The Impact of Concurrent-training on the Physiological Adaptations to Sport Specific Exercise in Elite Footballers

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ABSTRACT

Elite football players are required to train multiple metabolic and physical parameters simultaneously. Due to the nature of the competition schedule and training time available players often perform sports-specific endurance-training and high-load, low repetition resistance-training on the same day (Hoff et al., 2006). Empirical evidence highlights that when two disparate forms of muscular contraction are trained within the same training cycle, adaptations in strength and power related variables can become blunted - a situation most commonly referred to as the 'interference phenomenon' (Hickson, 1980). Experimental data suggest the organisation of each training stimulus can modulate the training response and exacerbate the 'interference phenomenon'. However at present few data exist concerning how elite football teams currently organise their concurrent-training programmes. Furthermore to the authors' knowledge no practical guidelines exist as to minimise the interference phenomenon within the constraints of the applied football environment. Therefore, the aim of this thesis was to investigate the impact of training organisation on the acute and chronic responses to football-specific concurrent exercise programmes in elite football players.

Initially we conducted a pilot study (chapter 3) to observe the concurrent-training strategies currently in place at a professional football club. The study had two aims (1) to describe the training frequency and training load across the first 10 weeks of a competitive season and (2) to characterise the acute organisation of training and nutritional intake around concurrent-training. It was found that training frequency and volume was greatest during the initial three weeks of the observation. Following this training frequency and training load decreased significantly. Although, following the decrease in training load there were no between week

fluctuations in training load. Together, these results suggested that the reduced ‘pre-season period’ (i.e. 3 weeks) and the lack of fluctuation in training volume and intensity from weeks 4 to 10 may not be optimal for longer-term muscle performance (Fleck, 1999). The secondary findings from this study demonstrated that when concurrent-training was performed on the same day, the order of aerobic and resistance exercise, the nutritional availability and the recovery period between training sessions was unsystematic. It was thought that this approach to the organisation of concurrent-training may not have been optimal for longer term muscle adaptation. Collectively, this study showed that despite large investment in sports science departments and highly experienced coaches, the application of periodised and well-structured training is not always possible. The lack of systematic training and nutritional intake observed at this football club could have exacerbated the ‘interference phenomenon’ and subsequently been sub-optimal for longer term muscle adaptation and athlete performance.

The purpose of study 1 and 2 (chapters 5 & 6) was to investigate if the concurrent exercise protocols previously observed could modulate the ‘interference phenomenon’. In a series of studies we investigated the muscular adaptations following 5 weeks of strength-training performed either before or after football-specific endurance-training (‘S + E’ and ‘E + S’). It was found that improvements in strength and power related variables become blunted in the S + E training group. It was hypothesised that the between group differences could be explained by the differences in muscle architecture adaptation observed in the E + S training group. As both training groups completed similar training loads it was thought that the recovery period and nutrient timing associated with each training group could have either ‘enhanced’ or ‘blunted’ underlying adaptive mechanisms respectively.

Although the underpinning molecular or metabolic process responsible for the between group differences in architectural adaptation could not be concluded from this study.

Study 3 investigated the hormonal responses to two concurrent-training and nutritional scenarios previously observed at a professional football club. This investigation demonstrated that the sequence of concurrent-training, the recovery period between exercise bouts and the nutritional support provided before, between and after training could influence acute exercise induced hormonal secretion. Whilst the hormonal hypothesis for increasing muscle hypertrophy is questionable (West et al., 2009) the present data in combination with the previous training study suggest that exercise induced hormonal secretion may be involved in other metabolic processes which influence the geometry of the fascicule (i.e. muscle architecture).

This thesis has highlighted the need for research to investigate the effect of concurrent-training the applied exercise setting. The lack of studies to investigate the effects of concurrent-training in elite football players has limited our understanding of the physiological effects of concurrent-training in elite football players. Whilst this thesis highlighted that the organisation of the training and nutrition can influence the interference phenomenon, more work is required to confirm these findings. Specifically, our understanding of the effect of manipulating acute training variables on the physiological mechanisms responsible for the effectiveness of concurrent-training programmes require further study. The incorporation of a range of scientific techniques in a controlled setting could lead to a theoretical framework for understanding how to plan and deliver concurrent-training programmes in the applied setting so that the interference phenomenon is minimised.

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LIST OF ABBREVIATIONS

Akt-mTOR-S6K; Akt/protein kinase B-mammalian target of rapamycin-p70 S6 kinase

AMPK; AMP-activated protein kinase

AMPK-PGC-1 α; adenosine monophosphate-activated kinase-peroxisome proliferator activated receptor gamma coactivator-1

ANOVA; Analysis of variance,

ASCC; Accredited Strength-and-Conditioning Coach

AT; anaerobic threshold

AU; Arbitrary unit

BLa;, Blood lactate

BPM; Beats per minute

C; Cortisol

Ca2+; Calcium

CMJ; Countermovement jump

CMJ-WO; Countermovement jump without arm swing

CON; Concentric

Cort; Cotisol

CV; Coefficient of variation

DOMS; delayed onset of muscle soreness

ECC; Eccentric

EMG; Electromyographic

F; Female

GH; Growth Hormone

GPS; Global positioning systems

HR; Heart rate

HRmax; Maximal heart rate

IMVC; Isometric Maximal voluntary contraction

IMVC-LR; Isometric Maximal voluntary contraction loading rate

ℓF; Vastus lateralis fascicule length

LoA; Limits of agreement

M; Male

MAP; maximal aerobic power

MAPK; mitogen-activated protein kinase;

