ST was the only condition to significantly increase lower body strength from mid to post-intervention (8.3 ± 2.8%, $p = 0.016$, Figure 5.8).

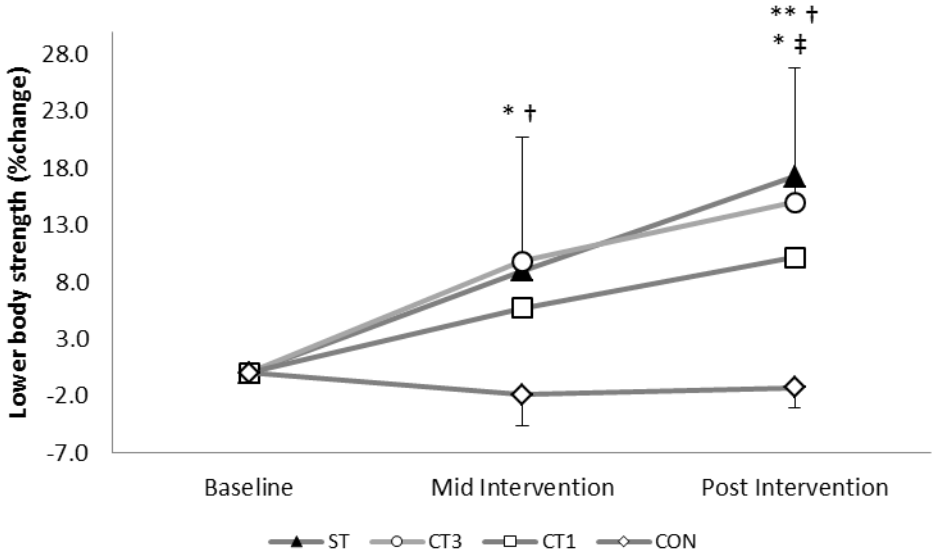

Figure 5.8. Mean relative changes in lower body strength (as assessed by back squat and deadlift) in response to respective training interventions in the ST (n = 8), CT3 (n = 8), CT1 (n = 8) and CON (n = 6) conditions. ST, strength training alone performed every session; CT3, strength performed every session, strength and endurance training performed every third session; CT1, strength and endurance training performed every session; CON, no strength or endurance training performed during experimental period. * significant increases from baseline in all training conditions ($p < 0.05$). ** significant increase from mid-intervention in ST ($p = 0.016$). † significantly greater increases than CON in training conditions ($p < 0.05$). ‡ ST significantly greater than CT1 ($p = 0.036$).

All training conditions improved lower body strength to a greater extent that CON at both mid and post-intervention (all $p < 0.05$). Post-training ST improved lower body strength 7.1 ± 2.4% more than CT1 ($p = 0.036$, Figure 5.8). Inferential analyses of the respective training interventions effects on lower body strength are detailed in Table 5.5.

Table 5.5. Effect of respective training interventions on lower body strength increases (as assessed by back squat and deadlift).

Condition	Mean effect±90% CI	Qualitative inference
Change from baseline to mid intervention		
ST	9.0 ± 3.1	Very likely beneficial
CT3	9.8 ± 6.5	Possibly beneficial
CT1	5.7 ± 2.0	Very likely beneficial
CON	1.9 ± 1.7	Most likely trivial
Change from baseline to post intervention		
ST	17.0 ± 6.0	Very likely beneficial
CT3	15.0 ± 6.4	Very likely beneficial
CT1	10.0 ± 3.5	Very likely beneficial
CON	1.3 ± 1.2	Most likely trivial

Note: Mean effect refers to the first named stage of intervention minus the second named stage of intervention. For the ±90% CI, add and subtract this number to the mean effect to obtain the 90% confidence intervals for the true difference. ST, strength training alone performed every session; CT3, strength performed every session, strength and endurance training performed every third session; CT1, strength and endurance training performed every session; CON, no strength or endurance training performed during experimental period

A significant time x group interaction ($F_{(5, 41)} = 2.895$, $p = 0.027$) and an effect of time ($F_{(2, 36)} = 31.510$, $p < 0.001$) were observed for upper body strength development. CT3 and CT1 both improved upper body strength between baseline to mid-intervention (6.2 ± 6.9%, $p = 0.024$ and 7.8 ± 4.5%, < 0.001 respectively, Figure 5.9). All training conditions increased upper body strength from pre to post-training (all $p < 0.05$). Upper body strength improved in all training conditions following training interventions (ST; 10.5 ± 5.2%, $p < 0.001$. CT3; 10.6 ± 10.7%, $p = 0.014$. CT1; 12.1 ± 6.9%, $p < 0.001$). ST was the only condition to improve upper body strength from mid to post-training (6.9 ± 0.1%, $p = 0.019$).

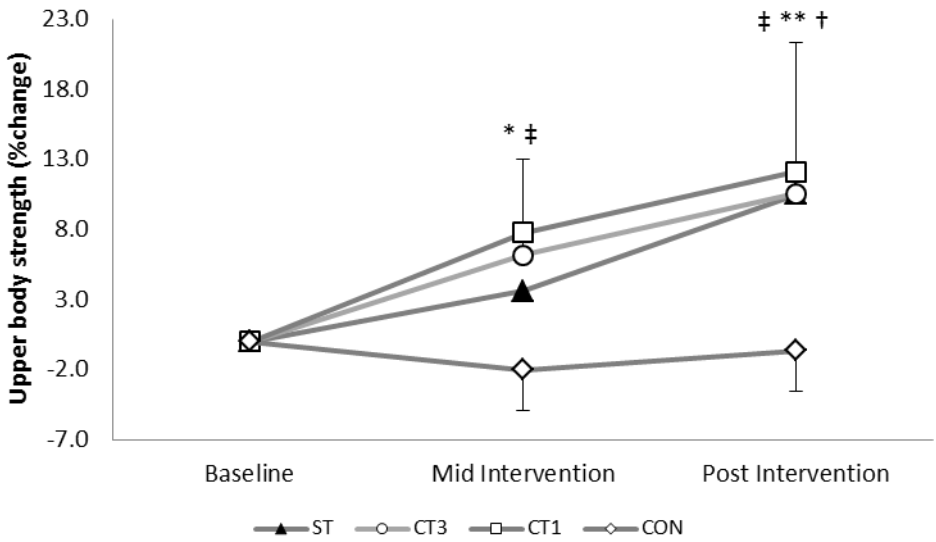

Figure 5.9. Mean relative changes in upper body strength (as assessed by bench press, bent over row and military press) in response to respective training interventions in the ST (n = 8), CT3 (n = 8), CT1 (n = 8) and CON (n = 6) conditions. ST, strength training alone performed every session; CT3, strength performed every session, strength and endurance training performed every third session; CT1, strength and endurance training performed every session; CON, no strength or endurance training performed during experimental period. * significant increases from baseline in CT3 and CT1 ($p < 0.05$). ** significant increases from baseline in all training conditions ($p < 0.05$). † Significant increase from mid-intervention in ST ($p = 0.019$). ‡ all training conditions greater than CON ($p < 0.05$).

All training conditions elicited significantly greater increases in upper body strength than CON at mid- and post intervention (all $p < 0.05$, Figure 5.9). Inferential analyses of the respective training interventions effects on upper body strength are detailed in Table 5.6.

Table 5.6. Effect of respective training interventions on increases in upper body strength (as assessed by bench press, bent over row and military press).

Condition	Mean effect±90% CI	Qualitative inference
Change from baseline to mid intervention		
ST	3.6 ± 3.2	Possibly beneficial
CT3	6.2 ± 4.0	Possibly beneficial
CT1	7.8 ± 2.1	Most likely beneficial
CON	2.0 ± 1.2	Unclear
Change from baseline to post intervention		
ST	11.0 ± 3.7	Most likely beneficial
CT3	11.0 ± 6.0	Likely beneficial
CT1	12.0 ± 3.3	Most likely beneficial
CON	0.6 ± 1.9	Unclear

Note: Mean effect refers to the first named stage of intervention minus the second named stage of intervention. For the ±90% CI, add and subtract this number to the mean effect to obtain the 90% confidence intervals for the true difference. ST, strength training alone performed every session; CT3, strength performed every session, strength and endurance training performed every third session; CT1, strength and endurance training performed every session; CON, no strength or endurance training performed during experimental period.

5.4.1.2 Lower body power

A significant time x group interaction ($F_{(6, 52)} = 3.236$, $p = 0.009$) and effect of time ($F_{(2, 52)} = 26.086$, $p < 0.001$) were observed for lower body power development. Both ST and CT1 increased CMJ from baseline to mid-intervention (ST; 8.7 ± 7.0%, $p = 0.003$. CT1; 3.0 ± 2.3%, $p = 0.002$). Post-intervention all training conditions elicited significant increases in CMJ from baseline (ST; 13.1 ± 7.3%, $p < 0.001$. CT3; 7.1 ± 3.7%, $p < 0.001$. CT1; 4.8 ± 2.3%, $p < 0.001$; Figure 5.10).

Participants in the ST condition achieved significantly higher CMJ than those following CT1 (7.0 ± 3.5%) and CON (5.7 ± 4.7%) conditions after 3 weeks of training (i.e. mid-intervention) (both $p = 0.04$). Following training (i.e. post-intervention), ST elicited 6.0 ± 3.6% greater increases in CMJ than CT3, 8.3 ± 5.0%

greater than CT1 and 10.9 ± 2.3% greater than CON (all $p < 0.05$). Inferential analyses of the respective training interventions effects on lower body power are detailed in Table 5.7.

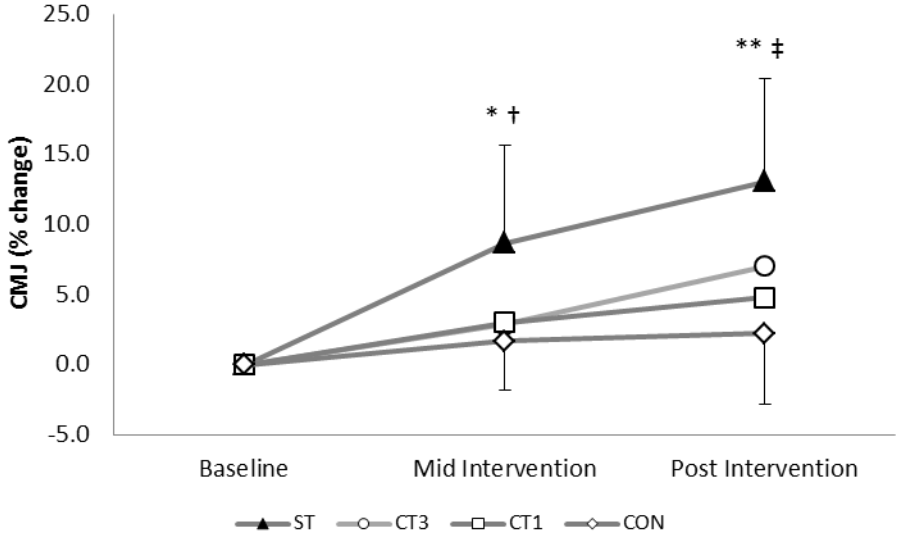

Figure 5.10. Mean relative changes in countermovement jump height in response to respective training intervention s in the ST (n = 8), CT3 (n = 8), CT1 (n = 8) and CON (n = 6) conditions. ST, strength training alone performed every session; CT3, strength performed every session, strength and endurance training performed every third session; CT1, strength and endurance training performed every session; CON, no strength or endurance training performed during experimental period. * ST and CT1 significantly greater than baseline ($p < 0.05$). ** ST, CT3 and CT1 significantly greater than baseline ($p < 0.001$). † ST significantly greater than CT1 and CON ($p < 0.05$). ‡ ST significantly greater than CT3, CT1 and CON (all $p < 0.05$).

Table 5.7. Effect of respective training interventions on increases in lower body power (as assessed by CMJ).

Condition	Mean effect±90% CI	Qualitative inference
Change from baseline to mid intervention		
ST	8.7 ± 3.7	Most likely beneficial
CT3	8.0 ± 4.7	Unclear
CT1	3.0 ± 1.2	Very likely beneficial
CON	1.7 ± 2.7	Unlikely beneficial
Change from baseline to post intervention		
ST	13.0 ± 3.5	Most likely beneficial
CT3	7.1 ± 1.7	Most likely beneficial
CT1	4.8 ± 1.7	Most likely beneficial
CON	2.2 ± 3.9	Unlikely beneficial

Note: Mean effect refers to the first named stage of intervention minus the second named stage of intervention. For the ±90% CI, add and subtract this number to the mean effect to obtain the 90% confidence intervals for the true difference. ST, strength training alone performed every session; CT3, strength performed every session, strength and endurance training performed every third session; CT1, strength and endurance training performed every session; CON, no strength or endurance training performed during experimental period.

5.4.1.3 Strength training performance

During the first 3 weeks of the training intervention all groups ability to maintain the required training intensity was similar ($F_{(3, 30)} = 1.063$, $p = 0.548$) and did not change significantly over time ($F_{(1, 30)} = 4.295$, $p = 0.062$). Similar results were observed in the final 3 weeks of the intervention as ability to maintain designated training load was not different between conditions ($F_{(3, 28)} = 1.301$, $p = 0.293$) or over time ($F_{(1, 28)} = 3.777$, $p = 0.052$).

5.4.2 Endocrine factors

5.4.2.1 Testosterone

Circulating basal testosterone concentrations at rest were not significantly different between conditions ($F_{(6, 52)} = 1.820$ $p = 0.113$, Table 5.6). Basal testosterone

levels did however change over time in the CT3 condition alone ($F_{(2, 52)} = 3.483$, $p = 0.038$). CT3 resulted in a 53.6 ± 51.9% ($p = 0.002$) increase in testosterone concentrations from baseline to post-intervention. A significant time x group interaction was observed for the testosterone response to strength training ($F_{(3, 26)} = 11.466$, $p < 0.001$). Testosterone responses to the respective training interventions also changed significantly over time ($F_{(1, 26)} = 130.683$, $p < 0.001$). Following the initial and mid sessions ST was the only condition to increase testosterone levels greater than CON (30.7 ± 5.0%, $p = 0.04$ and 37.1 ± 12.9% $p = 0.005$ respectively). CT3 was the only condition to elicit a greater increase in testosterone than CON post the final session (42.2 ± 10.5%, $p = 0.002$). ST and CT3 elicited significant increases from pre training in both the mid and final sessions (all $p < 0.05$). Testosterone was also increased post training in the CT3 condition following the final session ($p = 0.01$). No other increases were observed.

5.4.2.2 Cortisol

Circulating basal cortisol concentrations were not significantly different between training conditions ($F_{(6, 52)} = 1.540$, $p = 0.184$, Table 5.6) at any time during the experimental intervention. Basal cortisol levels did change over time in the CT1 alone ($F_{(2, 52)} = 2.535$, $p = 0.04$), with increases of 46.5 ± 58.4% from baseline to post-intervention ($p = 0.008$). A significant a time x group interaction ($F_{(3, 26)} = 7.592$, $p = 0.001$) and an effect of time ($F_{(1, 26)} = 101.852$, $p < 0.001$) were observed for cortisol responses to the respective training interventions. Following the initial session ST was the only condition to increase cortisol levels to a greater extent than CON (84.7 ± 22.1%, $p = 0.014$). Post training after the mid-intervention session CT1 was the only condition which resulted in significantly greater cortisol increases than

CON (49.2 ± 3.1%, $p < 0.001$). Following the final session, CT1 elicited 26.6 ± 8.4% greater cortisol increases than ST ($p < 0.008$). All training conditions elicited significant increases in cortisol post training on all assessed sessions (all $p < 0.05$)

5.4.2.3 Testosterone-cortisol ratio

No effects of group or time were present for basal testosterone:cortisol ratio (T:C ratio) ($F_{(6, 52)} = 1.903$, $p = 0.098$, and $F_{(2, 52)} = 1.513$, $p = 0.230$ respectively). There was no significant group effect for the T:C ratio response to training ($F_{(3, 26)}$, $p = 0.467$). There was however a time effect ($F_{(1, 26)}$, $p < 0.001$), this was observed following the final session in which T:C ratio was significantly greater than the equivalent time point following the mid-session in the CT3 group ($p = 0.048$, Table 5.8).

Table 5.8. Effects of respective training interventions on testosterone, cortisol and testosterone:cortisol (T:C) ratio.

Condition	Session					
	Initial		Mid		Final	
	Pre	Post	Pre	Post	pre	Post
ST						
Testosterone (nmol·L^{-1})	17.2 ± 4.0	23.4 ± 5.4*†	16.4 ± 2.7	23.7 ± 4.2*†	19.6 ± 10.0	27.3 ± 13.6
Cortisol (nmol·L^{-1})	262.6 ± 86.6	495.6 ± 150.0*†	254.4 ± 124.3	408.5 ± 145.3*	269.5 ± 116.0	389.1 ± 99.7*
T:C Ratio (x10^{3})	76.2 ± 46.3	53.5 ± 28.0	77.5 ± 36.0	63.4 ± 20.8	88.7 ± 69.7	77.67 ± 50.1
CT3						
Testosterone (nmol·L^{-1})	13.0 ± 1.6	17.6 ± 2.2*	15.4 ± 3.7	20.1 ± 4.2*	19.5 ± 4.6**	27.1 ± 5.6*†
Cortisol (nmol·L^{-1})	260.5 ± 114.6	522.0 ± 325.7*	284.7 ± 103.6	460.5 ± 134.6*	262.8 ± 90.9	428.7 ± 137.0*
T:C Ratio (x10^{3})	60.7 ± 31.5	50.3 ± 42.1	58.4 ± 16.6	48.4 ± 13.6	81.0 ± 28.5	68.6 ± 22.7‡
CT1						
Testosterone (nmol·L^{-1})	18.7 ± 7.5	24.4 ± 11.7	19.5 ± 5.2	24.5 ± 8.0	17.3 ± 4.3	21.9 ± 4.6
Cortisol (nmol·L^{-1})	278.2 ± 64.9	471.6 ± 186.9*	331.4 ± 17.1	499.9 ± 48.3*†	368.3 ± 51.8**	507.8 ± 45.2*†^{Æ}
T:C Ratio (x10^{3})	71.4 ± 33.9	57.6 ± 30.4	59.0 ± 15.1	49.1 ± 14.9	47.8 ± 12.5	43.0 ± 6.4
CON						
Testosterone (nmol·L^{-11})	16.1 ± 1.4	16.8 ± 1.1	16.2 ± 1.5	17.6 ± 1.4	18.5 ± 3.0	17.7 ± 2.1
Cortisol (nmol·L^{-1})	291.6 ± 65.0	311.5 ± 47.8	305.5 ± 91.1	320.6 ± 96.2	306.6 ± 115.8	330.2 ± 101.9
T:C Ratio (x10^{3})	58.1 ± 16.4	55.0 ± 9.0	57.0 ± 18.1	59.1 ± 17.8	58.4 ± 20.8	63.5 ± 26.0

* significantly greater than pre ($P < 0.05$), † significantly greater than CON ($p < 0.05$) ** significantly greater than pre initial session ($p < 0.01$), ‡ significantly greater than post mid-session ($p < 0.05$), ^{Æ} significantly greater than ST.

5.4.3 Anthropometrics

5.4.3.1 Lean mass

Participant's baseline lean mass was similar between experimental conditions, these data are presented in Table 5.9.

Table 5.9. Participant's basal lean mass.

Lean mass (kg)			
ST	CT3	CT1	CON
68.4 ± 6.8	66.1 ± 8.1	70.2 ± 3.7	66.9 ± 8.7

Note: ST, strength training alone performed every session; CT3, strength performed every session, strength and endurance training performed every third session; CT1, strength and endurance training performed every session; CON, no strength or endurance training performed during experimental period

Participants lean mass changed significantly over time throughout the 6 week training intervention ($F_{(2,\ 52)} = 5.782$, $p = 0.016$). Post-hoc analysis of the data indicated that those participants assigned to the ST condition experienced in an increase from baseline of 0.7 ± 0.9% at the mid-training point ($p = 0.04$, Figure 5.11). No other conditions elicited significant adaptations at this stage of the intervention. At the post-intervention time point, significant increases in lean mass were observed following the ST (4.0 ± 5.3%) and CT1 (2.3 ± 2.3%) training conditions (both $p < 0.05$) only. Inferential analyses of the respective training interventions effects on lean mass are detailed in Table 5.10.

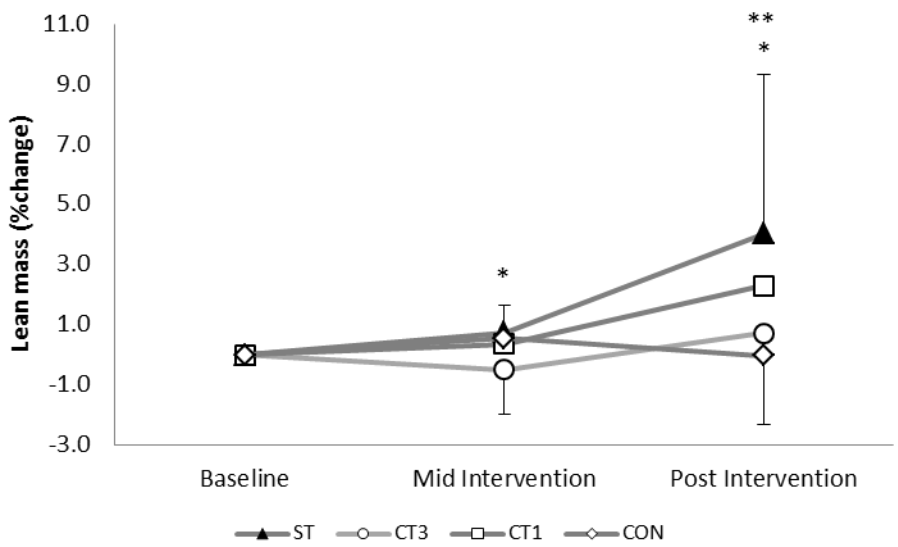

Figure 5.11. Mean relative changes in lean mass in response to respective training intervention s in the ST (n = 8), CT3 (n = 8), CT1 (n = 8) and CON (n = 6) conditions. ST, strength training alone performed every session; CT3, strength performed every session, strength and endurance training performed every third session; CT1, strength and endurance training performed every session; CON, no strength or endurance training performed during experimental period. * ST significantly greater than baseline ($p < 0.05$). ** CT1 significantly greater than baseline ($p < 0.05$).