MT; Muscle thickness

MVC; Maximal voluntary contraction

PGC-1α; peroxisome proliferator-activated receptor γ coactivator-1α

PK; Pyruvate kinase; PDK-4, pyruvate dehydrogenase-4

RM; Repetition maximum

RPE; Rating of perceived exertion

RPE-TL; Rating of perceived exertion training-load

RT; Resistance-training

SJ; Squat jump

SSG; Small sided games

T; Testosterone

T; Trained

TL; Training-load

UKSCA; United Kingdom Strength-and-Conditioning Association

UT; Untrained

VL θ; Vastus lateralis fascicule angle of penneation

VL; Volume Load

$\dot{V}O_2$ max; Maximal oxygen uptake

Yo-Yo IR2; Yo-Yo intermittent recovery test level 2

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CHAPTER ONE

GENERAL INTRODUCTION

1.0 INTRODUCTION

'Association football' more commonly referred to as 'soccer' or 'football' is a multi-facet sport characterised by physical, psychological, tactical and technical components. In order to be proficient at the highest level players require an advanced ability in a number of sport-specific skills (e.g. dribbling, passing and shooting) (Stolen *et al*., 2005). Elite players also require a high aerobic capacity and the ability to repeatedly perform explosive activities and movements (e.g. high-speed running, sprinting, jumping and tackling) (Bangsbo *et al*., 2006). In this regard, it is important that training interventions used by elite football teams are designed to affect a variety of key outcomes critical to match-play performance (Reilly, 2005).

Periodisation offers a framework for planned and systematic variation of training parameters, in a way that promotes physical performance at pre-agreed phases of the season (Fleck, 1999). Traditional models of periodisation stipulate that the season is divided into discrete segments, each with a specific training objective and that the training stress is progressed in a way that promotes recovery and adaptation (Bompa, 2009). Although, due to the nature of team sports, this training methodology is not always viable. The relatively short pre-season (6-8 Weeks) and the congested playing schedule (43 fixtures across 40 consecutive weeks) means that players may only have 3-4 days in between competitive matches, of which the emphasis is on recovery. This reduced training time restricts coaches' ability to periodise various aspects of physical conditioning throughout the season (Buchheit and Laursen, 2013). As a result, it is common for football players to train multiple physiological systems on the same day and within close proximity of each other (e.g. aerobic capacity and muscle strength) (Hoff and Helgerud, 2004a). This training arrangement is more commonly referred to as 'concurrent-training', and aims to achieve improvements in contrasting physiological goals at the same time.

There is evidence to suggest that when aerobic and strength-training are performed simultaneously muscle strength and power capacity is compromised (for review see; Wilson *et al*., 2012). This 'blunted' response in strength-related adaptation has been referred to as the 'interference phenomenon' (Hickson, 1980, Hickson *et al*., 1980). Across the past three decades scientists have attempted to explain the interference phenomenon via a number of mechanisms. These explanations can be broadly grouped into two hypothesis; (1) interference is caused by acute peripheral fatigue and in the inability to effectively train at appropriate intensities to achieve the desired outcome and (2) interference is a consequence of molecular and (or) biological events blocking strength-related adaptation (i.e. chronic interference). Importantly, both of these categories are influenced by the way in which the training stimulus is organised. Therefore, understanding the way in which concurrent-training programmes are delivered in the 'applied environment' may be important for football teams who aim to minimise the interference phenomenon. However, limited research is currently available relating to the acute or chronic responses to different concurrent-training protocols used by football teams. Research is required to investigate the effects of concurrent-training, training sequence and recovery duration in elite football players. A comprehensive investigation of the concurrent-training practices performed by football teams could advocate the design of more effective training strategies, which could ultimately translate to improvements in match-related performance.

1.1 AIMS AND OBJECTIVES OF THESIS

The aim of this thesis is to investigate the impact of training organisation on the acute and chronic responses to football-specific exercise programmes in elite football players. It is hoped that the studies contained in this thesis will help to inform acute training prescription guidelines so that the interference effects associated with concurrent-training are minimised.

The aims of this thesis will be achieved by the following objectives:

1. To characterise the training load and organisation of football-specific concurrent-training practices at an elite football club
2. To evaluate the reliability of a range of sports-specific testing protocols designed to detect changes following a concurrent-training programme.
3. To characterise the muscular adaptations following different concurrent-training protocols in elite football players.
4. To investigate the hormonal responses to different patterns of concurrent-training in elite football players.

CHAPTER TWO

REVIEW OF LITERATURE

2.0 INTRODUCTION

The aim of this review is to provide a rationale to investigate the effects of concurrent-training in elite football players. The content is presented in five sections. First, the demands of elite football competition will be discussed. Second, typical training practices of the modern football player will be provided. Thirdly, the key findings from the concurrent-training literature will be put forward. The fourth section aims to discuss physiological mechanisms which may explain the interference phenomenon. The final section will summarise the main findings of this literature review and provide the recommendations for the future research within the specific context of elite football.

2.1 THE DEMANDS OF FOOTBALL MATCHPLAY AND TRAINING

The following section is a brief overview of the physiological demands of match-play and training. This section provides reference to the physiological demands typically observed in elite-level competition and describes training methods that players use to cope with these requirements.

2.1.1 THE PHYSICAL AND METABOLIC DEMANDS OF MATCH-PLAY

Each competitive football match contains two 45 minute periods, separated by a 15 minute ‘half-time’ interval. During each game outfield players travel between 9 and 13 kilometres via intermittent phases of walking, jogging, high-intensity running and sprinting (Rampinini *et al*., 2007b). As each game is counterbalanced by high-intensity anaerobic activity and low-intensity aerobic activity, the average workload corresponds to the intensity associated with the lactate threshold (~85% of HR max) (Mohr *et al*., 2003). It is estimated that 90% of total energy turnover is derived through aerobic metabolism (Bangsbo *et al*., 2007), and as such, aerobic capacity has been identified as one of the most important fitness attributes of elite players (Bangsbo *et al*., 1991). However, more recent work suggests that the ability to perform repeated intense anaerobic activity is also vital for elite match play (Bangsbo *et al*., 2008). In 2006 Krustrup *et al*., described the fitness attributes of a range of elite and non-elite football players using a fitness test designed to assess the ability to perform high-intensity intermittent activity (Yo-Yo tests) (Krustrup *et al*., 2006). They observed that the ability to perform repeated high-intensity exercise could differentiate between international players, players who played in the highest domestic leagues, and players who played in the lower professional leagues (Krustrup *et al*., 2006). Collectively, this information suggests that the ability to perform repeated intense anaerobic activity is an important predictor of playing standard.

In addition to match-specific fitness, players' are also required to be physically strong and powerful. This can be attributed to the fact that football is a contact sport which requires players to exert force quickly during competitive situations (e.g. holding an opponent off when defending a set-play or accelerating away from an opponent) (Bangsbo *et al*., 2007). Indeed, Wisloff *et al*. (2004) observed a strong correlation between maximal strength and jumping (r = 078), and sprinting (r = 0.94) in elite football players (Wisloff *et al*., 2004), thus highlighting the importance of these characteristics to match-specific scenarios (for review of strength-training in football see; Hoff and Helgerud, 2004a).

To be successful in elite football, players require high levels of diverse fitness components. It is therefore important that training interventions are designed to affect the physiological mechanisms which underpin match-play demands. This approach is in keeping with the ergonomic model of football (Reilly, 2005). The following section will discuss the training approaches used by elite football teams.

2.1.2 TRAINING TO MEET THE DEMANDS OF FOOTBALL MATCHPLAY

Performance decrements during high-intensity intermittent exercise have been attributed broadly to three 'limiting factors' in the literature; (i) a reduced capability to supply energy (e.g. phosphocreatine) to the working muscles (ii) accumulations in metabolic products (e.g. inorganic phosphate) and (iii) a reduced ability of the nervous system to activate the muscle (Bishop *et al*., 2011, Girard *et al*., 2011). Therefore, training interventions that improve the body's ability to effectively supply energy to the working muscles, remove waste products, and activate the musco-skeletal system, may be beneficial in mitigating performance decrements during high-intensity exercise.

The literature highlights that high-intensity aerobic-training is seen as an effective strategy to positively affect the 'limiting factors' which contribute to reduced performance during high-intensity intermittent exercise. Chronic periods of high intensity aerobic-training are associated with an improved capacity for glucose utilisation (Churchley *et al*., 2007), improved fatty-acid metabolism, increased anaerobic enzyme activity (e.g. glycogen synthase activity), increased density of capillaries (Gibala *et al*., 2006), increased left ventricle size (Ekblom, 1969), increased myoglobin concentration, improved blood flow and artery dispensability (Laughlin and Roseguini, 2008). The net effect of these adaptations is an improved capacity of the cardiovascular system to transport oxygen, resulting in improved pulmonary kinetics and greater oxygen utilisation, ultimately improving aerobic performance (McKay *et al*., 2009).

These physiological adaptations play an important role in resisting fatigue during high-intensity intermittent exercise, such as that observed during football match-play (Mendez-Villanueva *et al*., 2011). Therefore, incorporating high-intensity interval training is a beneficial strategy for improving aerobic capacity and the players' ability to recover between repeated bouts of intense intermittent activity.

In the context of football, training both the technical and physical conditioning elements of the training programme simultaneously is seen as an efficient use of training time (Jones and Drust, 2007). As a result, small-sided games (SSG) using and 'interval format' have become an integral aspect of the modern training programme in team sports (Hill-Haas *et al*., 2009). Previous research advocates the use of SSGs as a reliable means to replicate the required intensity needed to improve the aerobic-anaerobic capacity specific to match-play (for review see; Hill-Haas *et al*., 2011). Therefore, it is regarded that SSGs can be used as an effective approach to improve multiple physiological and sports-specific goals critical to match-play.

In addition to high-intensity running and sprinting, players also perform 150 to 250 explosive movements throughout each game (Mohr *et al*., 2003). These brief actions require rapid development of muscular force. Muscular force and power development is underpinned by specific morphological and neuromuscular adaptations (for review see; Folland and Williams, 2007b). Morphological alterations include increased muscle thickness and cross-sectional area (Goldberg *et al*., 1975), increased size and number of individual muscle fibres (MacDougall *et al*., 1980), an increase in type IIa fibres,a decrease in type IIb fibres (Staron, 1991), and deviations in the geometric arrangement of muscle fibres, also known as changes in muscle architecture (Blazevich, 2006a). Neurological adaptations include; increased neural drive to the muscle, improved motor unit firing patterns (synchronization) (Sale *et al*., 1982), an increased capacity to activate agonist muscle groups (Cannon and Cafarelli, 1987), and more efficient inter-muscular coordination through altered sequencing of agonist and antagonist co-contraction (Milner-Brown *et al*., 1975). In order to promote specific types of adaptation (e.g. hypertrophy or nervous system adaptations), manipulation of the ‘acute resistance-training programme variables’ can be made (Spiering *et al*., 2008). These training variables include: intensity, volume, frequency and the specificity of exercise selection. The reader is directed toward the following reviews which describe underpinning scientific knowledge and rationale concerning the ‘acute programme variables’ and how they can be manipulated to achieve specific training objectives (Kraemer *et al*., 1998, Kraemer *et al*., 2002a, Bird *et al*., 2005). It is important that resistance-training programmes for football players are designed specifically to achieve outcomes central to football performance.