Table 5.10. Effect of respective training interventions on increases in lean mass.

Condition	Mean effect±90% CI	Qualitative inference
Change from baseline to mid intervention		
ST	0.7 ± 0.6	Very likely beneficial
CT3	0.5 ± 1.0	Unclear
CT1	0.4 ± 1.4	Unclear
CON	0.6 ± 10	Unclear
Change from baseline to post intervention		
ST	4.0 ± 3.2	Very likely beneficial
CT3	0.8 ± 2.3	Unclear
CT1	2.3 ± 1.4	Very likely beneficial
CON	0.1 ± 1.1	Unlikely beneficial

Note: Mean effect refers to the first named stage of intervention minus the second named stage of intervention. For the ±90% CI, add and subtract this number to the mean effect to obtain the 90% confidence intervals for the true difference. ST, strength training alone performed every session; CT3, strength performed every session, strength and endurance training performed every third session; CT1, strength and endurance training performed every session; CON, no strength or endurance training performed during experimental period.

5.4.3.2 Body fat %

A significant time x group interaction was observed for body fat % ($F_{(6, 52)}$ = 4.616, p = 0.001). Following the 6 week training intervention, CT1 resulted in 2.65 ± 0.04% greater decreases in body fat % than CON (p < 0.001) at the post-intervention time point. No other significant effects of time or group were observed for changes in body fat %. Inferential analyses of the respective training interventions effects on body fat % are detailed in Table 5.11.

Table 5.11. Effect of respective training interventions on changes in body fat %.

Condition	Mean effect±90% CI	Qualitative inference
Change from baseline to mid intervention		
ST	2.0 ± 4.8	Unclear
CT3	0.3 ± 8.7	Unlikely beneficial
CT1	7.6 ± 10.0	Likely beneficial
CON	1.1 ± 5.6	Unlikely beneficial
Change from baseline to post intervention		
ST	2.9 ± 4.0	Likely beneficial
CT3	6.6 ± 12.0	Likely beneficial
CT1	1.7 ± 6.1	Most likely beneficial
CON	1.1 ± 5.6	Unlikely beneficial

Note: Mean effect refers to the first named stage of intervention minus the second named stage of intervention. For the ±90% CI, add and subtract this number to the mean effect to obtain the 90% confidence intervals for the true difference. ST, strength training alone performed every session; CT3, strength performed every session, strength and endurance training performed every third session; CT1, strength and endurance training performed every session; CON, no strength or endurance training performed during experimental period.

5.4.4 Blood glucose and lactate

5.4.4.1 Blood glucose

No significant time x group or time effects were present for blood glucose ($F_{(3, 26)}$ = 0.856, p = 0.476 and $F_{(1, 26)}$ = 2.351, p = 0.177).

5.4.4.2 Blood lactate

A significant time x group interaction ($F_{(3, 26)} = 33.162$¸ $p < 0.001$) and effect of time were observed for Lac^- ($F_{(1, 26)} = 197.227$, $p < 0.001$). All training conditions elicited significant increases in Lac^- from pre to post training in the assessed sessions (all $p < 0.05$). Immediately post training ST and CT3 Lac^- were significantly greater than CT1 and CON in all assessed sessions (all $p < 0.05$) (Table 5.12). Lac^- were also significantly greater immediately following CT1 than CON in all assessed sessions (all $p < 0.05$).

Table 5.12. Effects of respective training interventions on blood lactate responses.

Condition	Session					
	Initial		Mid		Final	
	Pre	Post	Pre	Post	pre	Post
ST Lactate (mmol L^{-1})	1.7 ± 1.3	11.6 ± 2.3*†	1.5 ± 0.6	9.2 ± 2.4*†	1.3 ± 0.5	9.0 ± 2.7*†
CT3 Lactate (mmol L^{-1})	1.6 ± 0.5	8.7 ± 3.7*†	1.5 ± 0.5	8.9 ± 3.1*†	1.0 ± 0.3	8.4 ± 4.9*†
CT1 Lactate (mmol L^{-1})	1.1 ± 0.2	4.3 ± 1.8*‡	1.3 ± 0.4	3.1 ± 0.9*‡	1.2 ± 4.0	4.0 ± 2.0*‡
CON Lactate (mmol L^{-1})	1.5 ± 0.7	1.6 ± 0.5	1.3 ± 0.4	1.5 ± 0.4	1.4 ± 0.8	1.6 ± 1.0

* significantly greater than pre ($p < 0.05$), † significantly greater than CT1 and CON ($p < 0.05$), ‡ significantly greater than CON ($p < 0.05$).

5.4.5 Rate of perceived exertion

A significant time x group interaction was present for RPE ($F_{(5, 52)} = 2.744$, $p = 0.029$). At week 5 and 6 of the training intervention RPE was significantly lower in the ST group than CT1 (both $p < 0.05$) (Figure 5.12). No other interactions or effects were present.

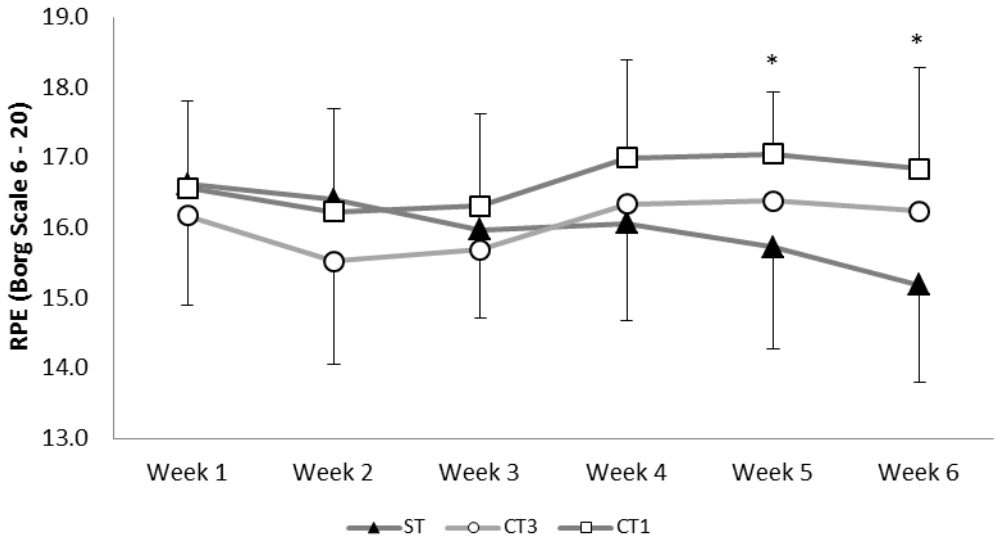

Figure 5.12. Mean RPE experienced in the ST (n = 8), CT3 (n = 8) and CT1 (n = 8) conditions. ST, strength training alone performed every session; CT3, strength performed every session, strength and endurance training performed every third session; CT1, strength and endurance training performed every session. * ST significantly lower than CT1 ($p < 0.05$).

5.5 Discussion

Whilst concurrent training has been extensively researched, the only data regarding strength-specific responses to identical strength training regimens with varying frequencies of endurance training are presented in the previous chapter of this thesis. The aforementioned data indicated that in an isolated limb model, increasing the frequency of endurance training in a concurrent training programme results in greater strength development interference than lower frequencies. As such,

the aim of the present study was to determine whether these findings could be replicated in a whole-body, multi-joint, functional training intervention.

The primary finding of this study was that an increase in the frequency of endurance training and total training volume within the concurrent training paradigm resulted in the attenuated development of lower body strength when compared to strength training alone. Following 6 weeks of training, ST and CT3 conditions resulted in similar increases in lower body strength, whereas those performing both strength and endurance training collectively 3 times per week (CT1) achieved lesser improvements in their lower body strength capabilities than those who conducted strength training in isolation (Figure 5.8). These findings reflect data presented in Chapter 4, in which ST and CT3 resulted in similar increases in maximal voluntary contraction (MVC), whereas increases in the CT1 condition were significantly lower (Figure 4.3). Although no other published research has examined differing frequencies of strength and endurance training on strength-related adaptation, studies employing concurrent training frequencies of ≥ 3 $d \cdot wk^{-1}$ have typically reported some manifestation of interference characteristics (Hickson, 1980; Dudley & Djamil, 1985; Hunter, Demment & Miller, 1987; Hennessy & Watson, 1994; Kraemer *et al.*, 1995; Horne *et al.*, 1997; Bell *et al.*, 2000; Häkkinen *et al.*, 2003; Cadore *et al.*, 2010; Karavirta *et al.*, 2011). Lower concurrent training frequencies (≤ 2 $d \cdot wk^{-1}$) have however resulted in similar development of strength related phenotypes following both concurrent and strength training programmes (Millet *et al.*, 2002; Chtara *et al.*, 2008; Wong *et al.*, 2010; Marta *et al.*, 2013). When combined, the findings of these studies are consistent with those of the present chapter. Concurrent training conducted 3 $d \cdot wk^{-1}$ (CT1) resulted in inhibited gains in maximal lower body strength, whereas performing concurrent training once per week with 2 strength

alone sessions (CT3; concurrent training frequency of 1 $d \cdot wk^{-1}$) elicited similar lower body strength increases than strength-training in isolation. The findings of this chapter and those of previous research indicate higher training volumes and elevated physiological stress may contribute to the presence of the interference phenomenon.

It was not only lower body maximal strength development that was attenuated as a result of higher frequencies of endurance training. Lower body power development was also inhibited following 3 and 6 weeks of training in the CT1 condition when compared with strength training alone (Figure 5.10). Furthermore, lower volumes of endurance training also resulted in attenuated increases in lower body power, as post-intervention participants who performed strength and endurance training at a ratio of 3:1 (CT3) exhibited improvements which were 6.0 ± 3.6% lower than those who performed strength training alone. As previously stated, maximal lower body strength development was not different between ST and CT3 conditions (Figure 5.8), which may indicate that power phenotypes are more susceptible to interference than maximal strength indices. This suggestion is supported by previous research indicating that development of variables including CMJ, rate of force development (RFD) and peak torques at high velocities have been inhibited as a result of combining strength and endurance training, yet maximal strength development remained uninhibited (Dudley & Djamil, 1985; Hunter, Demment & Miller, 1987; Nelson *et al.*, 1990; Craig *et al.*, 1991; Abernethy & Quigley, 1993; Häkkinen *et al.*, 2003). It had been hypothesised this is attributable to endurance training reducing the ability of the neuromuscular system to rapidly develop force (Ono, Miyashita & Asami, 1976).

Following the respective training interventions, unlike lower body strength and power development, increases in upper body strength were similar following

both strength training alone and both concurrent training conditions (CT3 and CT1). Furthermore, following 3 weeks of training CT1 resulted in 4.2 ± 0.8% greater increases than strength training alone (Figure 5.9), although this was not statistically significant (p = 0.09). Previous research has also reported concurrent training does not result in the inhibition of upper body maximal strength (Abernethy & Quigley, 1993; Bell *et al.*, 1997). Unlike the present study, which employed steady state running, previous research involved rowing (Bell *et al.*, 1997) and arm cranking (Abernethy & Quigley, 1993) as the endurance training modalities. It may be argued that the stimuli of arm cranking and rowing are further towards the strength end of the strength-endurance continuum (depicted in section 2.2, Figure 2.3) than steady state running. As such, it is reasonable to suggest that concurrent training may not differently affect the upper body musculature, but rather for interference to occur the assessed musculature must experience divergent contractile activity (i.e. strength and endurance stimulus) of contrasting intensities and durations. Running involves a far greater muscular contribution from the lower than upper limbs (Candau *et al.*, 1998), which may explain why upper body strength development was not inhibited by concurrent training in the present study. Furthermore, it is reasonable to suggest that the lower body musculature was placed in a greater state of conflict than the upper body, as both training stimuli directly affected hip dominant and lower limb muscle groups and only the strength training protocol required noteworthy contributions from the upper body musculature. Due to the relatively low number of high force contractions involved in strength training and the continuous lower force contractions experienced during endurance training, different patterns of motor unit activation are required. It is possible that the divergent demands placed on the neuromuscular system by strength and endurance training elicited differing

alterations in motor unit recruitment in the musculature of the lower limbs, previous research has also implicated altered neural activation during high force contractions as a potential mechanism for impaired strength development (Chromiak & Mulvaney, 1990; Leveritt & Abernethy, 1999; Kraemer *et al.*, 1995). Morevover, the potential alterered neural recruitment during rapid and high force contractions may have contributed to the inhibition of lower body power development as a result of both high and low frequncies of concurrent training (Figure 5.10).

Data presented in both Chapter 4 and the present chapter indicate that higher volumes of endurance training in a concurrent training programme result in amplified inhibition of lower body strength development. Since the impairment observed in Chapter 4 could not be attributed to mechanisms relating to neural inhibition, it is conceivable that elevated overall training stress may have resulted in the attenuated strength adaptation. It was therefore also hypothesised that this may be reflected in the endocrine anabolic:catabolic environment and that attenuated anabolism may contribute to impaired strength adaptation. It is plausible that increased training stress contributed to interference in the present study as post training CT1 was the only condition to significantly increase resting cortisol levels from baseline. Furthermore, following the final session increases in cortisol were significantly greater in the CT1 than the ST condition (Table 5.8). Elevated cortisol has been associated with increased training induced physiological stress (Kraemer & Ratamess, 2005), and this provides further support for the hypothesis that the inhibition of lower body strength could be due to elevated stress. It was also observed that participants RPE during strength training in the final 2 weeks of training was significantly greater in CT1 than ST (Figure 5.12). This may be attributed to increased fatigue due to the aforementioned training stress. The

elevations in cortisol following a concurrent training programme observed in the present chapter are consisted with comparable research. Kraemer *et al*. (1995), Bell *et al*. (1997) and Bell *et al*. (2000) have all reported greater elevations in cortisol following concurrent training strategies compared to strength training alone. Additionally both Kraemer *et al*. (1995) and Bell *et al*. (2000) employed a concurrent strength and endurance training volume of $\geq 3\ d \cdot wk^{-1}$ at a ratio of 1:1 (as CT1 in the present chapter) which resulted in elevated basal cortisol.

In the present study, increases in lean mass were similar between training conditions (Figure 5.11), this was reflected in inferential statistical analysis as both ST and CT1 were deemed "very likely beneficial" for improving lean mass following 6 weeks of training (Table 5.10). As such the inhibited strength development cannot easily be attributed to a lack of hypertrophic adaptation. In contrast Kraemer *et al.* (1995) reported impaired fibre hypertrophy as a result of concurrent training. Although the present study did not directly assess hypertrophy of individual muscle fibres the observed increases in lean mass where similar, and thus it may be speculated that morphological adaptations were consistent between conditions. The variance in the findings of the present study and those of Kraemer *et al.* (1995) are most likely due to the differing lengths of the respective training programmes. Kraemer *et al.* (1995) employed a 12 week intervention whereas in the present study participants trained for 6 weeks. As the CT1 condition resulted in the inhibition of strength development following 6 weeks of training it is perhaps reasonable to speculate that had the interventions been longer CT1 may have also resulted in impaired structural adaptation.

5.6 Practical applications

Data presented within this chapter contributes to answering the questions proposed earlier this thesis; i) can manipulation of simple programme variables within a concurrent regimen influence the response and magnitude of any interference experienced, and ii) what physiological mechanisms may contribute to the interference phenomenon?

The findings of this study build on the understanding of concurrent training developed in the isolated limb model discussed in Chapter 4. The data presented in this and the previous chapter indicate that if strength development is the primary goal of an applied training programme, endurance-training frequency should be kept to a minimum. It should however be noted, that this minimal dose of endurance training should be sufficient to maintain any necessary endurance performance characteristics. Also the elevations in resting and post exercise cortisol concentrations observed only in participants conducting strength and endurance training 3 times weekly indicate that overall training stress likely plays a key role in the inhibition of strength development. Therefore if a concurrent training programme must be performed it is imperative that appropriate monitoring strategies are employed to ensure training stress doesn't become too great and result in the plateau of strength development. Furthermore if development of power type characteristics is required then it appears that frequency and volume of endurance training should be minimized or omitted from the programme all together. This may be achieved via appropriate programme construction and periodization to allow power development to occur in periods in which endurance training can be kept to a minimum.

It appears that for inhibition of strength development to occur the assessed musculature must directly experience contractile activity, which is divergent from

strength training. This has implications for future research design, particularly in investigations seeking to examine the endurance training induced inhibition of anabolic signalling pathways as a mechanism for interference (discussed in Chapter 7 of this thesis). As such it is necessary that the endurance exercise stimulus requires high contributions from the assessed musculature in which tissue samples are taken from.

In the present investigation all concurrent training protocols were performed in the same order (strength then endurance training). It therefore remains unclear if the order in which strength and endurance training are performed in a concurrent training regimen influences the presence and/or magnitude of any interference experienced. The effects of differing sequencing of concurrent training and their influence on the endocrine environment associated with strength training adaptation is investigated in the subsequent chapter of this thesis.

6. The effects of acute strength- and endurance-training sequencing on endocrine responses to concurrent training

6.1 Abstract

Purpose: The present study examined the influence that manipulating the order in which strength and endurance training are performed has on endocrine factors associated with strength training adaptation.

Methods: 30 recreationally resistance-trained males completed one of four acute experimental training protocols; strength training (ST), strength followed by endurance training (ST-END), endurance followed by strength training (END-ST) or no training (CON). Blood samples were taken before the respective exercise protocols, immediately upon cessation of exercise, and 1 h post cessation of exercise. Blood samples were subsequently analysed for total testosterone, cortisol, glucose and lactate concentrations.

Results: Strength training performance standards were greater in ST and ST-END than END-ST (both $p < 0.05$). Immediately following the respective exercise protocols all training interventions elicited significant increases in testosterone (all $p < 0.05$). ST and END-ST resulted in greater increases in cortisol than ST-END (both $p < 0.05$). The testosterone:cortisol ratio was not differently affected by the respective exercise protocols. Blood lactate concentrations post-training were greater following END-ST and ST than ST-END (both $p < 0.05$).

Conclusions: Conducting endurance exercise prior to strength training resulted in impaired strength training performance. Blood cortisol and lactate concentrations were greater when endurance training was conducted prior to strength training than *vice versa*. Combined, these data may indicate that if strength type adaptation is the primary training objective strength training should be performed prior and not subsequent to endurance training.

6.2 Introduction

Whilst it appears that both anabolic and catabolic endocrine factors are influenced by chronic concurrent training (Kraemer *et al.*, 1995; Bell *et al.*, 1997; Bell *et al.*, 2000), the acute responses of 'primary' hormones such as testosterone and cortisol in response to concurrent training are yet to be fully elucidated. Previous research has indicated the responses of testosterone and cortisol may be influenced by the order in which strength and endurance training are performed (Cadore *et al.*, 2012b). Moreover, inappropriate scheduling of strength and endurance training has previously been implicated in the presence of strength and hypertrophic interference (García-Pallarés *et al.*, 2009; García-Pallarés & Izquierdo, 2011). This highlights the need for a greater understanding of the physiological responses to varying sequences of concurrent strength and endurance training.

A variety of sequencing protocols have been employed within research investigating concurrent training and the interference phenomenon. Previous research has involved; endurance before strength training in separate sessions (and days) (Sale *et al.*, 1990), strength before endurance training on separate days (Hortobagyi *et al*., 1991; Häkkinen *et al*., 2003), strength and endurance training on the same day but separate sessions (morning and evening) (Sale *et al*., 1990; Craig *et al*., 1991; Dolezal *et al*., 1998) and strength before endurance training (or *vice versa*) in the same session (Collins & Snow, 1993; Gravelle & Blessing, 2000; Chtara *et al.*, 2005; Chtara *et al.*, 2008; Cadore *et al.*, 2012b). Additional information on sequencing protocols employed within relevant literature is presented in section 2.5.3.5 (Table 2.3). Although previous research has utilised a range of sequences and scheduling of strength and endurance training, a dearth of studies have directly

assessed the effects of training sequence on strength development and/or interference characteristics.

The few studies which have investigated the effects of intra session sequencing of concurrent training on strength development have yielded somewhat inconclusive findings. Some previous research has demonstrated strength development is greater when strength training is conducted prior to endurance rather than *vice versa* (Collins & Snow, 1993; Cadore *et al.*, 2012a). In contrast, others have reported no differences in strength development following either sequence of strength and endurance training (Gravelle & Blessing, 2000; Chtara *et al.*, 2008). However, neither Chtara *et al.* (2008) nor Gravelle and Blessing (2000) reported any strength interference as a result of either concurrent condition regardless of sequence. As such, it appears that the training protocols in these studies were not suitable to elicit any inhibition of strength development. This may be due to the circuit type strength training employed by Chtara *et al.* (2008), and the fact Gravelle and Blessing (2000) investigated the effects of differing intra session sequencing in women rather than men.