Within the literature, a number of resistance-training recommendations have been proposed for elite football players. In order to maximize strength gains without increasing body mass (thus reducing aerobic power), high-load (>85% of 1RM), low-repetition (4 to 6 reps) for 3 to 5 sets using isoinertial concentric and eccentric resistance-training models have been recommended (Wisloff *et al*., 1998). A number of studies have demonstrated this type of resistance-training to be an effective means for improving muscle strength in elite football players (Hoff and Helgerud, 2004a, Wong *et al*., 2010, Helgerud *et al*., 2011). Within these studies, improvements in strength were also accompanied by enhanced vertical jump height (Helgerud *et al*., 2011) reduced linear sprint times (Wong *et al*., 2010) and a more efficient ability to perform repeated sprints (Bogdanis *et al*., 2011). Collectively, these studies demonstrated that resistance-training had a positive effect upon performance related outcomes in elite football players.

2.1.3 CONCURRENT-TRAINING IN FOOTBALL

A large number of studies have evaluated the physical fitness attributes needed for successful performance (Krustrup *et al*., 2003, Mohr *et al*., 2003, Impellizzeri *et al*., 2006, Rampinini *et al*., 2007a, Bradley *et al*., 2009). Elite players require high levels of sports-specific endurance, speed, agility, and muscle-strength (Stolen *et al*., 2005). As a result, a variety of diverse training interventions are implemented by football teams (Bishop *et al*., 2011, Girard and Bishop, 2012), although the periodisation of this training can be a challenge within the 'applied football environment'.

The periodisation of training stipulates progressive variation in training volume and intensity promoting adaptation and recovery (Bompa, 2009). The collective goal of periodisation is to ensure the athlete increases performance at pre-agreed times of the season (Gamble, 2006). Traditional models of periodisation are most common in individual sports (e.g. 'swimming' or 'cycling') where competitions (e.g. 'World Championships' or 'European Championships') are separated by significant periods of time. As a result, the season can be divided into segments, each with a specific training objective (e.g., develop muscular strength) thus, allowing the athlete to physically prepare for competition (Bompa, 2002). However, the structure of the football league in England does not allow the coaches to periodise training using this method. The length of the 'pre-season' and competition phase reduces training time, and subsequently restricts the coaches' ability to periodise other aspects of conditioning (Bompa, 1994). As training time is reduced because of the competition schedule, it is common for many elite football teams to employ concurrent-training models (Ronnestad *et al*., 2011b). Concurrent-training within football stipulates that both 'football-specific fitness training' and other training variables such as 'muscle strength-training' are performed within the same micro-cycle. However, a number of studies have highlighted that interference in the development of strength occurs following a concurrent-training programme (for review see; Wilson *et al*., 2012). Therefore, understanding how to organise acute training variables (e.g. training intensity, training sequence) with the aim of minimising this interference may have significant effects upon performance outcomes in professional football players. In order to gain a better understanding of the problem, the following sections will review the studies which have investigated the effects of concurrent-training.

2.2 CONCURRENT-TRAINING – *A BRIEF OVERVIEW*

Since the pioneering work by Hickson in 1980, it has been documented that training to improve muscular strength and aerobic power at the same time results in compromised strength adaptations. This blunted response was originally referred to as the 'interference phenomenon' (Hickson, 1980, Hickson *et al*., 1980). Hicksons' preliminary study used a strength (S) group, an endurance (E) group and a combined strength and endurance group (C). The S group performed leg strength exercises (load > 80% of 1 RM) five days/week, while the E group performed 40 minutes of interval cycling and continuous running 6 day/week. The C group combined S and E training. Over the first 7-weeks of training, the rate of strength improvement (measured by improvement in squat 1 RM) in the C group was similar to that of the S group (approximately 34%). However, this rate of improvement plateaued in the C group and then subsequently declined during the final 3-weeks of the programme (~25% reduction) whilst the S group continued to improve (~10% increase). As expected, strength remained unchanged for participants in the E group throughout the programme. This data (Figure 1) was the first study to highlight that when aerobic-training and resistance-training are combined, strength adaptations became 'blunted' when compared to independent resistance-training.