Whilst the aforementioned research provides valuable information relating to the physical performance responses to varying concurrent training protocols, there is limited research pertaining to the underlying physiological responses to differing sequencing of strength and endurance training. To the author's knowledge currently only one study has investigated the effects of such sequencing (strength then endurance or *vice versa*) of acute concurrent training on endocrine responses; specifically of testosterone and cortisol. The relevance of the hormonal responses (particularly testosterone and cortisol) to varying concurrent training protocols is demonstrated by research indicating that endocrine factors may contribute to

interference. Elevated secretion of testosterone following strength training enables greater binding to androgen receptors, which can result in subsequent increases in protein synthesis (Vermeulen, 1988; Ratamess *et al.*, 2005; Spiering *et al.*, 2008; Basualto-Alarcón *et al.*, 2013), contractile strength, and muscle fibre hypertrophy (Kahn *et al.*, 2002). In contrast, elevated cortisol has been found to be associated with the inhibition of protein synthesis (MacDougall, 1986; Florini, 1987) and may contribute to interference. As such it is reasonable to hypothesize that concurrent training protocols which result in large increases in testosterone, yet minimal cortisol elevations are most likely more "favourable" for strength related adaptation. Cadore *et al.* (2012b) reported elevations in testosterone were greater when strength training was conducted following endurance training, compared with strength prior to endurance training. Whilst this provides novel information, the authors did not employ any condition in which participants performed strength training alone. This makes it impossible to ascertain whether acute concurrent training differently influenced the anabolic and catabolic responses to strength training in isolation. Therefore, to determine if appropriate sequencing of strength and endurance training can promote a more optimal endocrine environment conducive to strength-specific adaptations, a condition in which participants performed strength training alone should be included for comparative purposes. In addition, Goto *et al.* (2005) reported that the growth hormone (GH) response to strength training was attenuated when strength training was performed 15 min after a bout of endurance training. However, as the authors did not include a concurrent condition in which strength training was conducted prior to endurance training, it cannot be ascertained which sequencing protocol promoted what may be considered a more 'favourable' endocrine response for strength-specific adaptation.

Findings from the previous chapter of this thesis, as well as previous research, indicate that elevated cortisol as a result of concurrent training may contribute to the inhibition of strength development (Kraemer *et al.*, 1995; Bell *et al.*, 1997; Bell *et al.*, 2000). Research has also demonstrated that during longer concurrent training interventions elevated cortisol and catabolism attributable to concurrent training resulted in attenuated fibre hypertrophy when compared with strength training alone (Kraemer *et al.*, 1995). Based on these findings it is reasonable to suggest that the relative responses and ratios of the anabolic and catabolic hormones testosterone and cortisol may shift the endocrine system in favour of catabolism following concurrent training (Kraemer *et al.*, 1995; Bell *et al.*, 1997; Bell *et al.*, 2000; Kraemer & Ratamess, 2005).

The physical performance responses to differing sequences of strength and endurance exercise are at present largely unclear. Additionally, it remains speculative whether an acute bout of concurrent training can elicit similar anabolic responses to strength training alone if the sequence of exercise is appropriately programmed. Therefore, the purpose of the present study was to investigate the effects of modulating the sequencing of strength and endurance training on strength training performance and endocrine factors which may impact upon strength training adaptation via anabolism and catabolism.

6.3 Methods

6.3.1 Experimental approach to the problem

A balanced, randomised, between-group study design was employed. Participants were randomly assigned to one of 4 experimental conditions: i) strength training (ST), ii) concurrent training with strength training conducted first (ST-

END), iii) concurrent training with endurance training first (END-ST) or iv) no training (CON). Participants in the ST group performed strength training alone; the ST-END group performed strength training immediately followed by an endurance training protocol; those participants designated END-ST performed endurance training immediately followed by strength training; while those assigned to CON performed no strength or endurance training. For a time line of the experimental protocol see Figure 6.1.

Prior to commencing any experimental interventions, assessment of $\dot{V}O_{2\mathrm{max}}$ and 1 repetition maximum (1RM) loads were performed for the purpose of normalising relative training load and intensity. To assess the effect of each intervention on specific endocrine factors considered to relate to strength and morphological adaptation, venous blood samples were taken and subsequently analysed for total testosterone, cortisol, glucose and lactate. Blood samples were taken immediately preceding (pre), immediately following (post), and 1 h post cessation of the strength training protocol. To determine if the sequence of strength and endurance training performed affected strength training performance, participant's ability to maintain their predetermined training load during the strength training protocol was assessed.

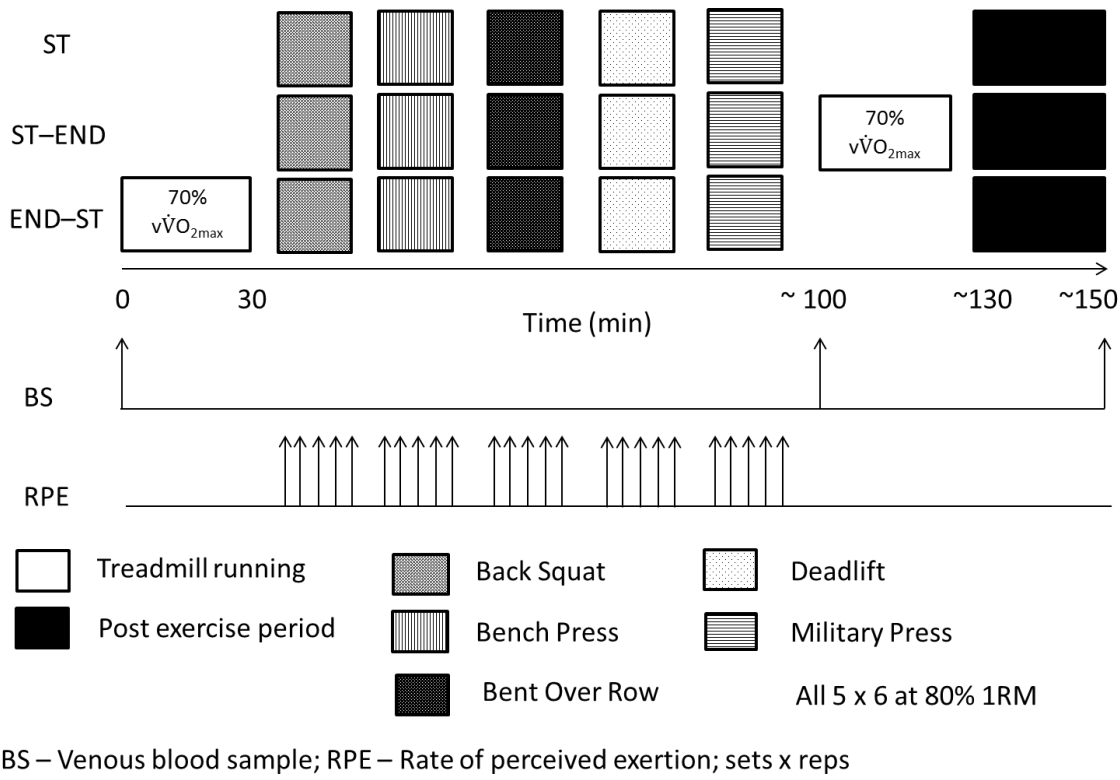

Figure 6.1 Schematic representation of experimental time line. ST (*n = 8*), ST - END (*n = 8*), END - ST (*n = 8*) and CON (*n = 6*).

6.3.2 Participants

Thirty healthy recreationally resistance-trained men (age: 24.0 ± 4.0 y; body mass: 80.0 ± 9.0 kg; height: 179.8 ± 6.8 cm; % body fat: 15.1 ± 5.3 %; sum of assessed 1RMs: 444.0 ± 50.0 kg; $\dot{V}O_{2max}$: 50.0 ± 6.3 ml·kg·min) volunteered to participate in the study. Participants were matched at baseline for age, body mass, body fat %, total of 1 RMs and $\dot{V}O_{2max}$ (all $p > 0.05$) then randomly assigned to a specific experimental condition. Additional information on study participants training status, nutritional restrictions and health status is presented in section 3.3.

6.3.3 Procedures

6.3.3.1 Strength training protocol

The strength training protocol consisted of the back squat, bench press, bent over row, military press and deadlift. These exercises were selected as they are compound movements that involve the major joints and muscle groups of the body and reflect exercises commonly used as part of a holistic strength training strategy for athletes and recreational exercisers alike. For each exercise within the strength training bout, 5 sets of 6 repetitions at 80% 1RM were completed. If participants were unable to maintain 80% 1RM load was adjusted to ensure 5 sets of 6 repetitions could be completed. This protocol and intensity has been shown to be appropriate for eliciting strength and hypertrophic responses in recreationally trained non-athletes (Peterson, Rhea & Alvar, 2004; 2005). Additionally, strength training protocols of this nature involving exercises which stimulate large muscle masses and involve shorter rest periods elicit large increases in the endocrine factors assessed within this study (Volek *et al.*, 1997; Kraemer *et al.*, 2008b).

All strength and/or endurance based exercise commenced at the same time of day (1000 h ± 1 h) to avoid any diurnal performance or endocrine variations (Hayes, Bickerstaff & Baker, 2010). Participants arrived at the lab having refrained from consuming food or caffeine for 2 h prior to assessment. Participants were also advised to abstain from exercise for 24 h pre visit.

6.3.3.2 Endurance training protocol

In all instances, the endurance training protocol required participants to run on a treadmill (hp Cosmos, Pulsar, Nussdorf-Traunstein, Germany) at 1% incline at 70% of their pre-determined running velocity at $\dot{V}O_{2max}$ (v$\dot{V}O_{2max}$).

6.3.3.3 Whole body strength assessments - 1 repetition maximum (1RM)

Participant's maximal strength capabilities were determined prior to the experimental protocol. All assessments were conducted in line with standardised procedures (Rønnestad, Hansen & Raastad, 2011) and additional details of 1RM determination are presented in section 3.5.

6.3.3.4 Maximal aerobic capacity - $\dot{V}O_{2max}$

Assessments of participant's maximal oxygen uptake and running velocity at $\dot{V}O_{2\mathrm{max}}$ were determined prior to the experimental protocol. All assessments were conducted in line with standardised procedures (Walshe *et al.*, 2010). Further details of $\dot{V}O_{2\mathrm{max}}$ determination are presented in 3.6.1.

6.3.3.5 Rate of perceived exertion

RPE was assessed immediately following the completion of each set of the strength training protocol. Further details of RPE assessment are presented in 3.7.

6.3.3.6 Blood sampling and storage

Venous blood samples were taken pre, 10 min post and 1 h post cessation of the exercise protocol. Further details of blood sampling are presented in 3.8.

6.3.3.7 Biochemical analysis

Blood samples were analysed for testosterone, cortisol, lactate (Lac^-) and glucose concentrations. Full details of biochemical analysis can be found in sections 3.9.1 and 3.9.2.

6.3.3.8 Statistical analysis

Data are presented as mean ± standard deviation. Values of testosterone and cortisol were transformed to percentage change (Δ%) from baseline for the purpose of analysis. Prior to analysis dependant variables were verified as meeting required assumptions of parametric statistics and changes in testosterone, cortisol, glucose and Lac^- were analysed using mixed model repeated measures ANOVA tests. Assumptions of sphericity were assessed using Mauchly's test of sphericity, if the assumption of sphericity was violated Greenhouse Gessier correction was employed. ANOVA analysed differences between 4 conditions (ST, ST–END, END–ST and CON) and 3 time points (pre, immediately post and 1 h post resistance exercise cessation). Participant's ability to maintain their individual required training intensity and RPE were analysed using one-way ANOVA. The ANOVA analysed differences between 3 conditions ST, ST–END and END–ST). The alpha level of 0.05 was set prior to data analysis. If significant effects between conditions or over time were observed *post-hoc* differences were analysed with the use of Bonferroni correction. Statistical power of the study was calculated post-hoc using G*Power statistical software (v3.1.3, Düsseldorf, Germany) using the effect size, group mean, SD and sample size of the primary outcome measures, in this case being strength training performance and endocrine factors. Power was calculated as between 0.8 and 1 indicating sufficient statistical power (Cohen, 1992).

6.4 Results

6.4.1 Strength training performance

The ability to maintain a required relative training load was different between groups ($F_{(2,\ 20)}$ = 11.25, p = 0.001). Participants in the ST group were able to maintain their designated relative training load 4.7 ± 1.7 % (p = 0.007; Figure 6.2) better than those in the END–ST (70.1 ± 3.9 % 1RM) group. The ST–END condition also resulted in participants achieving a significantly higher (p < 0.001) relative training intensity than the END–ST condition (7.6 ± 1.7 %). No significant difference was observed between ST and ST–END conditions (p > 0.05).

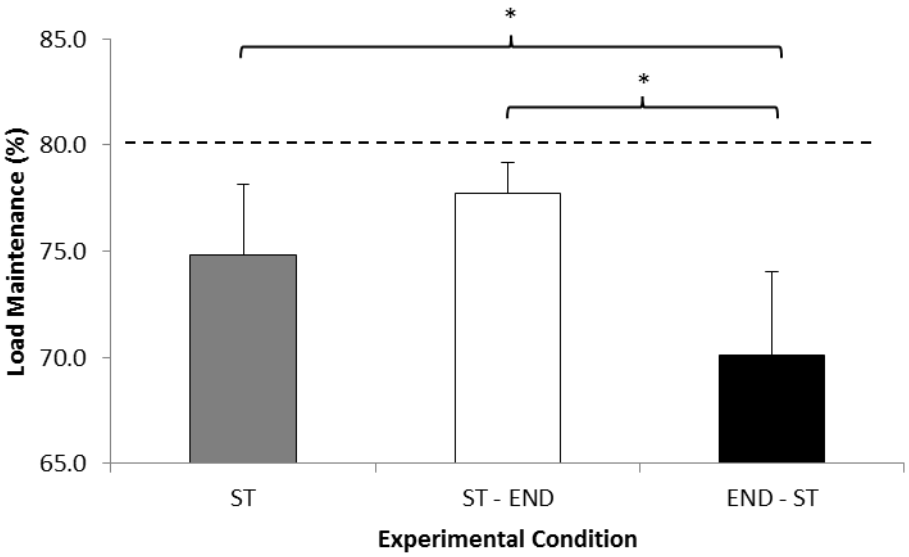

Figure 6.2. Mean training load achieved in the ST (n = *8*), ST–END (n = *8*) and END–ST (n = *8*) conditions. ST, strength training alone; ST–END, strength training followed by endurance training; END–ST, endurance followed by strength training. * significantly greater than END–ST (p < 0.05).

6.4.2 Endocrine factors

6.4.2.1 Testosterone

A significant time x group interaction ($F_{(4, 34)} = 5.577$, $p = 0.001$) and a time effect ($F_{(1, 34)} = 58.230$, $p < 0.001$) were observed for testosterone. All training conditions elicited significant increases in testosterone immediately following exercise cessation (ST; 44.1 ± 23.2%, ST–END; 28.6 ± 9.4%, END–ST; 36.1 ± 23.5%, all $p < 0.001$) (Figure 6.3). From immediately post-exercise to 1 h post exercise cessation testosterone levels decreased significantly in all training conditions (ST; 39.1 ± 15.5%, ST–END; 28.6 ± 5.7%, END–ST; 45.7 ± 17.8%, all $p < 0.05$). 1 h post resistance exercise cessation the END–ST condition resulted in significantly lower testosterone levels than base (9.6 ± 5.8%, $p < 0.001$). 1 h post strength training cessation the END–ST condition resulted in 14.6 ± 1.9% and 13.3 ± 9.3% lower testosterone levels than ST and ST–END (Figure 6.3) (both $p < 0.05$). All training conditions resulted in significantly greater post exercise increases in testosterone than CON (all $p < 0.05$).

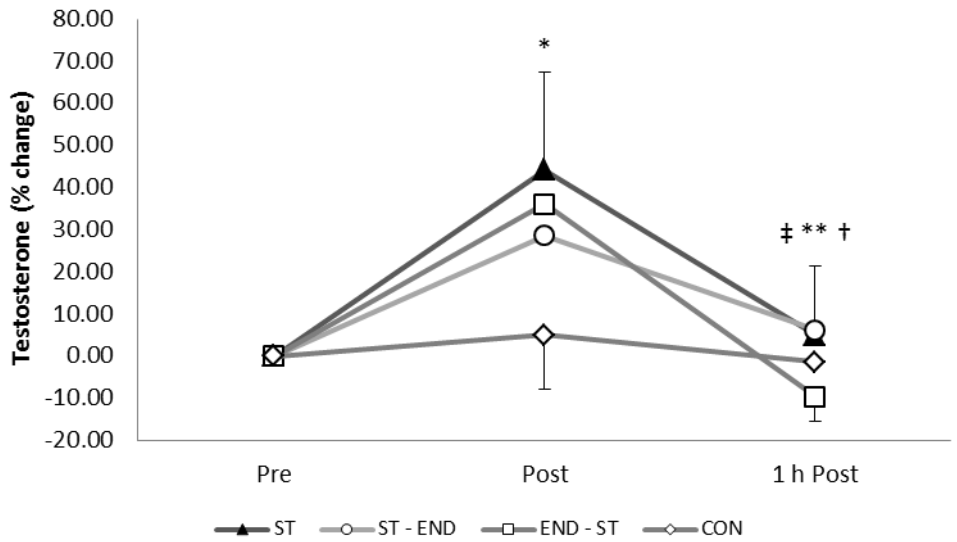

Figure 6.3. Mean relative testosterone responses the ST (*n = 8*), ST–END (*n = 8*) and END–ST (*n = 8*) conditions. ST, strength training alone; ST–END, strength training followed by endurance training; END–ST, endurance followed by strength training. * Significantly greater than pre in all training conditions ($P < 0.001$). ** Significantly lower than post in all training conditions ($p < 0.01$). † Significantly lower than pre in the END–ST condition ($p < 0.001$). ‡ ST and ST–END significantly greater than END–ST ($p < 0.05$).

6.4.2.2 Cortisol

A significant time x group interaction and a time effect were also reported for cortisol ($F_{(5, 40)} = 3.553$, $p = 0.005$ and $F_{(2, 40)} = 33.051$, $p < 0.001$ respectively). Immediately post training all conditions other than CON resulted in significant increases in cortisol (ST; 112.5 ± 52.4%, ST–END; 65.3 ± 34.3%, END–ST; 124.3 ± 73.1%, all $p < 0.001$) (Figure 6.4). After 1 h post resistance exercise cessation cortisol levels decreased significantly in all training conditions (ST; -93.2 ± 14.3%, ST–END; -52.3 ± 7.9%, END–ST; -101.0 ± 32.6%, all $p < 0.05$). Cortisol levels immediately post exercise increased significantly more in participants following the ST (47.2 ± 18.1%) and END–ST (59.0 ± 38.8%) conditions than those following ST–END (both $P < 0.05$, Figure 6.4). All training conditions resulted in significantly greater post exercise increases in cortisol than CON (all $p < 0.05$).

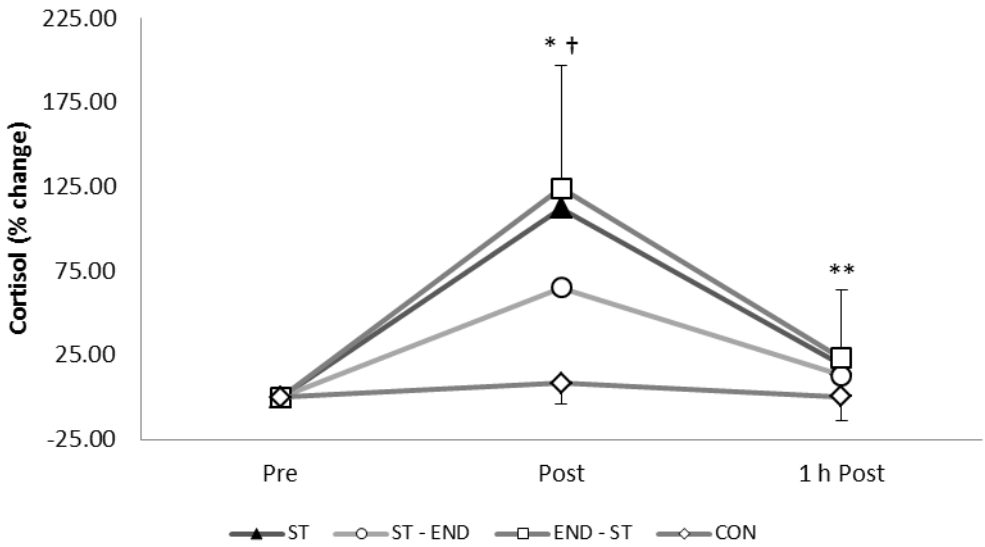

Figure 6.4. Mean relative cortisol responses the ST (*n = 8*), ST–END (*n = 8*) and END–ST (*n = 8*) conditions. ST, strength training alone; ST–END, strength training followed by endurance training; END–ST, endurance followed by strength training. * Significantly greater than pre in all training conditions ($p < 0.001$). ** Significantly lower than post in all training conditions ($p < 0.01$). † ST and END–ST significantly greater than ST–END ($p < 0.05$).

6.4.2.3 Testosterone-cortisol ratio

Testosterone:cortisol ratio (T:C Ratio) was not significantly different between conditions ($F_{(3, 26)} = 0.361$, $p = 0.361$) or over time ($F_{(1, 26)} = 2.442$, $p = 0.097$, Table 6.1).

Table 6.1. Effects of respective training interventions on testosterone:cortisol (T:C) ratio responses.

	Stage		
Condition	**Pre**	**Post**	**1 h post**
ST			
T:C Ratio ($x10^3$)	97.2 ± 112.1	66.1 ± 71.9	136.3 ± 242.5
ST - END			
T:C Ratio ($x10^3$)	65.6 ± 22.6	53.1 ± 18.3	63.4 ± 22.2
END – ST			
T:C Ratio ($x10^3$)	59.6 ± 18.7	43.0 ± 33.5	44.6 ± 11.0
CON			
T:C Ratio ($x10^3$)	58.1 ± 16.4	55.0 ± 9.0	58.5 ± 19.4

6.4.3 Blood glucose and lactate

6.4.3.1 Blood glucose

No time x group interaction was present for blood glucose. A significant effect of time was observed for blood glucose levels ($F_{(2, 46)} = 6.745$, $p = 0.003$). Blood glucose concentrations decreased by 35.9 ± 18.2% from post to 1 h post training in the ST condition ($p = 0.01$). No other significant time effects were present for blood glucose.