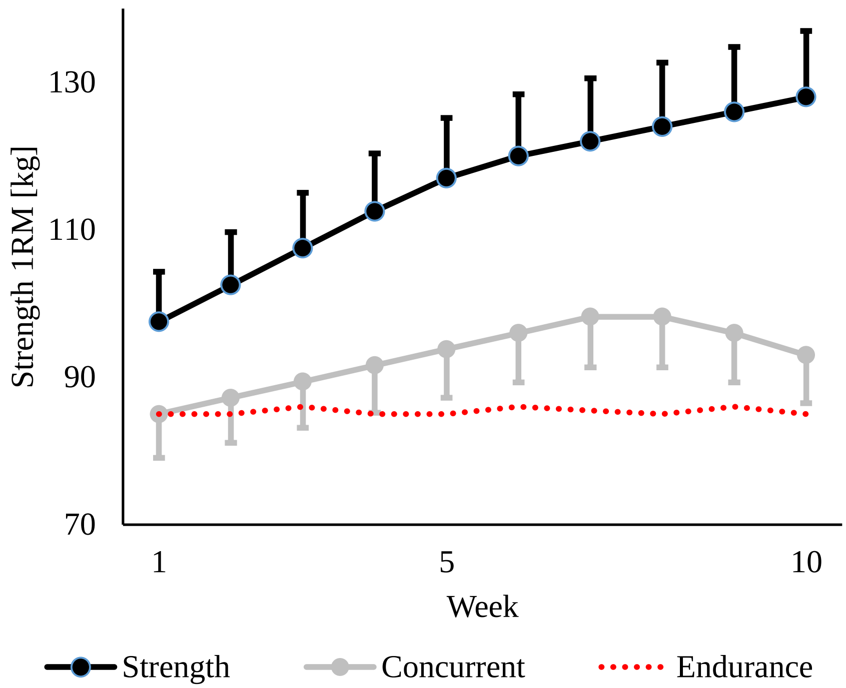

Figure 1: the results of Hicksons' study (1980) demonstrating interference following 7-weeks of concurrent-training.

Hicksons' preliminary findings provided the basis for the next 30 years of research. Table 1 illustrates the studies that have investigated the effects of concurrent-training in a variety of different settings. Whilst there have been a number of different methodological approaches used within these investigations, the 'interference phenomenon' has been replicated by the majority of these studies (see Table 1). Specifically, research groups have observed reductions in strength, (Hickson, 1980, Hickson *et al*., 1980, Kraemer *et al*., 2004, Kraemer *et al*., 1995, Dolezal and Potteiger, 1998, Hakkinen *et al*., 2003), hypertrophy, (Hickson, 1980, Hickson *et al*., 1980, Kraemer *et al*., 2004, McCarthy *et al*., 1995) and muscular power (Hunter *et al*., 1987, Leveritt *et al*., 2003, Baker, 2001, McCarthy *et al*., 2002, Hakkinen *et al*., 2003, Rhea *et al*., 2008) following concurrent-training.

Table 1: Summary of the training methods used by researchers investigating the effect of concurrent-training

Author	**Subjects**		**Training Frequency and Training Duration**		**Training Intensity**		**Training Mode**	**Exercise Sequence**	**Recovery period**	**Nutritional Availability**	**Findings**
Hickson, 1980	M	UT	6 d · wk^{-1}	10 wk^{-1}	80 % 1RM	> AT, < AT	Running & Cycling	Not reported	2 h	Not reported	Interference reported
Dudley *et al*., 1985	20 M & F	UT	3 d · wk^{-1}	7 wk^{-1}	> 80 % 1RM	> AT	Cycling	Not reported	Not reported	Not reported	Interference reported
Hunter, 1987	?	UT	4 d · wk^{-1}	12 wk^{-1}	75 - 73 % 1RM	< AT	Running	Not reported	Not reported	Not reported	Interference reported
Sale *et al*., 1990	16 M	UT	3 d · wk^{-1}	11 wk^{-1}	50 - 65 % 1RM	< AT	Cycling	Not reported	Not reported	Not reported	Interference reported
Sale *et al*., 1990	4 M & 4 F	UT	3 d · wk^{-1}	22 wk^{-1}	50 - 65 % 1RM	> AT	Cycling	S+E, E+S & on non-consecutive days	Not reported	Not reported	Training on separate days more beneficial
Nelson *et al*., 1990	14 M	UT	4 d · wk^{-1}	20 wk^{-1}	85 % 1RM	< AT	Cycling	Not reported	Not reported	Not reported	Interference reported
Craig, *et al*., 1991	9 M & 6 F	UT	3 d · wk^{-1}	10 wk^{-1}	80 - 85 % 1RM	< AT	Running	Not reported	Not reported	Not reported	Interference reported
Craig, *et al*., 1991	9 M & 6 F	UT	3 d · wk^{-1}	10 wk^{-1}	80 - 85 % 1RM	< AT	Running	Not reported	Not reported	Not reported	Interference reported
Abernethy *et al*, 1993	9 M	UT	3 d · wk^{-1}	7 wk^{-1}	> 80 % 1RM	> AT	Arm Crank	Not reported	Not reported	Not reported	No interference reported
Bell *et al*., 1993	20 F	UT	3 d · wk^{-1}	16 wk^{-1}	75 % 1RM	> AT, < AT	Rowing	Not reported	Not reported	Not reported	No interference reported
Collins *et al*., 1993	23F & 11M	UT	3 d · wk^{-1}	7 wk^{-1}	50 – 90 % 1RM	< AT	Running	E+S, S+E	No recovery	Not reported	Sequence did not cause interference