6.4.3.2 Blood lactate

A significant time x group interaction ($F_{(4, 34)} = 36.952$, $p < 0.001$) and an effect of time ($F_{(1, 34)} = 195.663$, $p < 0.001$) were observed for Lac^-. All conditions other than CON elicited significant increases in Lac^- post training (all $p < 0.001$). Significant decreases from post to 1 h post training were also observed in all conditions, with the exception of CON (all $p < 0.001$). END–ST was the only

condition in which Lac$^-$ remaining significantly elevated from pre training (p = 0.001).

ST resulted in 52.3 ± 84.6% and 49.5 ± 28.0% greater Lac$^-$ post and 1 h post training than ST–END (p < 0.001 and 0.002 respectively). END–ST also increased Lac$^-$ 67.7 ± 5.6% and 56.9 ± 16.2% greater than ST–END post and 1 h post training respectively (both p < 0.001, Figure 6.5).

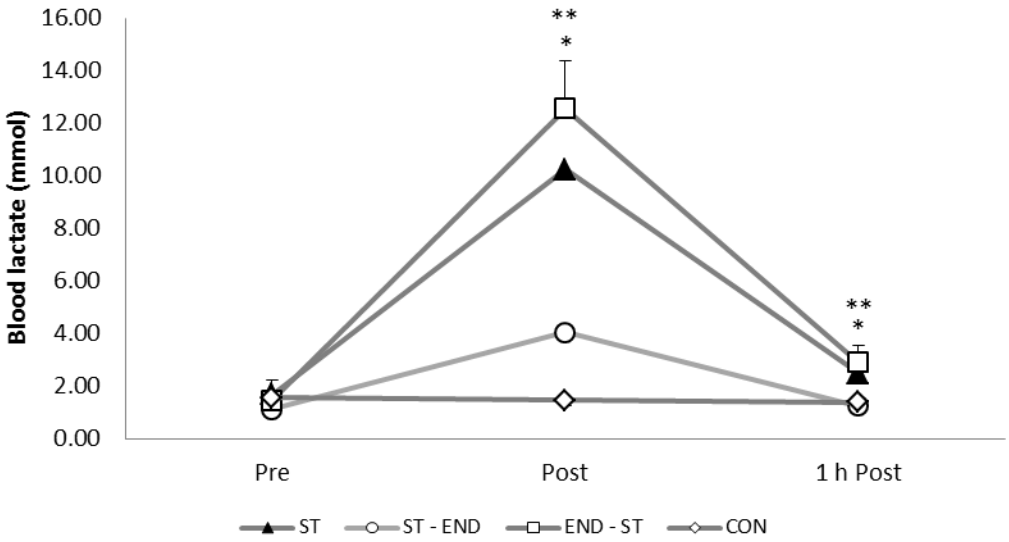

Figure 6.5. Mean blood lactate levels in the ST (n = *8*), ST–END (n = *8*) and END–ST (n = *8*) conditions. ST, strength training alone; ST–END, strength training followed by endurance training; END–ST, endurance followed by strength training. * ST significantly greater than ST–END (p < 0.01). ** END–ST significantly greater than ST–END (p < 0.001).

6.4.4 Rate of perceived exertion

No significant differences were observed between groups for RPE ($F_{(2, 20)}$ = 0.83, p > 0.05).

6.5 Discussion

The responses of the endocrine system to exercise are dependent on the intensity, volume, duration and modality of exercise performed (Tremblay, Copeland & Van Helder, 2004). These differing responses to contrasting exercise stimuli may result in varying anabolic and catabolic signalling which overtime may divergently alter the tissue characteristics of the trained musculature (Kraemer & Ratamess, 2005; Spiering *et al.*, 2008). The focus of the present chapter was to examine the influence of contrasting intra session sequencing of strength and endurance training on endocrine factors which may contribute to strength development and the interference phenomenon.

The primary finding of this study was that following the experimental protocols, strength training following an acute bout of endurance exercise resulted in greater elevations in cortisol and Lac^- than *vice versa*. Neither testosterone nor T:C ratio were differently affected by strength training alone (ST), strength then endurance training (ST-END) or *vice versa* (END-ST). All training conditions resulted in elevated testosterone and cortisol immediately post training. The large increases of testosterone and cortisol (44.1 ± 23.1% and 124.3 ± 71.3% respectively) may be attributed to exercise selection, with the lifts involving large muscle mass (back squat, deadlift and bench press) employed in the present study. Resistance exercises of this nature have previously been demonstrated to result in enhanced responses of testosterone and cortisol to strength training (Volek *et al.*, 1997; Ratamess *et al.*, 2005; Kraemer *et al.*, 2008b). Contrary to the findings of the present study testosterone has been reported to be greater when strength training is performed after endurance rather than *vice versa* (Cadore *et al.*, 2012b). As previously discussed in this thesis, elevated testosterone as a result of strength

training may contribute to increased protein synthesis, fibre hypertrophy and a more "optimal" endocrine environment for strength training adaptation (Vermeulen, 1988; Ratamess *et al.*, 2005; Spiering *et al.*, 2008; Basualto-Alarcón *et al.*, 2013). The 38.1 ± 33.1% larger increases in testosterone when strength training was conducted following endurance (as opposed to strength prior to endurance) are far greater than those reported in the present study (7.5 ± 14.2%). This variance may be attributed to the fact that during the endurance training protocol which followed strength training, testosterone levels in the study of Cadore *et al.* (2012b) returned to baseline. In the present study however, testosterone levels remained elevated from baseline following a 30 min endurance protocol. This disparity may reflect the greater testosterone responses elicited by the strength training protocol of the present study, as Cadore *et al.* (2012b) observed only modest increases in testosterone as a result of their strength training protocol. The authors employed a 4 exercise strength protocol at 75% 1RM with only 1 lift stimulating a large muscle mass, this being the back squat (Spreuwenburg *et al.*, 2006).

Although testosterone was not differently affected by training condition (Figure 6.3) cortisol was significantly lower immediately post training in the ST–END condition than END-ST (Figure 6.4). This may indicate decreased catabolism when strength training is conducted prior to endurance training as opposed to *vice versa*. This hypothesis should perhaps be interpreted with caution as blood samples were only drawn post and 1 h post both bouts of exercise and not after each individual bout. Furthermore, recent research has reported cortisol was the only endocrine factor (of free testosterone, growth hormone, IGF-1 and cortisol) to correlate with increases in type II fibre CSA and lean body mass following 12 weeks of strength training (West & Phillips, 2012). This however may be due to the fact the

authors employed a relatively high training frequency of 5 $d \cdot wk^{-1}$. In addition, unlike the present study in which all participants were considered habitually strength trained, West and Phillips (2012) tested individuals who had not been performing strength training for up to 8 months prior to the experimental protocol. As such it is perhaps reasonable to suggest the increased cortisol, fibre CSA, and lean mass were primarily due to the somewhat deconditioned nature of the study participants, and similar data would not have been reported in a population more accustomed to strength training stimulus.

When analysing the Lac^- response to the respective training protocols it becomes apparent that Lac^- follow a similar trend to cortisol (Figures 6.4 and 6.6). As both Lac^- and cortisol were significantly lower in the ST–END group than END-ST it may be suggested that the endurance training protocol employed in the present study was of insufficient intensity to maintain or further stimulate Lac^- or cortisol. Both lactate and cortisol have also been related to increased metabolic stress (Urhausen *et al.*, 1995). As such, it is possible this indicates the higher Lac^- (and cortisol) observed when endurance exercise preceded strength training are reflective of greater metabolic stress when compared with endurance exercise subsequent to strength training. In contrast, it has previously been suggested that metabolic stress may be greater when strength training is performed prior to endurance training (Coffey *et al.*, 2009b). Comparisons may however be difficult between these data and the present study, as the hypothesis formed by Coffey *et al.* (2009b) was based on the responses of the adenosine monophosphate activated protein kinase (AMPK) signalling network rather than endocrine and/or metabolic factors. In addition the time point at which the AMPK responses were observed was 3 h post exercise opposed to immediately post exercise in the present study. The aforementioned

elevated metabolic stress may be detrimental to both strength training performance (illustrated by the findings of the present chapter, Figure 6.2) and strength related adaptation via the activation of the energy modulating AMPK signalling network. Research has indicated AMPK's function is to monitor the energy status of muscle cells, or act as a "metabolic fuel gauge" (Winder, 2001), as such AMPK is primarily activated in response to decreased energy levels and metabolic stress (Hawley, 2009). The significance of increased AMPK phosphorylation is that it can inhibit ATP-consuming pathways associated with protein synthesis to allow greater activation of pathways involving carbohydrate and fatty acid catabolism to restore ATP levels (Hardie & Sakamoto, 2006). Moreover, the endurance training induced activation of AMPK and subsequent inhibition of protein synthesis has been proposed as a mechanism contributing to the interference phenomenon (Coffey & Hawley, 2007; Baar, 2009).

Recent research into the role of strength and endurance exercise sequencing and signalling variables has indicated that when repeated high intensity sprints are performed both prior and subsequent to strength training, a diminished anabolic response occurs; as assessed by insulin like growth factor-1 (IGF-1) mRNA signalling (Coffey *et al.*, 2009a). Although, as the authors included no strength alone condition it is difficult to determine if any attenuated anabolic response was in fact observed, regardless of training order. Furthermore high intensity sprint type activity is more similar to strength training than steady state endurance exercise, which is demonstrated by previous research reporting high intensity interval training does not attenuate strength development (Balabinis *et al.*, 2003; Rhea *et al.*, 2008; Wong *et al.*, 2010).

The greater increases in Lac^- at the post-training time point in the END-ST than ST-END condition may indicate greater intramuscular metabolic acidosis. This observation may be particularly pertinent as metabolic acidosis has been associated with decremented protein synthesis in both rodent and human skeletal muscle (Kleger *et al.*, 2001; Caso *et al.*, 2004). This coupled with increased catabolism, (demonstrated by greater cortisol levels) may indicate a reduced rate of protein synthesis when endurance exercise precedes strength training. Although testosterone responses were similar between concurrent training conditions it is possible that protein synthesis may have been inhibited at the mammalian target of rapamycin (mTOR) axis. This hypothesis of course remains speculative as no direct markers of protein synthesis or phosphorylation of the growth-associated pathways were analysed here.

Although increased Lac^- may indicate decremented protein synthesis when endurance exercise is conducted prior to strength training, there is also a body of evidence indicating that strength training protocols which stimulate Lac^- tend to result in substantial growth hormone (GH) responses (Kraemer *et al.*, 1990; Gotshalk *et al.*, 1997; Hoffman *et al.*, 2003; Kraemer *et al.*, 2003). Also protocols which elevate GH and Lac^- seem to elicit the greatest cortisol responses (Ratamess *et al.*, 2005). As high cortisol and Lac^- were reported post training in the END–ST condition it may then be reasonable to suggest secretion of GH was also elevated. It has however previously been reported that a preceding bout of endurance training suppresses the GH response to strength training (Goto *et al.*, 2005). As GH has been associated with tissue building properties and anabolism (Craig *et al.*, 1991; Piwien-Pilipuk, Huo & Schwartz, 2002) these observations are contrary to those of the present study as no differences in anabolism indicated by endocrine factors between

ST or either concurrent condition were reported. It should, however, be noted that the strength training protocol employed by Goto *et al.* (2005) was of insufficient volume and intensity to stimulate any increases in testosterone or cortisol. This is perhaps unsurprising as only two exercises at an intensity of 75% 1RM were employed (bench press and bilateral leg press).

Both ST and ST-END resulted in better performance during the strength training protocol than END-ST (4.7 ± 0.6 and 7.6 ± 2.4% respectively; Figure 6.2). These data indicate strength training performance and the ability to maintain a designated training load is negatively affected by a preceding bout of endurance training, which is consistent with previous research (Leveritt & Abernethy, 1999; Sporer & Wenger, 2003; García-Pallarés *et al.*, 2009). A potential mechanism for this is the compromised ability of the neuromuscular system to rapidly develop force due to residual fatigue (Craig *et al.*, 1991; Leveritt & Abernethy, 1999), although this was not analysed in the present study. It is likely that this compromised strength training performance as a result of prior endurance training can be attributed to a greater build-up of inorganic phosphates demonstrated by the 67.7 ± 5.6% greater Lac^- post training in the END-ST condition (Figure 6.5). An acute bout of strength training is insufficient stimulus to elicit performance or morphological adaptations (Baar, 2006). Over time, progressively overloaded strength training has repeatedly been demonstrated to result in increased contractile strength and muscle fibre cross sectional area (Häkkinen, 1989; Kraemer & Nindl, 1998; McCall *et al.*, 1999; Ahtiainen *et al.*, 2003a; West & Phillips, 2012). If strength training performance is repeatedly impaired as a result of preceding endurance training, the magnitude of strength training related adaptation may be attenuated compared to conducting strength training alone. This hypothesis has been confirmed by current research

demonstrating strength gains to be greater when strength training precedes endurance training or is performed in insolation (García-Pallarés *et al.*, 2009; Cadore *et al.*, 2012c).

This study sought to further elucidate the effects of acute sequencing of strength and endurance training on endocrine responses associated with strength training adaptation, anabolism and tissue growth. Additionally, the study was designed to contribute to the understanding of the potential underlying physiological mechanisms relating to concurrent training strategies and the interference phenomenon. The results of this study showed that the manipulation of the order of acute concurrent strength and endurance training can influence the magnitude of cortisol responses without any concomitant changes in circulating testosterone responses. END-ST resulted in greater cortisol and Lac^- than ST-END. This may indicate increased catabolism and metabolic acidosis and/or stress induced inhibition of protein synthesis, although both suggestions remain largely speculative and unsubstantiated by data presented in this chapter. In addition, whilst some previous research has investigated the signalling responses to differing sequencing of concurrent strength and endurance training it remains unclear which sequence is most favourable for strength-related adaptation. Furthermore the two studies which have investigated the influence of exercise order on anabolic signalling did not include a strength training alone condition. This makes it impossible to ascertain whether the acute concurrent training protocols differently influenced the signalling responses to strength training in isolation. As such, future work is needed to fully elucidate the responses of signalling pathways associated with tissue growth and anabolism to varying sequencing of divergent exercise stimuli. The present study's data does support the hypothesis that endurance training immediately prior to

strength training reduces the quality of the subsequent strength training, although the underlying mechanisms behind this phenomenon are yet to be fully elucidated.

6.6 Practical applications

Due to logistical and scheduling issues including access to facilities and competition schedules, at times it is inevitable that both athletes and recreationally trained individuals will have to perform a combination of strength and endurance training in the same session. Whilst testosterone responses were similar between conditions, performing endurance prior to strength training elicited greater increases in cortisol than *vice versa*. Based on these data strength should precede endurance training in a concurrent regimen if strength related adaptation is the primary aim of the intervention. This is due to the increased catabolism (as indicated by cortisol and metabolic acidosis) associated with conducting endurance training prior to strength training. Furthermore it is clear strength training immediately following endurance training results in diminished quality of strength training performance. If strength training is repeatedly performed under fatigue, with the presence of increased inorganic phosphates and a suboptimal anabolic environment, both strength and any hypertrophic adaptation over time may be impaired.

Applied conditioning practitioners working in elite sport often have limited contact time with their athletes due to intense competition schedules and other technical and skill based training commitments. If strength-related adaptation is the primary goal of the strength and conditioning professional, it is imperative that strength training should be performed when the athlete is not fatigued from a previous endurance-based session. As such, scheduling of strength and endurance

type training may play a critical role in optimizing strength, power and hypertrophic adaptation.

The data presented in this chapter may suggest anabolic signalling may play a role in the concurrent training and interference paradigm. Whilst there is also a growing body of research examining the role of the signalling in interference, there is no published data demonstrating that endurance training induced activation of AMPK can supress protein synthesis in humans. The fact also remains that sequencing of strength and endurance training is one of the lesser researched areas of concurrent training.

Although the underpinning mechanisms contributing to interference are not fully understood previous research and data presented within this thesis indicated endocrine factors play some role in the attenuated strength development associated with concurrent training. Moreover the findings of the present study demonstrate that these endocrine factors are influenced by the order in which strength and endurance training are performance, as such the sequencing of exercise should be considered when designing concurrent training interventions.

7. Early time course signalling responses to acute concurrent strength and endurance training sequencing

7.1 Abstract

Purpose: The present study examined the influence of manipulating the order in which strength and endurance training are performed within a given training session on molecular signalling variables associated with strength training adaptation and the potential influence of endurance training-induced inhibition of protein synthesis.

Methods: 18 resistance-trained males completed one of three experimental protocols; strength training (ST), strength followed by endurance training (ST-END) or endurance followed by strength training (END-ST). Muscle tissue samples were taken before each respective exercise protocol, upon cessation of exercise, and 1 h post cessation of strength training. Tissue was subsequently analysed for total and phosphorylated (p-) signalling proteins linked to the mTOR and AMPK networks, respectively.

Results: Strength training performance was similar between ST, ST-END and END-ST. p-S6k1 was elevated 1 h post training in ST and ST-END (both $p < 0.05$) but not in END-ST. p-4E-BP1 was significantly lower than base post ST ($p = 0.01$), while 1 h post exercise in the ST-END condition p-4E-BP1 was significantly greater than post exercise ($p = 0.04$). p-ACC was elevated from base both post and 1 h post exercise (both $p < 0.05$) in the END-ST condition; no such increases were observed in either ST or ST-END conditions.

Conclusions: ST and ST-END were the only conditions to elicit increased phosphorylation of the growth associated mTOR network, as indicated by up-regulation of p-S6k1. END-ST was the only condition to increase phosphorylation of the energy modulating AMPK network. Combined, these data may indicate that if strength type adaptation is the primary training objective, then strength training should be performed prior and not subsequent to endurance training.

7.2 Introduction

Various research studies, employing techniques from biochemistry and molecular biology, have reported both acute and chronic resistance exercise-induced activation of the PI3k/mTOR/PKB/S6k1/4E-BP1 growth associated signalling network (Baar & Esser, 1999; Nader & Esser, 2001; Bolster *et al.*, 2003; Koopman *et al.*, 2006). The repeated activation of the 'mTOR signalling network', induced by progressively overloaded strength training, can result in increased cross sectional area (CSA) and contractile strength of the trained muscles over time (Tang *et al.*, 2008). Importantly, there is a growing body of evidence that indicates the endurance training-induced activation of the energy modulating AMPK signalling network may be antagonistic to the mTOR network and any associated strength training adaptations (Baar, 2006; Dreyer *et al.*, 2006; Nader, 2006; Baar, 2009; Camera *et al.*, 2010).

The inhibition of intramuscular protein synthesis via endurance training mechanisms that activate AMPK remains a contentious issue in applied physiology. In murine models it is generally accepted that endogenous AMPK can mediate a suppressive effect on mTOR activity and consequent protein synthesis (Atherton *et al.*, 2005; Thomson, Fick & Gordon, 2008; Mounier *et al.*, 2011). In humans the interactions between the growth-associated and energy modulating pathways are yet to be fully elucidated as various researchers report no muting effect of AMPK on total and phosphorylated (p-) mTOR and subsequent signalling (Coffey *et al.*, 2006; Wilkinson *et al.*, 2008; Camera *et al.*, 2010; Vissing *et al.*, 2011; Apró *et al.*, 2013). Moreover, to the author's knowledge only two studies have investigated the effects of differing the order of acute concurrent strength and endurance training on

molecular and signalling responses associated with protein synthesis and strength training adaptation (Coffey *et al.*, 2009a; Coffey *et al.*, 2009b).

The studies which have investigated the molecular responses to acute intra session sequencing of concurrent training reported no effect of strength and endurance exercise order (strength then endurance or *vice versa*) on the mTOR signalling network (Coffey *et al.*, 2009a; Coffey *et al.*, 2009b). However, inconsistencies are present within these studies, as Coffey *et al*. (2009a) employed repeated high intensity sprints as the endurance stimulus rather than the more commonly used ~30 min of steady state exercise (Wilkinson *et al.*, 2008; Vissing *et al.*, 2011; Apró *et al.*, 2013). An additional confounding factor is that neither study included a condition involving strength training alone. As such, it cannot be accurately determined whether any inhibition of protein synthesis was caused by the endurance exercise stimulus. Furthermore, in both of these studies the respective exercise protocols were conducted in a fasted state (Coffey *et al.*, 2009a; Coffey *et al.*, 2009b). As such, no published data are available on the molecular responses to acute concurrent training in humans in a fed state. Conducting strength and/or endurance type exercise in a fasted state is associated with glycogen depletion; shown to be a prominent precursor to cortisol catabolising protein and phosphorylation of the AMPK network (Steinberg *et al.*, 2006). Furthermore, recent research has indicated low muscle glycogen may impair intracellular signalling pathways responsible for hypertrophy (Hawley, 2009; Rønnestad, Hansen & Raastad, 2011). As such it may be argued studies examining the signalling responses to concurrent training in which participants are fasted may not provide an accurate representation of anabolic signalling. In addition, the real world applications of these studies are lacking, as few individuals perform strength training fasted.

Data presented in Chapter 6 of this thesis combined with previous published work allow one to speculate that appropriate sequencing of strength and endurance training may promote a more optimal anabolic environment following concurrent training. It was observed in Chapter 6 that strength training subsequent to a preceding bout of endurance training resulted in greater cortisol and lactate (Lac^-) responses. Both these responses may be indicative of increased catabolism and a decremented rate of protein synthesis (Kleger *et al.*, 2001; Caso *et al.*, 2004; Kraemer & Ratamess, 2005). However, as no direct or indirect markers of protein synthesis were analysed the aforementioned decremented rate of protein synthesis remains speculative.

Various aspects of the molecular responses to concurrent strength and endurance training in humans remain inconclusive, and thus it is difficult to fully elucidate the specific mechanisms regulating adaptations to concurrent training strategies. Data previously reported in this thesis suggested that further investigation of the acute signalling responses to combined exercise may contribute to the greater understanding of the muted strength, power and hypertrophic responses associated with concurrent training. As such, the present study sought to answer two primary questions; i) does combining acute bouts of strength and endurance training result in the inhibition of protein synthesis as a result of the activation of the AMPK signalling network, and ii) does the order in which strength and endurance training are performed influence the response of the mTOR and AMPK signalling networks in a fed state?

7.3 Methods

7.3.1 Experimental approach to the problem

A balanced, randomised, between-group study design was employed. Participants were randomly assigned to one of 3 experimental conditions: i) strength training (ST), ii) concurrent strength and endurance training, with strength training first (ST-END) or iii) concurrent training, with endurance training first (END-ST). Participants in the ST group performed strength training alone; the ST-END group performed strength training immediately followed by an endurance training protocol; those participants designated END-ST performed endurance training immediately followed by strength training.

Prior to the experimental protocol assessments of maximal oxygen uptake ($\dot{V}O_{2max}$) and 1 repetition maximum (1RM) loads were performed to ensure training load and intensity was normalised between groups and relative to individual strength and endurance capabilities. In order to assess the effect of each intervention on molecular signalling factors related to strength and morphological adaptation, muscle tissue samples were collected before, 10 min post exercise and 1 h post cessation of the strength training protocol in ST, ST-END and END-ST conditions. The participants' ability to maintain their designated strength training load was assessed to determine if endurance exercise prior to strength training resulted in diminished strength performance.

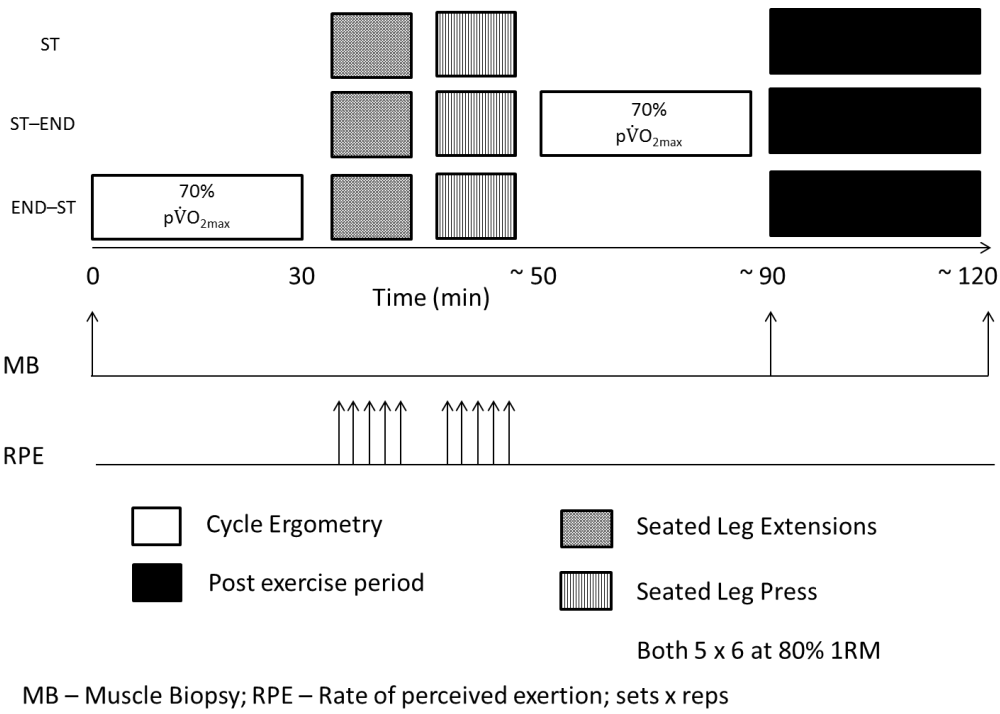

Figure 7.1 Schematic representation of experimental time line. ST (*n = 6*), ST-END (*n = 6*, END-ST (*n = 6*).

7.3.2 Participants

Eighteen recreationally resistance-trained men (age: 24 ± 3 y; body mass: 80.5 ± 9.9 kg; height: 177.8 ± 7.5 cm; % body fat: 17.5 ± 7.2%; sum of assessed 1RMs: 375.6 ± 56.3 kg; $\dot{V}O_{2max}$: 50.1 ± 7.2 ml·kg·min) volunteered to participate in the study. Participants were matched at baseline for age, body mass, body fat %, total of 1 RMs and $\dot{V}O_{2max}$ (all $p > 0.05$) then randomly assigned to one experimental condition. Additional information on study participants training status, nutritional restrictions and health status is presented in section 3.3.

7.3.3 Procedures

7.3.3.1 Diet and exercise control

Participants arrived at the lab in a fed state (≥ 1 h). Final nutritional intake was standardised prior to commencement of the experimental protocol (Figure 7.1)

and consisted of; 2 g carbohydrate/kg body mass, 0.5 g protein/kg body mass and 0.15 g fat/kg body mass. Participants were also advised to abstain from exercise, alcohol and caffeine for 24 h pre visit.

7.3.3.2 Strength and endurance training protocols

The strength training protocol consisted of seated leg extensions and seated leg press as these exercises have been demonstrated to activate the *vastus lateralis* (VL) and have previously been employed within the literature in comparable research (Coffey *et al.*, 2009b; Beck *et al.*, 2010). It was critical that the VL muscle was activated consequent to the strength training protocol as this muscle was used for harvesting tissue. For each exercise within the strength training bout, 5 sets of 6 repetitions at 80% 1RM were completed. This protocol and intensity has been shown to be appropriate for eliciting strength and hypertrophic responses in recreationally trained non-athletes (Peterson, Rhea & Alvar, 2004; 2005). Furthermore this set/rep scheme has elicited increases in critical anabolic and catabolic biochemical variables (Chapters 5 and 6) and strength (Chapters 4 and 5) in previous chapters of this thesis and has been employed in comparable literature (Coffey *et al.*, 2009a; Coffey *et al.*, 2009b).

In all instances, the endurance exercise protocol involved participants completing 30 min of submaximal cycle ergometry at 70% power at maximal oxygen uptake (p$\dot{V}O_{2max}$). Visual feedback for pedal frequency, power output and elapsed time were provided to participants. All strength and/or endurance based exercise commenced at the same time of day (0900 h ± 1h) to avoid any diurnal performance, molecular and cell signalling variations (Adam & Oswald, 1983).

7.3.3.3 Maximal strength testing - 1 repetition maximum (1RM)

Participants 1RM in seated leg extension and leg press exercises (Figures 7.2 and 7.3) were determined prior to commencing the experimental protocol. All assessments were conducted in line with standardised procedures and further details are presented in section 3.5.

Figure 7.2. Seated leg extension.

Figure 7.3. Seated leg press.

7.3.3.4 Maximal aerobic capacity - $\dot{V}O2max$

Assessments of participant's $\dot{V}O_{2max}$ and power output at $\dot{V}O_{2max}$ (p$\dot{V}O_{2max}$) were determined on a cycle ergometer prior to the experimental protocol. All assessments were conducted in line with standardised procedures. Further details of $\dot{V}O_{2max}$ determination are presented in 3.6.2.

7.3.4 Rate of perceived exertion

RPE was assessed immediately following the completion of each set of the strength training protocol. Further details of RPE assessment are presented in 3.7.

7.3.5 Muscle tissue sampling and storage

Muscle biopsies were taken samples were taken from the VL at baseline, 10 min post exercise and 1 h post cessation of the strength training protocol. All muscle tissue was extracted via the puncture biopsy technique from the VL (Figure 7.4). Prior to incision, local anaesthetic (Bupivacaine Hydrochloride, 0.5% Marcaine) was injected into biopsy site by a certified physician. Initially 1 ml was injected, and if a visible raise in the subcutaneous volume did not appear the needle was slightly retracted and an additional 1 ml injected. The needle was then removed and reinserted into the injection location at 45° and a further 1 ml injected. Following a ≥ 3 min period in which the anaesthetic had taken effect, an incision was made longitudinally to the line of the VL to cut through subcutaneous tissue and fascia. Following insertion the biopsy needle (gauge 9, 10 cm length, Bard Biopsy Systems, Tempe, AZ, USA) was then inserted perpendicular to skin surface until initial resistance was overcome. When the tip of the needle had passed the muscle facia the angle of the needle was flattened to ~45°, fired, and then immediately withdrawn.

The extracted tissue was immediately removed from the instrument, cleaned with saline, weighed using laboratory scales, and snap frozen in liquid nitrogen before storage at -80°c. This process was repeated until sufficient tissue (40 – 60 μg) was obtained for biochemical analysis; this typically required 2 – 3 passes.

Figure 7.4. Muscle tissue collection via the microbiopsy or puncture biopsy technique.

7.3.6 Signalling protein analysis – western blotting

Processed muscle tissue was analysed for total and phosphorylated signalling proteins associated with the mTOR and AMPK signalling networks. The analysed signalling proteins within the mTOR network included; 4E binding protein 1 (4E-BP1), mammalian target of mTOR, protein kinase B (PKB) and 70-kDa S6 protein kinase (S6k1). For a schematic representation of the mTOR growth associated

network please refer to Figure 2.5. The analysed signalling proteins of the AMPK network included; acetyl-CoA carboxylase (ACC), AMPK, eukaryotic elongation factor 2 (eEF2), mitogen-activated protein kinase (p38), and tuberous sclerosis complex 2 (TSC2). A schematic representation of the energy modulating AMPK network is presented in Figure 2.6.

Muscle tissue (10–15 ug) was scissor minced in lysis buffer on ice (50 mM Tris, pH 7.5, 250 mM sucrose, 1 mM EDTA, 1 mM EGTA, 1% Triton X-100, 1 mM NaVO4, 50 mM NaF, 0.50% protease inhibitor cocktail). Samples were then shaken for 1 h (800 rpm) at 4°C before centrifugation for 60 min at 12000 g. The supernatant was subsequently removed from the pellet to a clean tube and used to determine protein concentration via a DC Protein Assay (Bio-Rad Laboratories, Hertfordshire, UK). Equal amounts of protein were first boiled in Laemmli sample buffer (250 mM Tris-HCl, pH 6.8, 2% SDS, 10% glycerol, 0.01% bromophenol blue, 5% β-mercaptoethanol). Subsequently 10-30 μg protein from each sample was separated on precast Criterion (Bio-Rad Laboratories) SDS polyacrylamide gels (4–20% gradient gels) for ~75 min at 150 V. Proteins were transferred to a Protran nitrocellulose membrane (Whatman, Dassel, Germany) at 30 V for 4 h. Membranes were then blocked in 5% BSA-Tris-buffered saline with 0.1% Tween-20 (TBST) and then incubated overnight at 4°C with the appropriate primary antibody. The antibodies were used at the following dilutions: rabbit monoclonal GAPDH 1:5,000, rabbit polyclonal 1:1,000 4E-BP1$^{ser37/41}$, ACC^{ser79}, AMPK^{Thr172}, eEF2^{Thr56}, mTOR^{ser2448}, p38$^{Thr80/Thy182}$, PKB^{ser437}, S6k1^{Thr389} and TSC2^{ser939} (14C10; Cell Signaling Technology, Danvers, MA).

Following overnight incubation, the membranes underwent 3 × 5 min washes in TBST. The membrane was then incubated for 1 h at room temperature with

horseradish peroxidase-linked anti-rabbit IgG (1:10,000; Abcam, Cambridge, UK) or anti-mouse (1:10,000; Abcam, Cambridge, UK), diluted in 5% BSA-TBST. The membrane was then cleared of the antibody using TBST. Antibody binding was detected using enhanced chemiluminescence (GE Healthcare Biosciences, Pittsburgh, PA). Molecular weight was estimated using molecular weight Kaleidoscope Prestained Standards (Bio-Rad Laboratories). To improve antibody performance, reduce nonspecific bands and the variability of quantifying different membranes the following procedure was performed: prior to transfer, the gels were cut at the molecular weight markers which corresponded to the molecular weight (KDa) of the proteins analysed in the respective runs. All of the gel segments for the entire data set were transferred onto a single membrane for each protein. This allowed clearer visualization of the time course response of the proteins. Following imagining and band quantification of phosphorylation of the analysed proteins membranes were stripped for 30 min at 50°C in stripping buffer (65 mM Tris HCl, 2% SDS vol/vol, 0.8% mercaptoethanol vol/vol) and reblocked, followed by an overnight incubation in the corresponding total primary antibody. All imaging and band quantification were carried out using a bioimaging Gel Doc system (Bio-Rad Laboratories). Quantified phosphorylated 4E-BP1$^{ser37/41}$, ACC^{ser79}, AMPK^{Thr172}, eEF2^{Thr56}, mTOR^{ser2448}, p38$^{Thr80/Thy182}$, PKB^{ser437}, S6k1^{Thr389} and TSC2^{ser939} were divided by the total corresponding protein. Where it was not possible to determine total protein content GAPDH or total eEF2 were used for normalisation.

7.3.7 Statistical analysis

Performance and RPE are presented as mean ± standard deviation and molecular data are presented as mean ± standard error. Molecular and signalling data

were transformed to arbitrary units and normalised to individual baseline data, which is consistent with compatible research (Wilkinson *et al.*, 2008; Coffey *et al.*, 2009b). Prior to analysis dependant variables were verified as meeting required assumptions of parametric statistics and changes in molecular variables were analysed using mixed model repeated measures ANOVA tests. ANOVA analysed differences between 3 conditions (ST, ST–END and END–ST) and 3 time points (pre, post and 1 h post resistance exercise cessation). Participant's ability to maintain their individual required training intensity and RPE were analysed using one way ANOVA tests. ANOVA analysed differences between 3 conditions ST, ST–END and END–ST). The alpha level of 0.05 was set prior to data analysis. Assumptions of sphericity were assessed using Mauchly's test of sphericity, if the assumption of sphericity was violated Greenhouse Gessier correction was employed. If significant effects between conditions or over time were observed *post-hoc* differences were analysed with the use of Bonferroni correction. Statistical power of the study was calculated post-hoc using G*Power statistical software (v3.1.3, Düsseldorf, Germany) using the effect size, group mean, SD and sample size of the primary outcome measures, in this case being the signalling proteins of the mTOR network. Power was calculated as between 0.8 and 1 indicating sufficient statistical power (Cohen, 1992).

7.4 Results

7.4.1 Strength training performance

Participants ability to maintain their assigned strength training load was not affected by experimental condition ($F_{(2, 15)} = 0.491$, $p = 0.621$; Figure 7.5).

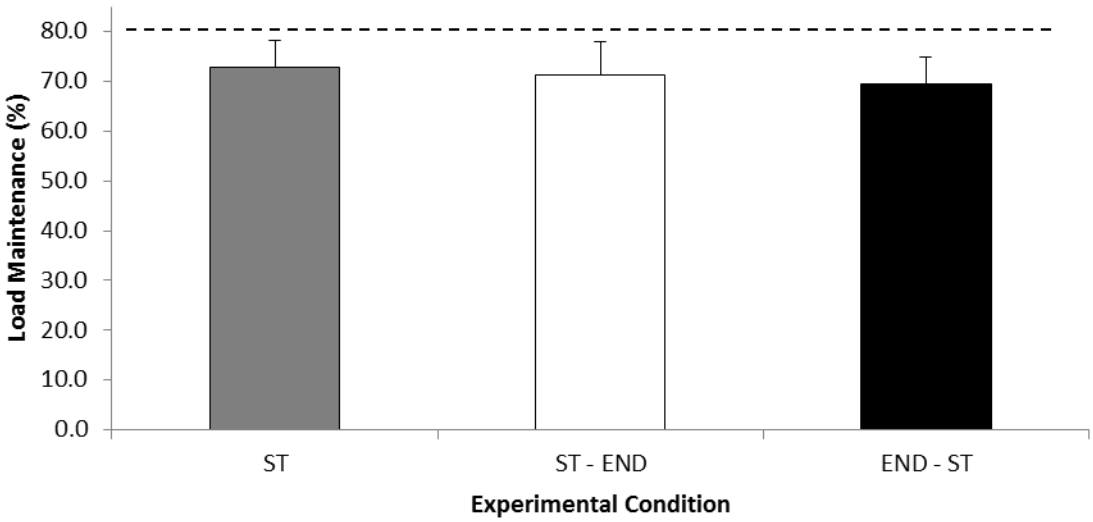

Figure 7.5. Mean training load achieved in the ST (*n* = *6*), ST – END (*n* = *6*) and END–ST (*n* = *6*) conditions. ST, strength training alone; ST–END, strength training followed by endurance training; END–ST, endurance followed by strength training. Dashed line indicates required training intensity.

7.4.2 Signalling responses

7.4.2.1 4E-BP1

4E-BP1 is downstream regulator of protein synthesis in the mTOR network. No time x group interaction was reported for p-4E-BP1 ($F_{(4, 28)} = 0.405$, $p = 0.804$). However, p-4E-BP1 changed significantly over time as a result of the experimental protocol ($F_{(2, 28)} = 4.943$, $p = 0.015$). p-4E-BP1 was significantly lower than base line values post exercise in participants following the ST condition (29.6 ± 13.6%) ($p = 0.01$). 1 h post exercise in the ST-END condition p-4E-BP1 was 41.1 ± 7.2% greater than post exercise ($p = 0.04$) although no difference was observed between pre and post exercise ($P = 0.10$). No differences were observed in the END-ST condition (both $p > 0.05$).

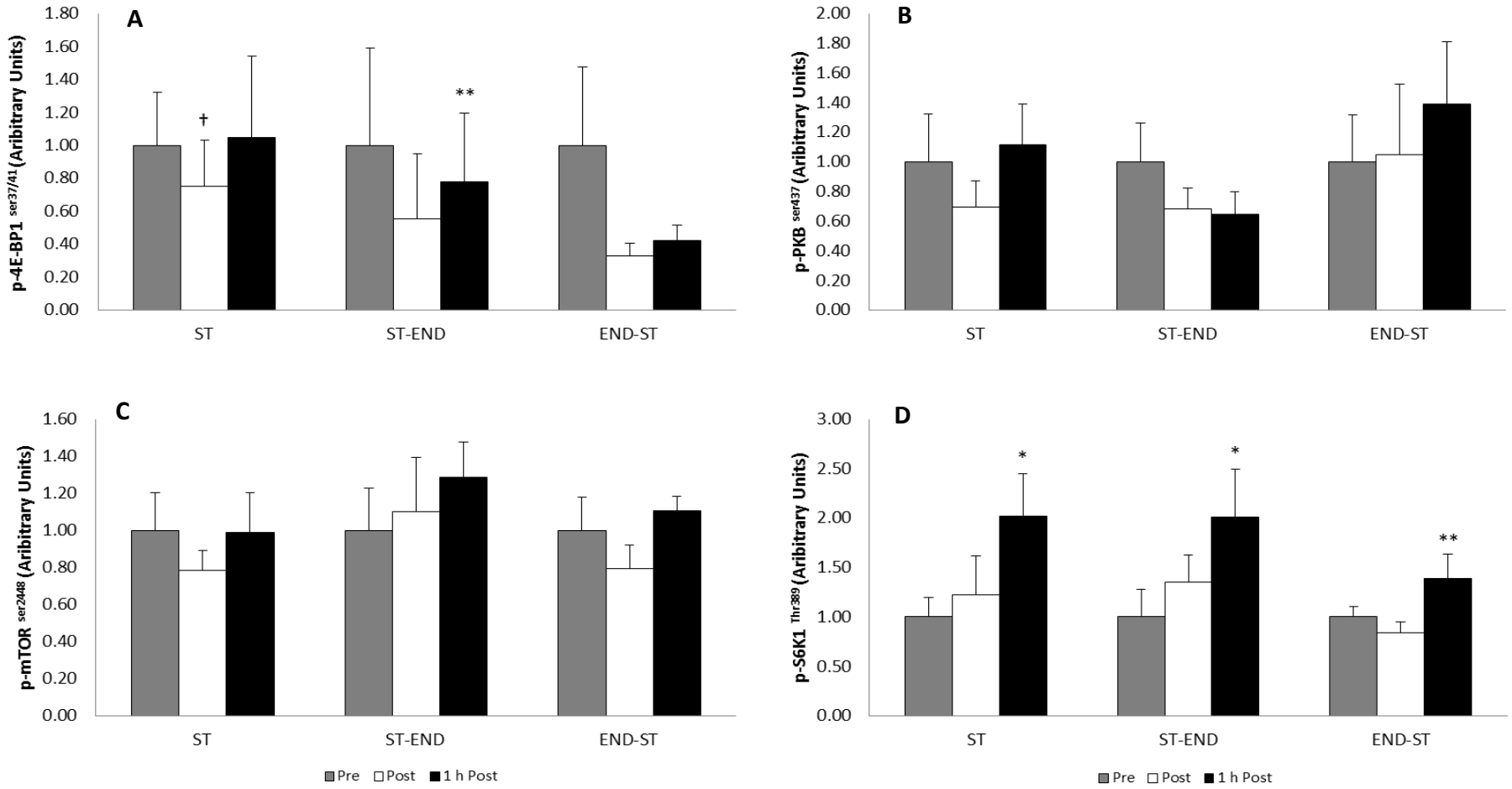

Figure 7.6. Mean responses of the mTOR signalling network in ST (*n* = *6*), ST–END (*n* = *6*) and END–ST (*n* = *6*) conditions. ST, strength training alone; ST–END, strength training followed by endurance training; END–ST, endurance followed by strength training. (**A**) p-4E-BP1, (**B**) p-PKB, (**C**) p-mTOR and (**D**) p-S6k1. * Significantly greater than pre ($p < 0.05$). ** Significantly greater than post ($p < 0.05$). † Significantly lower than pre ($p < 0.05$).