Author	Subjects		Training Frequency and Training Duration		Training Intensity		Training Mode	Exercise Sequence	Recovery period	Nutritional Availability	Findings
Hennessey *et al*, 1994	56 M	UT	5 d · wk^{-1}	8 wk^{-1}	70 - 100 %1RM	> AT, < AT	Running	Not reported	Not reported	Not reported	Interference reported
McCarthy *et al*., 1995	30 M	UT	3 d · wk^{-1}	10 wk^{-1}	83 - 87 % 1 RM	< AT	Cycling	E+S, S+E	10 - 20 min	Not reported	No interference reported
Kraemer *et al*., 1995	35 M	UT	4 d · wk^{-1}	12 wk^{-1}	75 - 85 5-1RM	> AT, < AT	Running	E+S	4 h	Not reported	Interference reported.
Bell *et al*., 1997	20 M & 13 F	UT	3 d · wk^{-1}	16 wk^{-1}	65 - 85 % 1RM	> AT, < AT	Cycling	Not reported	Not reported	Not reported	Interference reported
Dolezal *et al*., 1998	30 M	UT	3 d · wk^{-1}	10 wk^{-1}	67 - 85 % 1RM	< AT	Running	S+E	Not reported	Not reported	Interference reported
Bell *et al*., 2000	27 M & 18 F	UT	6 d · wk^{-1}	12 wk^{-1}	70 - 85 % 1RM	> AT, < AT	Cycling	non-consecutive days	24 - 28 h	Not reported	Interference reported
Hoff *et al*., 2002	19 M	T	3 d · wk^{-1}	8 wk^{-1}	85 % 1RM	> AT, < AT	Skiing	Not reported	Not reported	Not reported	Improvements observed, no strength controls
Mcarthy *et al*., 2002	30 M	UT	3 d · wk^{-1}	10 wk^{-1}	83 - 87 % 1RM	< AT	Cycling	non-consecutive days	24 - 28 h	Not reported	No interference reported
Hakkinen *et al*., 2003	32 M	UT	4/2 d · wk^{-1}	22 wk^{-1}	50 - 80 % 1RM	> AT, < AT	Cycling	Not reported	Not reported	Not reported	No interference reported
Balabinis *et al*., 2003	26 M	UT	4 d · wk^{-1}	7 wk^{-1}	80 - 85 % 1RM	> AT	Running	S+E	Not reported	Not reported	Interference reported

Author	Subjects		Training Frequency and Training Duration		Training Intensity		Training Mode	Exercise Sequence	Recovery period	Nutritional Availability	Findings
Glowaki *et al*., 2004	41 M	UT	3 d · wk^{-1}	12 wk^{-1}	75 - 85 % 1RM	< AT	Cycling	non-consecutive days	24 - 28 h	Not reported	No interference reported
Kraemer *et al*., 2004	35 M	UT	4 d · wk^{-1}	12 wk^{-1}	75 - 85 5 1RM	> AT, < AT	Running	E+S	4 h	Not reported	No interference reported
Izquierdo *et al*., 2004	31 M	UT	4 d · wk^{-1}	16 wk^{-1}	75 - 87 % 1RM	> AT	Cycling	non-consecutive days	24 - 28 h	Not reported	Interference reported
Chtara *et al*., 2005	48 M	UT	2 d · wk^{-1}1	12 wk^{-1}	< 50 1RM	> AT	Running	E+S, S+E	No recovery	Not reported	Improvements observed, no strength controls
Jackson *et al*., 2007	23 M	T	3 d · wk^{-1}	10 wk^{-1}	50 (or) 85 % 1RM	> AT, < AT	Cycling	Not reported	1 - 2 h	Not reported	Improvements observed, no strength controls
Chtara *et al*., 2008	48 M	UT	2 d · wk^{-1}	12 wk^{-1}	< 50 1RM	> AT	Running	E+S, S+E	No recovery	Not reported	Sequence did not cause interference
Mikkola *et al*., 2008	19 M	T	2 d · wk^{-1}	8 wk^{-1}	67 - 85 % 1RM	> AT, < AT	Skiing	Not reported	Not reported	Not reported	No interference reported.
Rhea *et al*., 2008	16 M	T	4 d · wk^{-1}	18 wk^{-1}	90 - 95 % 1RM	> AT, < AT	Running & Cycling	Not reported	Not reported	Not reported	No interference reported
Davis *et al*., 2008a	28 F	UT	3 d · wk^{-1}	11 wk^{-1}	50 % 1RM	< AT, > AT	Cycling	S+E, integrated S+E	No recovery	Not reported	Improvements observed, no strength controls

Author	Subjects		Training Frequency and Training Duration		Training Intensity		Training Mode	Exercise Sequence	Recovery period	Nutritional Availability	Findings
Davis *et al*., 2008b	20 M 30 F	UT	3 d · wk^{-1}	11 wk^{-1}	50 % 1RM	< AT	Cycling	S+E, integrated S+E	No recovery	Not reported	Improvements observed, no strength controls
Sillanpaa *et al*., 2008	53 M	UT	?	21 wk^{-1}	40 - 90 % 1RM	> AT, < AT	Cycling	Not reported	Not reported	Not reported	Improvements observed, no strength controls
Kelly *et al*., 2008	16 F	UT	3 d · wk^{-1}	10 wk^{-1}	60 - 85 % 1RM	> AT, < AT	Running	S+E	8 h	Not reported	Improvements observed, no strength controls
Santtila *et al*., 2009	72 M	UT	6 d · wk^{-1}	8 wk^{-1}	30 - 100 % 1RM	< AT	Running & Cycling	Not reported	Not reported	Not reported	Interference reported
Gergley *et al* 2009	22 M / 8 F	UT	2 d · wk^{-1}	9 wk^{-1}	67 - 80 % 1RM	< AT	Cycling	Different days	24 - 28 h	Not reported	Interference reported
Wong *et al*., 2010	39 M	T	5 d · wk^{-1}	6 wk^{-1}	85 % 1RM	> AT, < AT	Running	S+E	5 h	Not reported	Improvements observed, no strength controls
Wong *et al*., 2010	51 M	T	5 d · wk^{-1}	8 wk^{-1}	< 50 % of 1RM	> AT, < AT	Running	Not reported	Not reported	Not reported	Improvements observed, no strength controls
Ronnestad *et al*., 2010	20 M	T	2 d · wk^{-1}	12 wk^{-1}	75 - 90 % 1RM	> AT, < AT	Cycling	S+E	Not reported	Not reported	Improvements observed, no strength controls
Ronnestad *et al*., 2012	18M	UT / T	6 d · wk^{-1}	12 wk^{-1}	75 - 90 % 1RM	> AT, < AT	Cycling	S+E	Not reported	Met ACSM Guidelines timing not reported	Interference reported
McGawley *et al*., 2013	18 M	T	3 d · wk^{-1}	5 wk^{-1}	75 - 87 % 1RM	> AT, < AT	Running	E+S, S+E	5 min recovery	Not reported	Sequence does not cause interference