7.4.2.2 S6k1

S6k1 is downstream regulator of protein synthesis in the mTOR network. No time x group interactions were observed ($F_{(4, 28)} = 0.638$, $p = 0.64$). A main effect of time was however observed for p-S6k1 ($F_{(2, 28)} = 11.733$, $p < 0.001$). Both ST and ST-END elicited increases from base (18.5 ± 58.7% and 57.9 ± 93.9% respectively) in p-S6k1 1h post exercise (113.4 ± 119.3% and 145.6 ± 191.4%; both $p < 0.05$). No such increases from base were observed 1 h post exercise in the END-ST group ($p = 0.19$). The END-ST condition did however elicit significant increases in p-S6k1 from post to 1 h post exercise ($p = 0.04$).

7.4.2.3 ACC

ACC is a signalling protein within the energy modulating AMPK network. No time x group interactions were observed for p-ACC ($F_{(4, 28)} = 1.884$, $p = 0.141$), however phosphorylation changed over time ($F_{(2, 28)} = 5.751$, $p = 0.008$; Figure 7.7). END-ST resulted in significant elevations from base both post (91.2 ± 22.4%) and 1 h post exercise (51.5 ± 33.9%; both $p < 0.05$). No such increases were observed in either ST or ST-END conditions.

7.4.2.4 mTOR

Neither time x group interactions ($F_{(4, 28)} = 0.873$, $p = 0.492$), nor effects ($F_{(2, 28)} = 2.494$, $p = 0.101$) of time were reported for p-mTOR (Figure 7.5).

7.4.2.5 PKB

PKB was not differently affected by the respective experimental ($F_{(4, 28)}$ = 1.340, p = 0.282) conditions and did not change over time ($F_{(2, 28)}$ = 0.645, p = 0.533, Figure 7.6).

7.4.2.6 AMPK

Neither time x group interactions ($F_{(4, 28)}$ = 0.804, p = 0.533) nor effects of time ($F_{(2, 28)}$ = 1.508, p = 0.239) were observed in p-AMPK (Figure 7.6).

7.4.2.7 eEF2

The separate experimental conditions did not elicit any differing responses in eEF2 ($F_{(4, 28)}$ = 1.005, p = 0.422). Moreover, phosphorylation of eEF2 was not different over time ($F_{(2, 28)}$ = 0.331, p = 0.721).

7.4.2.8 p38

The responses to p-p38 were not different between experimental conditions ($F_{(2, 14)}$ = 0.656, p = 0.540), nor did they change over the time course of the protocols ($F_{(1, 14)}$ = 2.737, p = 0.120).

7.4.2.9 TSC2

Neither time x group interactions ($F_{(2, 14)}$ = 0.383, p = 0.710), nor effects of time ($F_{(1, 14)}$ = 2.158, p = 0.163) were observed for p-TSC2.

Representative images of the aforementioned signalling proteins are presented in Figure 7.8.

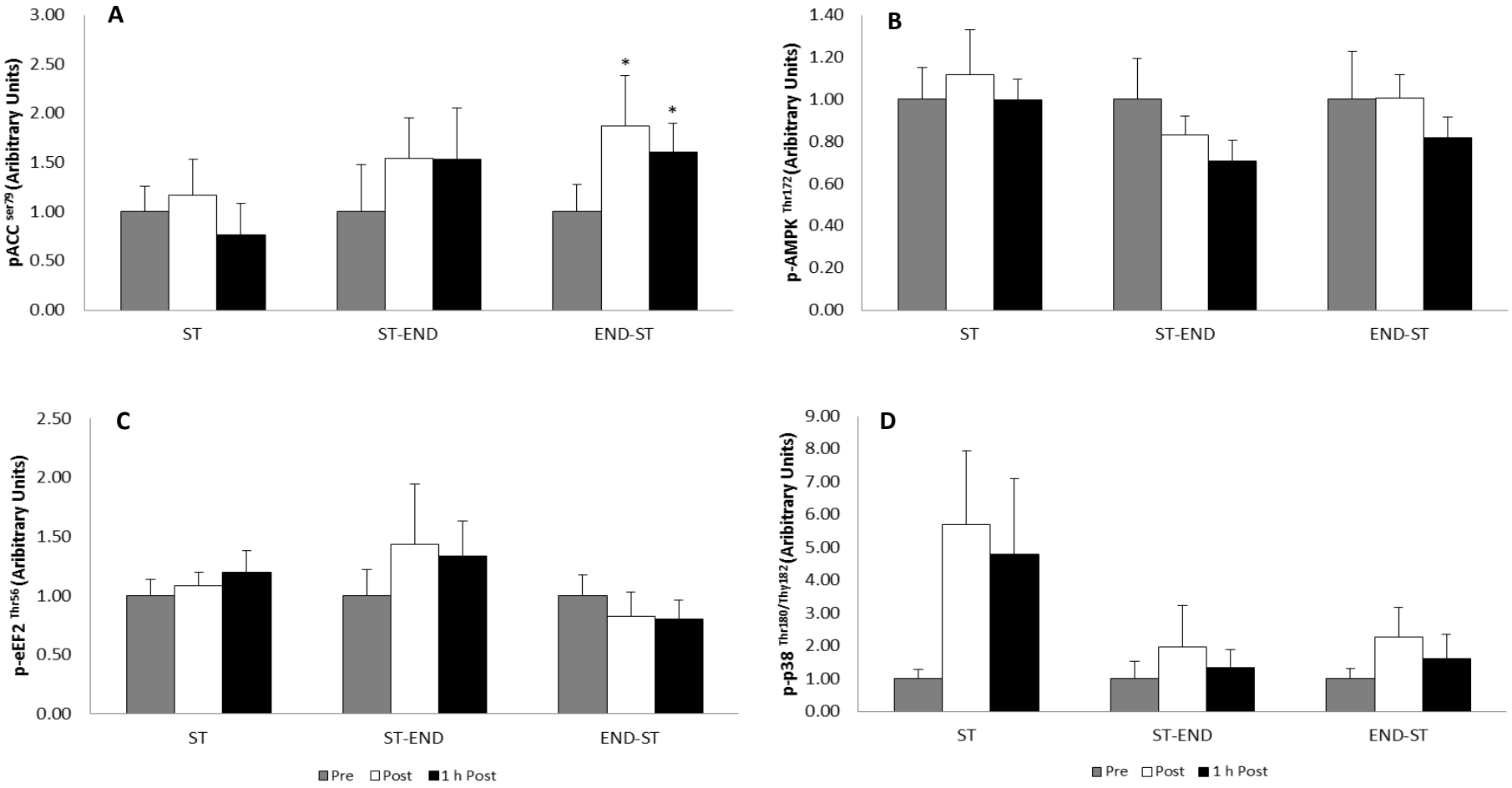

Figure 7.7. Mean responses of the AMPK signalling network in the ST (*n* = *6*), ST–END (*n* = *6*) and END–ST (*n* = *6*) conditions. ST, strength training alone; ST–END, strength training followed by endurance training; END–ST, endurance followed by strength training. (**A**) p-ACC, (**B**) p-AMPK, (**C**) p-eEF2 and (**D**) p-p38. * Significantly greater than pre ($p < 0.05$).

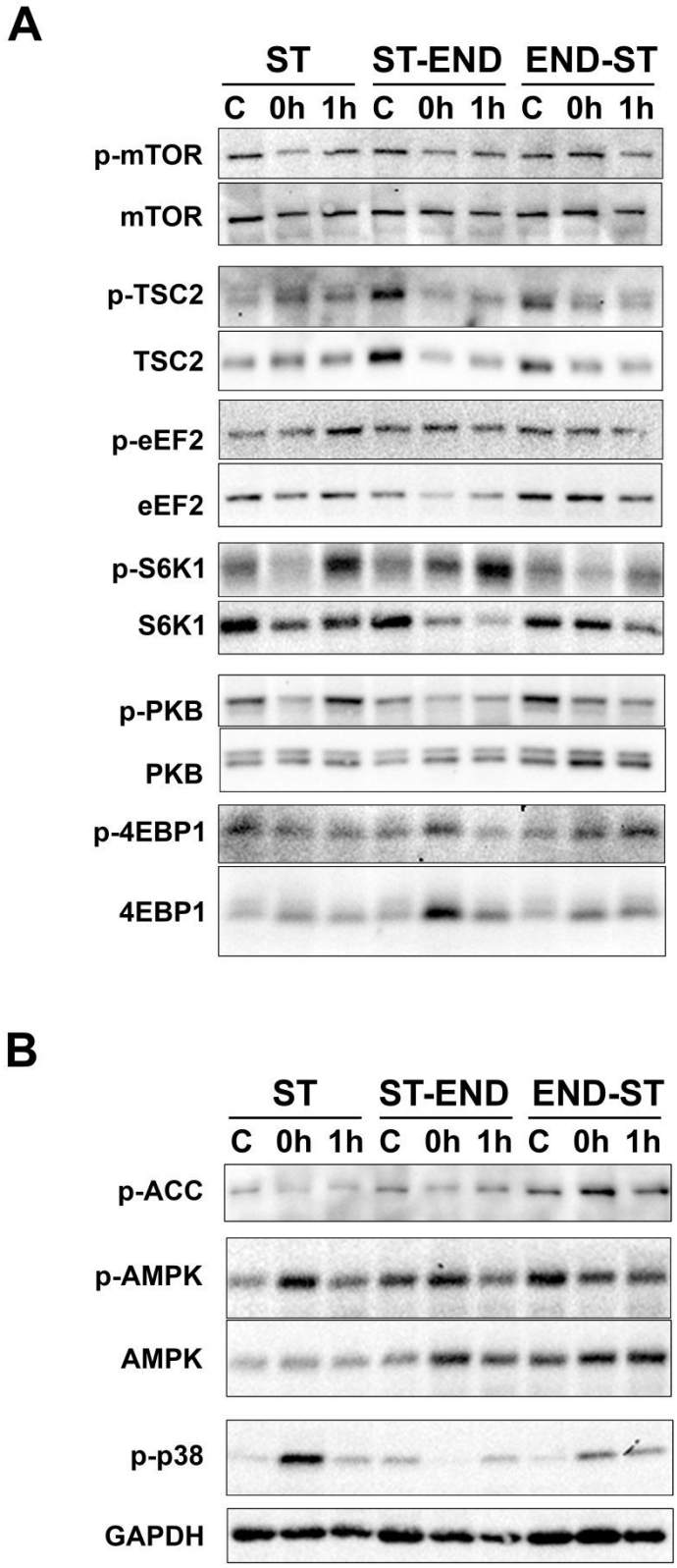

Figure 7.8. Representative images of signalling proteins analysed. (**A**) Representative images of mTOR, TSC2, eEF2, S6k1, PKB and 4E-BP1. (**B**) Representative images of ACC, AMPK p38 and GAPDH. C = pre, 0h = post and 1h = 1 h post.

7.4.3 Rate of perceived exertion

No significant differences in RPE were observed between groups ($F_{(2, 15)}$ = 0.258, p = 0.776).

7.5 Discussion

Increased protein synthesis following acute and chronic strength training is a key factor in the development of contractile strength and other fibre specific characteristics (Baar & Esser, 1999; Kraemer & Ratamess, 2005; Spiering *et al.*, 2008; Baar, 2009). In contrast, improved energy modulation and maintenance via activation of the AMPK signalling network is an important factor in endurance performance and adaptation (Hardie & Sakamoto, 2006; Hawley, 2009). Owing to the specific and divergent nature of these responses and adaptations it is perhaps unsurprising that research has indicated that antagonism and inhibition between these two pathways may occur (Nader & Esser, 2001; Inoki, Zhu & Guan, 2003; Baar, 2006; Nader, 2006; Baar, 2009).

The aim of this study was to examine whether combining acute bouts of strength and endurance training results in the inhibition of the growth associated mTOR network as a result of the activation of the AMPK energy modulating network. In addition, a secondary objective was to assess whether the order in which strength and endurance training are performed, influence the responses of the aforementioned signalling networks in a fed state.

The primary finding of the study was that protein synthesis, represented by p-S6k1 as a proxy of synthetic rate, similarly increased following strength training alone and strength followed by endurance training, with no such increases observed when strength training was performed subsequent to endurance training. These data

indicate that strength prior to endurance training may promote more similar growth associated signalling to strength training alone than *vice versa.* Moreover, it may also be suggested that conducting strength prior to endurance training may be more conducive to strength related adaptation than endurance prior to strength training. This suggestion is supported by research reporting correlations between training induced increases in p-S6k1 and subsequent hypertrophy in both rats (Baar & Esser, 1999) and humans (Terzis *et al.*, 2008).

In similar fashion to the findings of the present study, previous research has also reported elevations in p-S6k1 following both strength training in isolation and concurrent training (Coffey *et al.*, 2009a; Coffey *et al.*, 2009b; Camera *et al.*, 2010; Lundberg *et al.*, 2012; Fernandez-Gonzalo *et al.*, 2013). The similar increases in p-S6k1 following strength training and strength training closely followed by endurance training (Figure 7.6) are consistent with recent research (Apro *et al.*, 2013). Additionally, Coffey *et al.* (2009a) also reported up-regulation of S6k1 activity following strength training, however no such increases were observed when strength training was performed following a bout of high intensity interval training. It was suggested that strength training performed after repeated sprints was undertaken in the presence of greater metabolic acidosis (confirmed by greater elevated blood lactate concentrations) when compared with the initial exercise bout, which contributed to the attenuated increase in S6k1. This hypothesis is supported by research demonstrating associations between metabolic acidosis and protein degradation in both rodents and humans (Kleger *et al.*, 2001; Caso *et al.*, 2004). Although blood lactate concentrations and metabolic acidosis were not assessed in the present study, it may be speculated that the similar lack of elevation in p-S6k1 in the END-ST group may be attributed to strength training being performed under

greater metabolic acidosis. However, comparisons between the present study and that of Coffey *et al.* (2009a) may be difficult, as the authors employed 10 x 6 s maximal sprint efforts on a cycle ergometer, in contrast to the submaximal intensity of 70% p$\dot{V}O_{2pmax}$ for 30 min utilised in this chapter. In contrast to the findings of the present study, Lundberg *et al.* (2012) reported that conducting endurance training prior to a bout of strength training resulted in augmented anabolic signalling activity (represented by p-S6k1) when compared with strength training alone. These conflicting findings are most likely attributable to the variances in experimental protocols employed between studies. In the present study, the individual strength and endurance sessions were conducted with minimal time between the respective training protocols, whereas, Lundberg *et al.* (2012) allowed 6 h recovery between strength and endurance training. These data elude to residual fatigue due to close proximity of strength and endurance training resulting in impaired anabolic signalling associated with concurrent training, and may explain why the present study and other studies involving short time periods between strength and endurance training (Coffey *et al.*, 2009a; Coffey *et al.*, 2009b) observed attuenated anabolic signalling. Additionally, research has demonstrated that the inhibition of strength development within a concurrent regimen may be avoided if sufficient recovery periods (6 – 8 h) are allowed between strength and endurance training (García-Pallarés & Izquierdo, 2011). These findings have implications for programming, as it appears that endurance and strength type training should be isolated from each other, to ensure adequate recovery time is considered within periodized training plans.

Unlike much other research investigating signalling proteins in response to concurrent strength and endurance training (Coffey *et al.*, 2009a; Coffey *et al.*, 2009b; Camera *et al.*, 2010), the present experimental protocol was conducted

following a standardised feeding strategy. This was designed to replicate conditions in which strength training would typically be conducted, as there is little value in performing strength training in a fasted state (Hawley, 2009; Rønnestad, Hansen & Raastad, 2011) and low glycogen content has been shown to blunt signalling responses consequent to strength training (Creer *et al.*, 2005). However, during the experimental period no nutritional intake (other than water) was permitted. It is possible that this may have resulted in glycogen depletion following the initial bout of endurance training in the END-ST condition, which may be reflected in the responses of the AMPK network. Glycogen depletion is a prominent precursor phosphorylation of the AMPK network (Steinberg *et al.*, 2006), which only increased (as indicated by p-ACC) 1 h post exercise, as a result of endurance prior strength training. As previously stated, contrasting findings to the present study have been reported by Lundberg *et al.* (2012), who observed p-S6k1 to be greater when strength training was conducted following endurance exercise than strength training alone. Not only did the authors allocate a 6 h interval between endurance and strength training, but also provided participants with a meal (containing; 2.02 g CHO·kg^{-1} bw, 0.62 g protein ·kg^{-1} bw and 0.49 fat·kg^{-1} bw) and a commercially available energy drink following endurance exercise/prior to the strength training protocol. This resulted in glycogen levels being similar between trials involving endurance prior to strength training and strength training in isolation, and may account for the augmenting effect of prior cycling exercise on the anabolic responses to strength training, as opposed to an inhibitory effect observed in the present study. Combined, these findings indicate that if strength training is to be performed subsequent to endurance training on the same day, or within the same session, a feeding strategy between exercise bouts may prevent glycogen depletion and

“unfavourable” signalling responses for strength training related adaptation, like those observed in the present study.

Strength training performance in the present study was similar between conditions (Figure 7.5), and demonstrates that a preceding bout of endurance training had no effect on participant’s ability to maintain the required training intensity. This is contrary to data presented in Chapter 6 of this thesis and much previous research which has indicated strength training quality and quantity is decremented when performed after endurance training (Craig *et al.*, 1991; Leveritt & Abernethy, 1999; Sporer & Wenger, 2003; García-Pallarés *et al.*, 2009; García-Pallarés & Izquierdo, 2011). This may indicate the endurance training protocol employed in the present study was of insufficient volume and intensity to induce any noteworthy fatigue and impair subsequent strength training performance. This suggestion is partly supported by the fact that of the 6 signalling proteins associated with endurance exercise analysed only p-ACC (a marker of activation of the AMPK network) increased as a result of the experimental protocol. A similar protocol was employed by Coffey *et al.* (2009b) (30 min cycling at a power output that elicited ~70% of $\dot{V}O_{2peak}$). Whilst these authors did not report strength training performance it was reported that p-AMPK did not significantly increase from base at any point of the experimental protocol (strength then endurance training or *vice versa*). These data may suggest that those seeking to further investigate the molecular adaptations to strength and endurance training should employ an endurance protocol that does not consist of 30 min cycling at ~70% $\dot{V}O_{2peak}$/p$\dot{V}O_{2max}$, as limited phosphorylation of the relevant analysed signalling protocols occur following this protocol. The similar ability to maintain the required training intensity between conditions may also account for the similar responses of the molecular pathways associated with strength training

adaptation. This however was not assessed in the present study and as a result remains speculative. There is also some evidence to suggest that individual strength and endurance training results in a similar time course response of the mTOR network within 1 h of exercise (Camera *et al.*, 2010). It may also be reasonable to suggest that the similar phosphorylated mTOR, PKB and 4E-BP1 responses between conditions are due to the fact cycling as an exercise modality may stimulate increased phosphorylation of the aforementioned signalling proteins (Mascher *et al.*, 2011). This suggestion is also supported by evidence indicating cycling can be as effective as strength training alone in eliciting hypertrophy (Mikkola *et al.*, 2012), however unlike the present study both Mascher *et al.* (2011) and Mikkola *et al.* (2012) utilised untrained participants. Additionally, it is reasonable to suggest that the resistance and cadence of the employed cycling protocol may influence the signalling responses to this exercise modality. Research has indicated, that whilst untrained individuals display more general signalling responses to exercise training, trained individuals display more "refined" signalling responses (Fernandez-Gonzalo, Lundberg & Tesch, 2013). This was demonstrated by the failure of strength training to elicit any transcriptional activity of genes involved with endurance type adaptation in training accustomed individuals, whereas in untrained participants signalling of peroxisome proliferator-activated receptor gamma, co activator 1 alpha (PGC-1α; associated with mitochondrial biogenesis) was similar following both strength and endurance training. These data have implications for research design, as it appears untrained individuals respond similarly to divergent exercise stimuli, those more accustomed to training should perhaps be employed in studies investigating the effects of diverse contractile activity on anabolic signalling.

The findings of this chapter contribute to the understanding of how manipulation of simple programme variables may influence strength related adaptation in a concurrent training paradigm; an overarching aim of this thesis. In addition, the data presented further elucidate the role of impaired anabolic signalling as a contributing mechanism behind the interference phenomenon. Moreover, this study is the first to investigate the molecular responses to acute diverse contractile activity in a fed state. ST and ST-END were the only conditions to elicit increases in protein synthesis as indicated by p-S6k1 and these similar increases are consistent with recent research (Apró *et al.*, 2013). Moreover, END-ST was the only condition to elicit any increases in the activity of the AMPK network, which is thought to respond to exercise stress and is responsible for energy modulation. As strength training performance was similar between trials it may be speculated that the decremented rate of protein synthesis following END-ST due to strength training being performed in the presence of greater metabolic acidosis (Coffey *et al.*, 2009a). If the protein synthesis signalling in response to strength training is continually decremented (as following END-ST), it is reasonable to suggest that over time strength and hypertrophic development would be attenuated as a result of performing strength training subsequent to endurance exercise. As such, data presented in this chapter indicate that if strength and hypertrophic development are the priorities within a concurrent training regimen, strength should be performed prior to endurance training and not *vice versa*.

7.6 Practical applications

Appropriate scheduling of training may allow for simultaneous development of differing performance phenotypes, whilst poor and inappropriate programming

may result in compromised adaptation to the prescribed training stimulus. The data presented in this study indicate that if strength training adaptation is the primary aim of a concurrent training intervention, strength training should precede endurance training and not *vice versa*. If however, strength training must be performed subsequent to a bout of endurance training, previous research has indicated that training should be scheduled with a ~6 h interval between sessions (Fernandez-Gonzalo, Lundberg & Tesch, 2013; García-Pallarés *et al.*, 2009). Furthermore, it may be suggested that nutrition should be provided in-between sessions, to ensure the subsequent strength session does not take place in the presence of glycogen depletion, which research has demonstrated can impair the anabolic responses to strength training (Fernandez-Gonzalo, Lundberg & Tesch, 2013; Hawley, 2009; Rønnestad, Hansen & Raastad, 2011).

The endurance training protocol employed in the present study only resulted in increased phosphorylation of 1 of the 6 signalling proteins associated with endurance exercise analysed. Moreover, previous research has also demonstrated a comparable protocol did not result in any increases in p-AMPK nor TSC2. These findings indicate those seeking to further investigate the molecular adaptations to concurrent strength and endurance training should employ an endurance protocol that does not consist of 30 min cycling at p$\dot{V}O_{2max}$, as it cannot be accurately determined whether the AMPK/TSC2 axis influences the mTOR network if phosphorylation of the energy modulating proteins is not increased.

Training status appears to influence the signalling responses to differing exercise stimuli, and research has indicated strength and endurance training may promote similar signalling responses in untrained individuals. In contrast, trained individuals appear to respond more specifically to divergent exercise stimuli. Based

on these findings, studies investigating the effects of contrasting exercise stimulus and their effects on signalling and gene expression should utilise participants who are accustomed to exercise, to ensure the responses within the muscle milieu are truly representative of the exercise stimuli.

8. General discussion

8.1 Aims and objectives of this thesis

The aim of this thesis was to examine and elucidate the underlying mechanisms that have been suggested to attenuate strength, power and hypertrophic responses following concurrent strength and endurance training strategies; known as "the interference phenomenon" (Hickson, 1980). The five sequential yet individual studies conducted in this line of research also sought to examine the effects of manipulating specific concurrent training protocols on strength and muscular growth-related phenotypes. It was hoped that the evidence gained from these research studies would serve to better understand the role of concurrent training in athletic development and physical performance; the research also sought to provide valuable information applicable to practitioners seeking to optimise concurrent training paradigms.

8.2 Chapter reviews

8.2.1 Chapter 4

Research conducted here examined the effects of manipulating the ratio of strength and endurance training performed within a concurrent regimen on strength development and morphological adaptations associated with strength training. Moreover, this study was designed to determine whether the ratio of strength and endurance training influenced the presence and magnitude of any interference experienced. In addition, the study sought to investigate the role of neuromuscular adaptations in the interference phenomenon. As previously stated, this study was conducted in an isolated limb model and all strength and endurance training consisted of leg extensions of the dominant limb for differing durations and at contrasting training intensities.

The primary finding was that the magnitude of interference in strength development experienced as a result of combining strength and endurance training was dependant on the frequency and volume of endurance training performed. As increases in the girth of the trained limb were attenuated consequent to concurrent training, and neuromuscular adaptations were similar between conditions, it was postulated that the inhibition was due to lack of structural adaptation.

8.2.2 Chapter 5

The attenuated strength development as a result of higher volumes of concurrent training reported in the previous chapter was not attributable to neuromuscular factors. Therefore, it was hypothesised that inhibited strength development may have been due to increased overall training stress. It was also thought that this physiological stress may be reflected in the anabolic and catabolic responses of the endocrine system, which have previously been demonstrated to influence strength development in a concurrent training programme. The aims of this study were to determine in the findings of the previous chapter could be replicated when following a functional, whole-body, multi joint training intervention. Additionally, the study sought to examine if endocrine anabolic and catabolic responses may contribute to any interference experienced.

It was confirmed that frequency of endurance exercise in a whole-body concurrent training regimen is a key predictor of the magnitude of interference in the development of strength-related physical qualities. However, this only seems to be the case in the muscle groups which directly experience the contractile stimulus of both strength and endurance training (e.g. back squats and running). This suggestion is supported by the fact that whilst lower body strength (as assessed by back squat

and deadlift 1RM) was inhibited by higher frequencies of endurance training, upper body maximal strength (as assessed by bench press, bent over row and military press 1RM) improved similarly following concurrent and strength training alone. Unlike maximal strength, explosive strength development (as assessed by maximal countermovement jump height) was inhibited by endurance training of both high and low frequencies, indicating explosive strength phenotypes may be more susceptible to interference than maximal strength indices. As the current condition with highest overall training frequency (strength 3 $d \cdot wk^{-1}$ and endurance 3 $d \cdot wk^{-1}$) was the only condition to result in elevated cortisol levels following the training intervention, it is possible that the concurrent training-induced attenuation of maximal and explosive lower body strength was due to elevated overall training stress.

8.2.3 Chapter 6

Whilst the findings of Chapter 5 indicated that endocrine factors may influence strength development within a concurrent training programme, the effects of intra session sequencing of strength and endurance training on the responses of testosterone and cortisol are currently not fully understood. Therefore the purposes of this study were to examine the effects of differing sequencing of strength and endurance training in close proximity on strength training performance, testosterone, and cortisol.

Testosterone and testosterone:cortisol ratio were not differently affected by strength training alone, strength training immediately followed by endurance training (ST-END) or *vice versa* (END-ST). However, cortisol and blood lactate concentrations (Lac^-) were both greater immediately following END-ST than ST-END. The greater cortisol increases may indicate elevated catabolism following

training, which over time may contribute to attenuated strength and hypertrophic development. The fact Lac^- were greater when strength training was conducted following 30 min of steady state running may indicate a diminished rate of protein synthesis as a result of increased metabolic acidosis. This however remains speculative as no markers of protein synthesis were assessed in this chapter. Strength training performance was similar between strength training alone and ST-END whereas participant's ability to maintain the required training intensity was decreased as a result of prior endurance training.

The data presented in this chapter may suggest that strength prior to endurance training is more similar to that of strength training alone than *vice versa*, thus be more favourable for strength type adaptations.

8.2.4 Chapter 7

As it appears that strength prior to endurance training in close proximity elicits more "optimal" endocrine responses for strength related adaptation than *vice versa*, there is also value in examining the influence of intra session sequencing on molecular signalling factors associated with both strength type adaptation and interference.

Following training, data indicate that protein synthesis (interpreted by the up-regulation of phosphorylated (p-) 70-kDa S6 protein kinase (p-S6k1); a proxy of protein synthetic activity) increased following strength training alone and ST-END but not END-ST. Activation of the adenosine monophosphate activated protein kinase (AMPK) signalling network responsible for energy modulation and conservation (as indicated p-acetyl-CoA carboxylase (ACC) was only increased when endurance training was conducted prior to strength training. Although

differences between groups were not statistically significant, increased activation of the mTOR network following ST and ST-END and increased activation of the AMPK network following END-ST may allow one to speculate that ST-END promotes a more favourable environment for protein synthesis and anabolism than END-ST.

Like the findings of the previous chapter, the data presented in Chapter 7 also indicate that strength prior to endurance training is more similar to that of strength training alone than *vice versa.* It may therefore also be argued that this sequencing protocol is more favourable for strength type adaptations within the concurrent training paradigm.

8.3 General discussion

8.3.1 Programme variables

The research conducted as part of thesis modified fundamental programme variables central to the planning and programming of any training strategy; including frequency, exercise modality, and sequencing of exercise(s). Despite extensive research into concurrent training and the interference phenomenon, comparatively few studies have examined how manipulation of these variables may affect the presence or magnitude of strength, power and hypertrophic interference experienced in a concurrent training regimen.

8.3.1.1 Frequency of exercise

The findings of both Chapters 4 and 5 indicate an endurance training frequency of ≥ 3 $d \cdot wk^{-1}$ typically elicits inhibition of maximal strength development in a current training regimen (Figures 4.1 and 5.6). In contrast, lower frequencies of

concurrent training (CT3; 3 strength and 1 endurance session(s) $\cdot wk^{-1}$) may allow simultaneous training to be performed without any inhibition of maximal strength development (also illustrated in Figures 4.1 and 5.6). These findings are consistent with previous published work which has indicated interference may only occur when training frequency remains high ($\geq$ 3 $d \cdot wk^{-1}$) (Craig *et al.*, 1991; Hennessy & Watson, 1994; Kraemer *et al.*, 1995). Others who have reported no inhibition of strength development employed comparably lower training frequencies (Sale *et al.*, 1990; Abernethy & Quigley, 1993; McCarthy *et al.*, 1995).

As it appears that higher training frequencies in a concurrent regimen result in interference and lower frequencies potentially do not, it is perhaps likely that interference is related to the physiological 'stress' of training. This was reflected in the findings of Chapter 5 where CT1 (3 strength and 3 endurance sessions $\cdot wk^{-1}$) was the only condition to elicit significant elevations in resting cortisol levels following a 6 week training intervention (Table 5.5). This was also coupled with inhibited lower body maximal strength development (refer to Figure 5.8). Furthermore in the final 2 weeks of the 6 week training intervention, RPE was significantly greater in CT1 than ST alone; indicating greater perception of effort as a result of higher volumes of concurrent training. This elevated cortisol coupled with attenuated strength development following a concurrent but not a traditional strength training programme is consistent with previous research (Kraemer *et al.*, 1995; Bell *et al.*, 2000).

The inhibition of maximal strength development following 6 weeks of 3 $d \cdot wk^{-1}$ of unilateral leg extensions (at differing intensities and durations depending on the required stimulus; full details are presented in Chapter 4) cannot be fully attributed to training stress-induced fatigue, as post training intervention

neuromuscular activation (as assessed by electromyography (EMG)) during maximal contractions were similar between both concurrent (CT1 and CT3) and strength training conditions (Figure 4.5). However, the morphological development of the trained limb (as assessed by limb girth) was inhibited where higher frequencies (3 $d \cdot wk^{-1}$) of endurance training were employed. These data suggest that the inhibition of maximal strength development observed in Chapter 4 as a result of an increased frequency of endurance training was most likely due to impaired structural adaptation and not elevated training stress or fatigue. Conversely, in Chapter 5 changes in lean mass were similar between all conditions (which were the same as employed in Chapter 4) yet both cortisol and RPE were greatest in the concurrent condition with the highest endurance training frequency (CT1). In this case it seems extremely likely that the inhibition of maximal strength development can be attributed to increased training stress and associated fatigue mechanisms.

The differing factors contributing to interference observed in Chapters 4 and 5 may be attributable to the differing training modalities employed. The training modality for both strength and endurance training in Chapter 4 consisted solely of unilateral leg extensions of the dominant limb. In contrast, Chapter 5 involved a multi joint strength training programme which required numerous compound exercises which stimulated large muscle masses and treadmill running as the endurance training protocol. Due to the contrasting nature of the respective training interventions it is very likely that the training protocol employed in Chapter 5 was a far more potent metabolic stressor than that employed in Chapter 4. It may therefore be concluded that the variance in mechanisms behind the observed interference (Chapter 4; morphological and Chapter 5; physiological stress) were due to variances in the nature of the prescribed interventions.

Unlike maximal strength development it appears the inhibition of explosive strength development is not dependant on the frequency of endurance training performed. The is illustrated by data presented in Chapter 5, as performing concurrent training with both high and low frequencies of endurance training (CT1 and CT3) resulted in attenuated development of lower body power (Figure 5.10). As neither concurrent condition resulted in any noteworthy improvements in countermovement jump height (CMJ) it may be suggested that the inhibition of explosive strength development may occur even when concurrent training programme involve low volumes of endurance training. This hypothesis is supported by previous research indicating that 'explosive strength' phenotypes may be more susceptible to interference than 'maximal strength' indices (Dudley & Djamil, 1985; Hunter, Demment & Miller, 1987; Nelson *et al.*, 1990; Craig *et al.*, 1991; Abernethy & Quigley, 1993; Häkkinen *et al.*, 2003).

8.3.1.2 Sequence of exercise

Practitioners supporting athletes competing in sports and events which require concurrent development of both strength and endurance capabilities face various challenges whilst programming. Appropriate scheduling of strength and endurance training may elicit the concomitant development of contrasting performance phenotypes, whereas poor programming may result in attenuated adaptation to the prescribed training stimulus. There is presently limited published data pertaining to the order in which strength and endurance training are performed and how this may subsequently influence strength type adaptations. As such, it presently remains unclear if the training order can influence strength development within a concurrent training regimen.

Data presented in Chapter 6 indicates that conducting strength training immediately following endurance training results in decreased strength performance (Figure 6.2), which is consistent with previous research (Leveritt & Abernethy, 1999; Sporer & Wenger, 2003; García-Pallarés *et al.*, 2009). This impaired strength performance during training would not result in impaired strength adaptation following an acute and isolated bout of concurrent training. However, it is reasonable to suggest that if performance during strength training is repeatedly impaired as a result of prior endurance training the magnitude of strength development would be lesser than if strength training were performed in isolation. In contrast participant's ability to maintain the strength training intensity prescribed in Chapter 7 was similar in all conditions regardless of the addition of endurance training or training sequence (Figure 7.5). This discrepancy in findings may be attributable to the respective strength training protocols employed in the separate studies. Although the intensity and set/rep schemes were similar there were marked differences in the exercises employed. The experimental exercise protocol utilised in Chapter 7 involved seated leg press and seated leg extensions, whereas the prescribed strength training session of Chapter 6 involved back squats, bench presses, bent over rows, deadlifts and military presses. The strength session employed in Chapter 6 (described above) required an increased contribution from both the upper and lower body musculature than seated leg presses and extensions in isolation. Furthermore, the multi joint strength session (Chapter 6) involved a notably greater metabolic workload than the strength session of Chapter 7. It is reasonable, to suggest that the more physically demanding multi joint session was more susceptible to fatigue induced decremented strength performance than the session involving only 2 lower body strength exercises.

The findings of both Chapters 6 and 7 indicate that performing strength training prior to endurance training in close proximity has increased commonality to the stimulus of strength training alone than strength-type exercise following endurance training. This is reflected in both the cortisol and p-S6K1 (a cell signalling marker of protein synthesis) responses to the respective experimental conditions of ST, ST-END and END-ST (Figures 6.4 and 7.5). Furthermore neither ST nor ST-END training strategies resulted in any significant phosphorylation of the AMPK network, whereas END-ST resulted in significant up-regulation of p-ACC (a marker of AMPK activity) post and 1 h post exercise (Figure 7.7). Although the existence of AMPK/TSC2 induced inhibition of protein remains unclear in humans, based on the findings presented here it may be suggested that performing exercises focusing specifically on strength development before endurance-type training promotes a more optimal environment for protein synthesis and strength related adaptations than *vice versa.*

The findings of Chapters 6 and 7 indicate that strength prior to endurance training in close proximity elicits more similar endocrine and molecular anabolic responses to those of strength training in isolation to performing strength subsequent to endurance training. Additionally, performance during strength training is greater when conducted before endurance training when compared with strength training following endurance exercise. Combined, these inferences suggest that if strength type adaptation is the priority of a concurrent training intervention strength exercises should precede endurance training, and wherever possible not be performed in close proximity to a prior bout of endurance exercise.

8.3.1.3 Modality of exercise

Physiological adaptations consequent to the selection of exercise modality was not directly assessed in this thesis; nevertheless it seems an important issue to address within the context of concurrent training and the current position stand of surrounding literature.

It has previously been suggested that interference may be body part specific, as the few studies which have employed upper body strength and endurance training reported no inhibited upper body strength gains (Abernethy & Quigley, 1993; Bell *et al.*, 1997). However, these studies employed arm cracking and rowing as the endurance training modality. Therefore, it is reasonable to suggest that the stimulus of the aforementioned modes of exercise are more similar to that of strength training than other endurance exercise modalities such as running. This may account for the non-inhibition of maximal strength development when rowing and arm cranking are employed as the endurance exercise protocol in a concurrent training intervention. Following a 6 week training intervention incorporating multi joint resistance training and treadmill running, lower body strength development was inhibited as a result of concurrent training (Chapter 5, Figure 5.8). In contrast, similar increases in upper body strength were observed in concurrent and strength training conditions (Figure 5.9). This indicates that for interference in maximal strength development to occur the assessed musculature must directly experience divergent contractile stimulus of both strength and endurance training. Treadmill running (the endurance protocol employed in Chapter 5) has been reported to involve a greater contribution from the lower limbs than the upper body musculature (Candau *et al.*, 1998). This may explain why lower body strength was inhibited as a result of concurrent training yet

upper body maximal strength development was similar between all training conditions.

The examination of the signalling pathways and their role concurrent training and the interference phenomenon requires muscle tissue collection from the mid-thigh. Therefore, it is imperative that the endurance exercise modality involves sufficient local contractile activity of the VL to elicit increased phosphorylation of the respective signalling networks. As such, previous research investigating the potential molecular mechanisms behind the interference phenomenon have used cycle ergometry as the endurance exercise stimulus (Coffey *et al.*, 2009a; Coffey *et al.*, 2009b; Camera *et al.*, 2010; Apró *et al.*, 2013). However, it appears cycling may not promote interference to the same extent as other lower limb dominant endurance training modalities such as running. This has been reflected in recent meta-analysis conducted by Wilson *et al.* (2011) who revealed current training with running, but not with cycling, resulted in significant inhibition of lower body strength and hypertrophy.

Data presented in Chapter 7 indicates strength prior to endurance training elicits similar increases in protein synthesis associated signalling (as indicated by p-ACC) to strength training performed in isolation, this is also consistent with recent research (Apró *et al.*, 2013). These data may be interpreted in two ways: Firstly, strength training followed by endurance training is similarly effective as strength training alone in increasing rates of protein synthesis, or secondly that cycling may stimulate the growth associated mTOR network to a similar extent as strength training. Based on previous research it appears the latter hypothesis may be more likely. Indeed, it has been demonstrated that the signalling pathways associated with strength training adaptation and protein synthesis can be similarly activated by

cycling and strength training (Coffey *et al.*, 2009a; Coffey *et al.*, 2009b; Camera *et al.*, 2010). In addition, cycling alone may stimulate increases in contractile strength of the trained limbs without any additional strength training in untrained individuals (Macaluso *et al.*, 2003; Mikkola *et al.*, 2012).

8.3.2 A proposed model for predicting maximal interference in strength development

A model has previously been proposed to illustrate how the manipulation of strength and endurance training intensity may predict the presence of any strength development interference (Figure 2.8) (Docherty & Sporer, 2000). As previously detailed, less than modest support from scientific literature is available for this model (a full critique is presented in section 2.5.4). Based on previous research and data presented in this thesis a new model is proposed to predict the inhibition of maximal strength development in a concurrent training regimen (Figure 8.1). Details of which are provided below;

- The findings of chapters 4, 5 and previous research demonstrates interference appears to occur when concurrent training frequency is ≥ 3 $d \cdot wk^{-1}$, yet may be avoided when concurrent training frequency equates to ≤ 2 $d \cdot wk^{-1}$.
- It appears interference may occur when running is employed as the endurance exercise modality but may be avoided when cycling is utilised.
- Data presented in this thesis indicates strength prior to endurance training in close proximity promotes anabolic responses more conductive to strength type adaptation than *vice versa*.

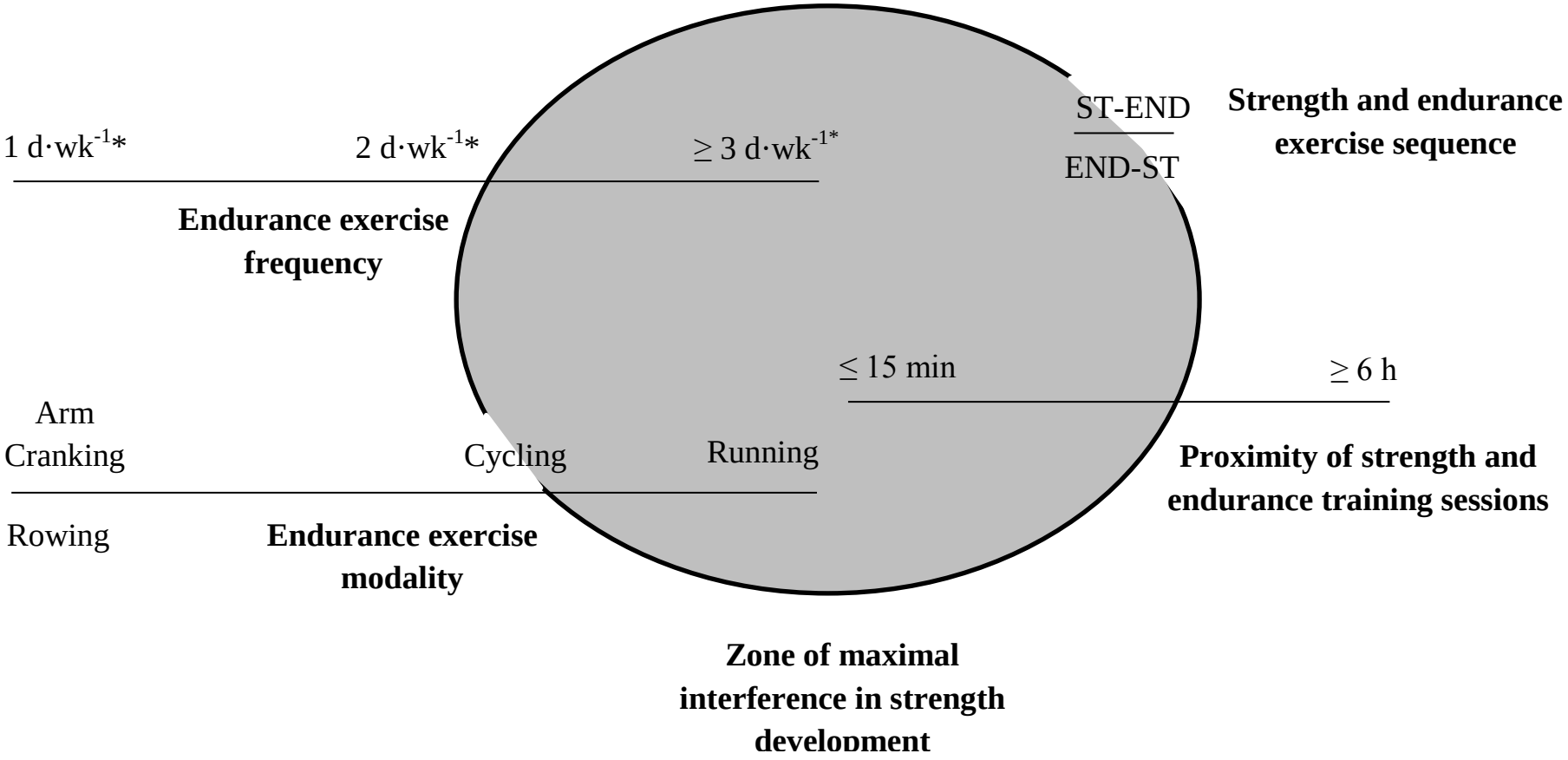

Figure 8.1. A proposed model for predicting maximal interference in strength development based on the previous published research and data presented in this thesis.1RM = 1 repetition maximum, * inhibition of explosive strength may also occur at these frequencies, ST-END = strength before endurance training and END-ST = endurance before strength training.