In order to gain a better insight into what is causing the interference phenomenon it may be important to consider the training approaches used by researchers who have investigated the effects of different concurrent-training programmes. Understanding the methodological designs between studies may help to formulate the theoretical basis for training recommendations to minimise the interference phenomenon in football. Table 1 illustrates the different training protocols used to investigate the effects of concurrent-training to date. Closer examination of the concurrent-training literature highlights that researchers have used a range of training methodologies, making it difficult to compare and contrast the findings and apply them to the elite football player. Research groups have used ‘free-weight resistance’ (McCarthy *et al*., 1995), ‘machine resistance’ (Kraemer *et al*., 1995), ‘circuit resistance-training’ (Chtaha *et al*., 2008), isokinetic training (Dudley and Djamil, 1985) and combinations of the above to improve strength in the upper and (or) lower musculature. Whilst, running (Craig *et al*., 1991), arm-cranking (Abernethy and Quigley, 1993), cycling (Bishop *et al*., 1999) and rowing (Izquierdo-Gabarren *et al*., 2010) have been used to improve aerobic fitness. Sub-maximal (Hunter *et al*., 1987), high-intensity (Chtara *et al*., 2008) and a combination (Kraemer *et al*., 2004) of low and high training intensities have been used to improve both strength and aerobic capacity. Furthermore, some studies have failed to report the ‘order’ or ‘sequence’ of concurrent-training (Jackson *et al*., 2007) and those who reported training sequence did not always report the recovery period between training bouts (Balabinis *et al*., 2003). Moreover, some researchers have asked subjects to train on 3 days per week (Abernethy and Quigley, 1993) whilst other investigators have instructed the participants to train on 6 days of the week for the duration of the training programme (Santtila *et al*., 2009). Finally, the majority of studies investigating the effects of concurrent-training have used untrained participants. Differences in methodological design between studies could have influenced the adaptive response, making comparisons between studies difficult. for example a recent meta-analysis of the concurrent-training literature has revealed that when compared to other forms of aerobic-training, running can increase interference in strength related adaptation. Moreover, concurrent-training on more than 3 days per week has been shown to reduce hypertrophy and muscle strength (for meta analysis see; Wilson *et al.*, 2012). Therefore, the contrasting training protocols used to date make it inherently difficult to compare and contrast the findings between studies and apply them to elite football players. At present it is therefore impossible to suggest any training guidelines that may minimise the interference phenomenon in elite football players. Whilst many concurrent-training studies have reported interference few authors have attempted to address why the interference in strength adaptation occurs. The following section aims to discuss the theoretical models which have been previously put forward to explain why interference occurs. A deeper understanding of why interference occurs may aid the design of future studies investigating the effects of concurrent-training.

2.3 MECHANISMS TO EXPLAIN THE INTERFERENCE PHENOMENON

Over the three decades a variety of hypothesis have been suggested to explain the interference phenomenon. These include; an inability to adapt as a consequence of contrasting training intensities (Docherty and Sporer, 2000), an incompatible hormonal (Bell *et al*., 2000) and (or) molecular signalling environment (Atherton *et al*., 2005) the ‘sequence’ or ‘order’ of training (Chtaha *et al*., 2008), the recovery time between training bouts (Craig *et al*., 1991) and the frequency of aerobic-training (Wilson *et al*., 2012) causing overtraining (Dudley and Fleck, 1987). As these explanations are interrelated, they can be broadly categorised into ‘acute’ and ‘chronic’ hypothesis:

The acute hypothesis

(i) Interference is caused by residual fatigue from the endurance component of concurrent-training resulting in the inability to effectively develop tension during the strength element of concurrent-training.

The chronic hypothesis

(ii) Skeletal muscle cannot adapt metabolically or morphologically as a consequence of acute intramuscular events blocking chronic adaptation.

Notably, both categories can be influenced by the way in which the training stimulus is organised and delivered. This may have particular relevance for football teams who are required to perform concurrent-training on the same day. The following section aims to discuss the effect of concurrent-training organisation upon acute peripheral fatigue and its effect upon biological and (or) molecular events that may influence the training response.

2.3.1 THE ACUTE HYPOTHESIS

The acute hypothesis first proposed by Craig *et al*., (1991) was based on the assumption that muscle force capacity can be reduced when endurance-training is performed prior to resistance-training. It was believed by Craig and colleagues that the reduced capacity to train at higher intensities during the resistance component of the programme caused interference in adaptation. Indeed, reductions in muscle force have been observed following an acute bout of submaximal and high-intensity intermittent aerobic-exercise, (Carroll *et al*., 1998, Leveritt and Abernethy, 1999, Lepers *et al*., 2000). Localised muscle inhibition is pronounced following high-intensity exercise and typically lasts between 6 and 48 hours following aerobic-exercise (Fitts, 1994, Lepers *et al*., 2000). Reductions in force capacity following an acute bout of exercise have been attributed to central (e.g. central nervous system fatigue) (McCarthy *et al*., 2002) and (or) peripheral mechanisms (e.g. depletion of muscle glycogen) (Haff *et al*., 2003). Therefore, the acute hypothesis suggested that the training intensity and the way training is organised (i.e. the sequence of training and the recovery time between training bouts) would affect the adaptive process.