8.3.3 Mechanisms contributing to the interference phenomenon

As well as examining the manipulation of specific acute training programme variables in a concurrent regimen and their effects on strength-related adaptation, this thesis also sought to examine the underlying mechanisms behind the interference effect with the objective of gaining insight into the physiological factors contributing to the attenuated strength development associated with concurrent training.

8.3.3.1 Neuromuscular factors

Due to the specific demands placed on the neuromuscular system by strength and endurance training, it has been proposed that concurrent training may alter neural adaptations (particularly during contractions at high velocities) to strength training in isolation (Leveritt *et al.*, 1999). This is contrary to the findings of Chapter 4. Whilst 6 weeks of single limb concurrent training resulted in the inhibition of maximal strength development neural adaptations to strength and concurrent training of both high and low frequencies were similar (Figure 4.5).

The lack of evidence for differing neural adaptation to concurrent and strength training may in part be due to the nature of endurance training performed in the initial study of this thesis. This endurance training protocol consisted of 30 min of repeated unilateral leg extensions at 30% maximal voluntary contraction (MVC); an exercise strategy that was considered a valid representation of prolonged, steady state, work capacity type activity. Although the duration and intensity was different between conditions, the movement pattern was identical to that of the strength training protocol (unilateral leg extensions, 5 sets of 6 at 80% 1RM). Other studies which have reported neural inhibition as a result of concurrent training have employed endurance exercise modalities including cycling and walking (Häkkinen *et*

al., 2003; Cadore *et al.*, 2012c). As well as differing durations and intensities these exercise modalities involve different movement and contractile patterns to strength training modalities. As such it may be hypothesised that endurance training which places the neuromuscular system in the most enhanced state of conflict (i.e. contrasting movement patterns, durations and intensity) may promote greater neural inhibition as a result of concurrent training. This hypothesis is supported by data presented in Chapter 5 as improvements in CMJ were inhibited by concurrent training regimens with steady state running for 30 min at 70% v$\dot{V}O_{2max}$ (Figure 5.10). Although neural adaptations were not directly assessed via EMG, it is reasonable to suggest the in inhibition of lower body power was due to impaired neural adaptation. This suggestion is supported by research indicating performance in explosive movements require high neural contributions to rapidly develop force (Ono, Miyashita & Asami, 1976).

In summary, based on data presented within this thesis it appears that neural adaptations in a concurrent regimen are most inhibited when the endurance training modality differs in duration, intensity and contractile pattern to the strength training stimulus.

8.3.3.2 Endocrine factors

After 6 weeks of concurrent training involving multi joint strength training and treadmill running of high frequencies (strength and endurance training 3 d·wk^{-1}, CT1) resulted in the inhibition of maximal lower body strength development. In contrast, strength training and concurrent training of lower frequencies (strength 3 d·wk^{-1} and endurance 1 d·wk^{-1}, CT3) resulted in similar gains in maximal strength. Not only was CT1 the only condition to result in interference, but also the only

condition to elicit increases in basal cortisol levels following the intervention (Chapter 5). These data indicate the inhibition of maximal lower body strength was perhaps due to enhanced training stress as a result of a higher overall training volume. As changes (or lack thereof) in testosterone and T:C ratio were similar between training conditions it is unlikely that anabolism and tissue building responses were different between conditions. Furthermore, changes in lean mass in response to training were shown to be similar between conditions. Based on these observations it seems that changes in the endocrine environment were less mechanistic and more reflective of increased training stress that resulted in the inhibition of lower body maximal strength and power development.

There is an extensive body of research which has investigated both the endocrine responses to strength training and the influence of anabolic and catabolic hormones in training induced adaptations (Fry *et al.*, 1994; Gotshalk *et al.*, 1997; Kraemer *et al.*, 1998b; Kraemer *et al.*, 1999a; Kraemer *et al.*, 1999b; Kraemer *et al.*, 2008a; West & Phillips, 2012; Basualto-Alarcón *et al.*, 2013). Moreover, whilst there is limited research into the role of endocrine factors in interference, it has been reported that concurrent training can result in differing anabolic and catabolic responses to strength training alone (Kraemer *et al.*, 1995; Bell *et al.*, 1997; Bell *et al.*, 2000). This is consistent with the findings of Chapter 5 as the aforementioned studies all reported elevated cortisol following concurrent but not strength training. Unlike the findings of Chapter 5, Kraemer *et al.* (1995) reported a decrease in the testosterone:cortisol as a result of concurrent training. This variance in findings may be due to the longer training intervention employed by Kraemer *et al.* (1995) (12 weeks) and that of Chapter 5 (6 weeks). Furthermore, Kraemer *et al.* (1995) did not observe any changes in testosterone:cortisol until the eighth week of the 12 week

intervention. As such it is perhaps reasonable to speculate if the training intervention of Chapter 5 were longer, changes in basal cortisol would have been coupled with decreased testosterone:cortisol ratio. Due to the variance in findings and small number of studies it currently remains unclear if the interference effect occurs as a result of the endocrine environment shifting in favour of catabolism, or the variations in testosterone and cortisol in a concurrent training programme simply reflect overall training stress.

Like the endocrine responses reported in Chapter 5, neither testosterone nor T:C ratio were differently affected by the respective experimental conditions employed in Chapter 6 (ST, ST-END and END-ST). It was however observed that post training both cortisol and Lac^- were greater when endurance preceded strength training. This may be indicative of increased catabolism and metabolic acidosis both of which are unfavourable for strength related adaptation due to decremented rates of protein synthesis (Kleger *et al.*, 2001; Caso *et al.*, 2004). From another perspective elevated Lac^- following strength training has previously been associated with increased growth hormone (Kraemer *et al.*, 1990; Gotshalk *et al.*, 1997; Hoffman *et al.*, 2003; Kraemer & Ratamess, 2003b), an acute response which may promote anabolic signalling and strength related adaptation. This however was beyond the scope of research in this thesis.

As previously stated, the endocrine responses to concurrent training are not fully understood but data presented in this thesis indicates they may contribute to the overall interference paradigm, particularly in training protocols encompassing high volumes of both strength and endurance training. This is consistent with previous research indicating increased cortisol and lack of elevations in testosterone can contribute to impaired strength development within a concurrent regimen (Kraemer

et al., 1995). What remains largely unclear is the role that the endocrine system has in anabolic signalling in response to differing sequencing of strength and endurance training.

8.3.3.3 Signalling and molecular factors

The findings of Chapter 7 indicate that strength prior to endurance training results in protein synthesis responses of increased commonality to strength training alone than *vice versa* (Figure 7.6). Although it was not assessed in Chapter 7 it is perhaps reasonable to suggest that an increased build-up of inorganic phosphates contributed to the attenuated phosphorylation of S6K1 when endurance training was conducted prior to strength training. This was observed in the Lac^- responses to END-ST in Chapter 6 (Figure 6.5). Additionally, the sequencing of END-ST was the only condition to result in increased activation of the AMPK network (as assessed by p-ACC), which may have played a role in the attenuated protein synthesis response when compared with ST and ST-END conditions. There is however contrasting evidence that strength prior to endurance training elicits greater phosphorylation of AMPK 3 h post exercise, greater metabolic stress, and a "sub optimal" anabolic response to strength training (as assessed by insulin like growth factor-1 (IGF-1) mRNA signalling) (Coffey *et al.*, 2009b). This is perhaps a speculative conclusion made by the authors as although anabolic signalling was more favourable than a condition involving strength followed by endurance training no exclusive strength training only condition was included. As such it cannot be determined if the anabolic signalling following either condition was different or similar to strength training alone.

In contrast to the findings of the Chapter 7, it has been reported that conducting endurance training prior to strength training can result in greater anabolic signalling (represented by p-S6k1) than training alone (Lundberg *et al*., 2012). This however, was only observed when strength training was conducted follow a 6 h recovery period and a feeding strategy. These data make it reasonable to suggest that residual fatigue due to close proximity of strength and endurance training resulting in impaired anabolic signalling associated with concurrent training. This may also explain why the END-ST condition employed in Chapter 7 and other experimental protcols involving short intervals between strength and endurance training (Coffey *et al.*, 2009a; Coffey *et al.*, 2009b) resulted in attuenated reponses of the mTOR network (Figure 8.1). Additionally, as a feeding strategy (meal containing; 2.02 g CHO·kg^{-1} bw, 0.62 g protein ·kg^{-1} bw and 0.49 fat·kg^{-1} bw) between strength and endurance exercise resulted in greater anabolic signalling than strength training alone (Lundberg *et al*., 2012) it is possible that glycogen depletion may contribute to impaired anabolic signalling following concurrent training (Creer *et al.*, 2005).

The role of mTOR and AMPK cross talk in interference remains unclear as previous research has indicated no inhibitory effect of endurance training on protein metabolism (Coffey *et al.*, 2006; Wilkinson *et al.*, 2008; Camera *et al.*, 2010; Vissing *et al.*, 2011; Apró *et al.*, 2013). The AMPK network is thought to act as a "metabolic fuel gauge" which regulates energy maintenance during exercise (Nader, 2006; Baar, 2009). Within this role AMPK may switch off or inhibit energy consuming pathways (such as the AKT/mTOR axis) in response to exercise stress (Nader, 2006; Baar, 2009). As such it is logical that in response to elevated physical stress mTOR phosphorylation and subsequent protein synthesis may be supressed as a result of concurrent strength and endurance training. As previously stated

throughout, many researchers have failed to replicate this cross talk observed in murine models (Atherton *et al.*, 2005; Thomson, Fick & Gordon, 2008; Mounier *et al.*, 2011). This may be due to the fact many studies have employed cycling as the endurance training modality (Coffey *et al.*, 2009a; Camera *et al.*, 2010; Vissing *et al.*, 2011; Apró *et al.*, 2013) which in itself has been demonstrated to stimulate both AMPK and mTOR (Mascher *et al.*, 2011). It is clear that the role of anabolic signalling in interference warrants further investigation. Before this research is conducted the responses of the AMPK and mTOR network to various endurance exercise modalities must be further elucidated.

8.4 Practical applications

The findings of this thesis provide useful inferences for applied practitioners involved in sports and events in which concurrent strength and endurance training is necessary and require the development of maximal strength and power phenotypes. The two principle programme variables assessed within this thesis were: i) concurrent training frequency and ii) sequencing of strength and endurance training.

Higher frequencies of concurrent training resulted in the inhibition of maximal strength development, whereas lower frequencies did not. Furthermore, higher frequencies of concurrent training elicited elevated cortisol, which previous research has implicated as a marker of physiological stress (Kraemer & Ratamess, 2005). This may indicate that the inhibition of strength development associated with concurrent training may be attributable to elevated stress. This however only appears to be the case when the musculature in which maximal strength is assessed directly experiences strength and endurance stimuli. As such, those programming for strength in specific muscle groups should perhaps avoid endurance exercise modalities which

require high contributions from the musculature in which strength development is required. As previously stated within this thesis if strength development is the primary goal of a training programme endurance training frequency should be kept to a minimum. If maintenance of endurance type performance characteristics is also a priority high intensity interval training should be utilised. Although not assessed in this thesis previous research has indicated the stimulus of high intensity interval training is more similar to that of strength training than continuous endurance exercise and may not result in interference (Wong *et al.*, 2010). Moreover, if a concurrent training programme must be performed it is imperative that appropriate monitoring strategies are employed to ensure training stress doesn't become too great and result in the plateau of strength development. Interference in power development appears to occur following concurrent training of both high and lower frequencies. As such, if the development of power type performance characteristics are required then it appears that frequency and volume of endurance training should be minimized or omitted from the programme all together. The findings of the experimental chapters investigating training frequency and its role in interference suggest that interference may be dependent on the volume of endurance training performed with a concurrent regimen. This suggests interference may be avoided via appropriate programming and periodization strategies. Furthermore as the findings of Chapter 5 indicate interference may be due to elevated training stress the implementation of fatigue monitoring strategies may serve as an effective means of avoiding interference following a concurrent training regimen.

Owing issues such as limited access to facilities and demanding competition schedules, at times it is inevitable that both athletes and those training recreationally will perform strength and endurance training in close proximity. It is therefore

important that the order in which strength and endurance training are performed elicit physiological responses conducive to strength-type adaptation. Performing strength prior to endurance training can elicit similar endocrine (Chapter 6) and molecular (Chapter 7) responses to strength training performed in isolation. In contrast, strength training performed subsequent to endurance exercise can result in elevated cortisol (Chapter 6) and inhibited anabolic signalling (Chapter 7) when compared with strength training alone. In addition, performing strength following endurance training in close proximity was demonstrated to impair performance during strength training (Chapter 6). Combined, these finding demonstrated that if strength and endurance must be programmed in close proximity, strength prior to endurance training and not *vice versa* may result in physiological responses which are more favourable for maximal strength development. Although not assessed within this thesis previous research has also indicated the provision of a high CHO meal in between strength and endurance training can result in greater anabolic signalling than strength training conducted in isolation (Lundberg *et al.* 2012). Although somewhat speculative this may indicate that the provision of CHO between strength and endurance training may result in similar strength development with between those performing concurrent training and strength training alone.

8.5 Future research directions

Whilst the findings of this thesis contribute to the existing body of literature pertaining to concurrent training and the interference phenomenon, the underlying physiological mechanisms contributing to muted strength development are yet to be fully elucidated. Definitive conclusions regarding the underpinning mechanisms contributing to interference unfortunately cannot be drawn from the findings of this

thesis, as there remain inconsistencies in the responses of the neuroendocrine and anabolic signalling variables. Moreover, whilst data presented within this thesis provides useful inferences for applied practitioners, further research is warranted to determine the most effective means of avoiding interference in the development of maximal strength.

As previously stated, strength prior to endurance training appears to elicit comparable anabolic signalling to strength training alone, whereas strength following endurance training results in elevated cortisol and lack of elevations in growth associated signalling. These data, may allow one to speculate that concurrent training with strength performed prior to endurance exercise would not result in interference, whereas a longitudinal regimen involving strength subsequent to endurance exercise would result in attenuated strength development. This hypothesis warrants controlled scientific investigation involving 3 experimental conditions; strength training alone, strength followed by endurance training and endurance followed by strength training. It is imperative that a strength alone condition is included to determine if strength development in the concurrent conditions is comparable to strength training performed in isolation. Moreover, there is value in assessing the responses of endocrine and molecular factors which may contribute to interference following longitudinal concurrent regimens of differing sequences.

Presently the most actively researched aspect of concurrent training and interference is the potential inhibition of protein synthesis via endurance training induced activation of AMPK and TSC2. Whilst there is value in furthering the understanding of the influence of signalling on adaptations to training, it is apparent that further research is needed to determine the responses of the AMPK and mTOR signalling networks to differing endurance exercise modalities. This is illustrated by

research indicating cycling can elicit increased phosphorylation of both the AMPK and mTOR signalling networks (Camera *et al.*, 2010; Mascher *et al.*, 2011). If the endurance training modality stimulates increases in the pathway associated with strength training, any differences in growth associated signalling as a result of varying concurrent training protocol may remain undetected. In addition, previous research has indicated, that whilst untrained individuals display more general signalling responses to exercise training, trained individuals display more "refined" signalling responses (Fernandez-Gonzalo, Lundberg & Tesch, 2013). As it appears untrained individuals respond similarly to divergent exercise stimuli, those more accustomed to training should perhaps be employed in studies investigating the effects of diverse contractile activity on anabolic signalling.

8.6 Conclusions

Research conducted within this thesis has explored the influence of manipulating various programme variables within concurrent training protocols on the magnitude of strength development and physiological factors associated with strength-type adaptations. In addition, the underpinning neuroendocrine and molecular mechanisms which may contribute to the presence of the interference phenomenon were investigated. This research has indicated that the interference effect, first proposed by Hickson (1980) is not all encompassing, and strength development within a concurrent training regimen may be dependent on training frequency, sequence and the resultant physiological responses and adaptations.

One of the primary conclusions of this thesis is that the volume of endurance training in a concurrent regimen appears to be a key predictor of interference. When endurance training frequency is ≥ 3 $d \cdot wk^{-1}$ maximal strength development is

attenuated even in programmes of a relatively short duration (6 weeks). In an isolated limb model involving strength and endurance training which follow similar movement and contractile patterns (yet differ in duration and intensity) this inhibition may be due to lack of morphological adaptation. In a functional multi joint model in which strength and endurance training involve contrasting movement patterns and involve a greater metabolic demand the inhibition of strength development is attributable to increased overall training stress. These findings indicate that those who are training for the development of maximal strength phenotypes yet also require endurance capabilities, and/or the need for caloric energetics for body composition management, as a secondary performance characteristic should limit endurance training frequency to $\leq 2\ d \cdot wk^{-1}$ if strength development is to remain uninhibited.

Whilst overall training volume and frequency appear to influence maximal strength development, improvements in power may be inhibited following both low and high frequencies of concurrent training. This demonstrates that explosive strength development is more susceptible to interference than maximal strength, and is attenuated following even short duration and low frequency concurrent training (strength training $3\ d \cdot wk^{-1}$, endurance training $1\ d \cdot wk^{-1}$ for 6 weeks). These data have important implications for programming as it may be suggested that if the development of power and explosive strength capabilities are the primary goals of training then endurance type activity should be avoided all together. An effective strategy to avoid the endurance training induced attenuation of strength and power development may be appropriate planning and periodization of training.

If due to time and scheduling constraints strength and endurance training must be performed in close proximity, it seems that strength prior to endurance

training is more optimal for strength and hypertrophic adaptation than *vice versa*. This is indicated by greater cortisol elevations and lack of increases in growth associated signalling when strength is performed subsequent to endurance training. This may be attributable to a prior bout of endurance exercise resulting in the build-up of inorganic phosphates and activation of the energy modulating AMPK network. Combined, this may promote a "sub optimal" anabolic environment. In contrast when strength is conducted prior to endurance training both the endocrine and molecular responses to training are similar to that of strength training alone.

The research conducted as part of this thesis contributes to the extensive and ever growing body of research examining concurrent training and the interference phenomenon. It is clear that combining strength and endurance training within the same training regimen can result in inhibited strength development when compared with strength training alone. Furthermore, it is apparent that any inhibition is highly dependent on volume, frequency, sequencing, modality and nature of both strength and endurance training performed. It is also clear that manipulation of these variables influence neuroendocrine and molecular factors associated with strength-type adaptation and interference. To conclude, higher frequencies of concurrent training result the interference of strength development and elevations in the catabolic hormone cortisol. Additionally, performing strength subsequent to endurance training can result in impaired performance during strength training, elevated cortisol and absence of elevations in hypertrophic association signalling. In contrast, strength prior to endurance training can elicit similar endocrine and molecular responses to strength training in isolation.

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Appendices

INFORMED CONSENT FORM

Project Title:

Principal Investigator: Thomas W. Jones

Participant Number: _____

	please tick where applicable
I have read and understood the Participant Information Sheet.	☐
I have had an opportunity to ask questions and discuss this study and I have received satisfactory answers.	☐
I understand I am free to withdraw from the study at any time, without having to give a reason for withdrawing, and without prejudice.	☐
I agree to take part in this study.	☐
I would like to receive feedback on the overall results of the study at the email address given below. Email address……	☐

Signature of participant..... Date.....……..

(NAME IN BLOCK LETTERS).....…….

Signature of Parent / Guardian in the case of a minor

.....

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

(NAME IN BLOCK LETTERS).....…….

General Health Screen

Please read the following list carefully. You are not eligible to participate in the research if:

1. You have a history of neurological, vascular or psychiatric illness (excluding depressive illness and anxiety).
2. You do not have normal or corrected-to-normal vision.
3. You have a current diagnosis of depression and/or anxiety.
4. You have a history or current diagnosis of drug/alcohol abuse.
5. You suffer with any form of blood clotting disorder.
6. You have any form of blood born communicable disease.
7. You have a known intolerance to local anaesthetic.
8. You have a heart disorder.
9. You have high blood pressure.
10. You have any endocrine or metabolic disorder.
11. You have current or recent muscle or joint injuries.
12. You smoke.
13. You are currently taking any prescribed (excluding contraceptives) medication or herbal/food supplements.
14. You have taken herbal/food supplements for more than 2 consecutive days or 3 days in total in the past 30 days.

If you suffer or have ever suffered from any of the above conditions or any of the above applies to you unfortunately you will be ineligible to participate in the present study.

If you are unsure or wish to discuss any of these points with the researcher then you are welcome to do so.

Signature of participant: ……..

Signature of test supervisor: ……..

Date: ……

6 – 20 Rate of Perceived Exertion Scale

Rating	Desciption
6	No exertion at all
7	
8	Extremely Light
9	Very Light
10	
11	Light
12	
13	Somewhat hard
14	
15	Hard (Heavy)
16	
17	Very Hard
18	
19	Extremely Hard
20	Maximal Exertion