Despite a number of studies demonstrating acute force inhibition following aerobic-exercise, few studies have investigated the long term effect of concurrent-training sequence. Those who have investigated the effect of concurrent-training sequence have reported conflicting results. for example, authors report performance improvements in strength when aerobic-training is performed first (Chtara *et al*., 2005, Lundberg *et al*., 2013) and when resistance-training is performed first (Sale *et al*., 1990, Davis *et al*., 2008a, Davis *et al*., 2008b). While, others conclude no advantage to performing either mode of exercise first (Collins and Snow, 1993, Chtara *et al*., 2008, McGawley and andersson, 2013). Discrepancies between these studies may be due to a number of methodological design issues. for example; in order to improve aerobic capacity different forms of aerobic-training have been used (e.g. cycling and running). Authors have suggested that when compared to running protocols, a synergistic relationship exists between cycling and resistance protocols (Hamilton *et al*., 2013). This is supported by the fact that studies investigating the effects of concurrent-training sequence that report no interference by training sequence have used cycling protocols (Chtara *et al*., 2005). Furthermore, the above studies that have investigated the effects of concurrent-training sequence have used a variety of training intensities. The manipulation of training intensity may have increased or decreased the central and (or) peripheral fatigue causing the discrepancies observed in these studies (Docherty and Sporer, 2000). Figure 2 describes how the manipulation of training intensity can increase or decrease acute interference.

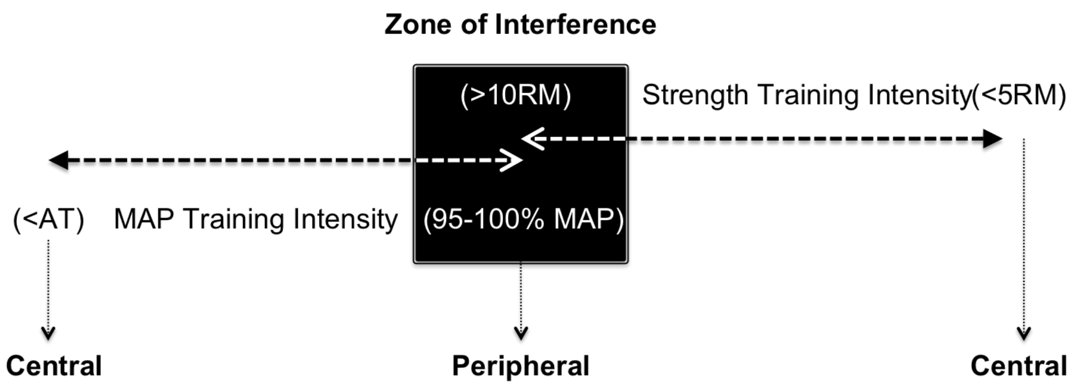

Figure 2: The intensity continuum of interference described by Doherty and Sporer, (2000).

Figure Key; Left side = aerobic-training. Right side = strength-training. MAP = maximal aerobic power (MAP), AT = anaerobic threshold, RM = repetition maximum, ↑ = increased. [Modified from Docherty and Sporer (2000) p. 390]

In 2000 Docherty and Sporer proposed that interference may be maximised if both aerobic and strength parameters 'tax' peripheral mechanisms at the same time. Conversely, the authors recommended that concurrent-training programmes below the anaerobic threshold and above 85% of 1RM for aerobic and strength parameters respectively would minimise the interference effect. It was hypothesised that greater demands on the neurological system would reduce the interference phenomenon (Docherty and Sporer, 2000). Studies that have investigated the effects of concurrent-training sequence have used a mixture of intensities which are likely to exacerbate the interference phenomenon (Chtara *et al*., 2008, Collins and Snow, 1993). The conflicting findings observed may therefore be explained by the intensities prescribed by each research group. Furthermore, the subjects used in these studies have been untrained. Given that acute responses to training appears to be different between trained and untrained individuals (Saunders *et al*., 2004, Smith and McNaughton, 1993), the acute time-course of muscle fatigue presented in the literature is likely to be less applicable to trained populations. Therefore, at present it is not possible to conclude of the acute hypothesis proposed by Craig *et al*., (1991) can be applied to the elite football player. Using the training methods used by elite football teams, future research could investigate the acute and chronic effects of concurrent-training sequence. Considering that elite football players often perform concurrent strength and football training on the same day, it may be important to gain a deeper understanding of the most effective way to deliver the concurrent-training stimulus.

In addition to the acute peripheral fatigue hypothesis, it is also possible that the interference phenomenon can be explained by the acute interference in the biological and (or) molecular processes associated with each type of training. The following section aims to discuss how the organisation of training (i.e. the sequence and recovery time between training bouts) could influence the acute intramuscular events associated with 'end-point' adaptations.

2.3.2 THE CHRONIC HYPOTHESIS

Adaptations to training are dependent upon the exercise mode, intensity, duration and frequency of the training stimulus (Nader, 2006). Following extended periods of endurance and resistance-training contrasting adaptations are typically observed. Endurance-training is associated with mitochondrial biogenesis and angiogenesis ultimately resulting in an improved capacity to resist fatigue. Whereas, resistance-training initiates muscle protein synthesis eventually resulting in muscle hypertrophy and improvements in maximal contractile force output. In the past 15 years advances in sample processing and deoxyribonucleic acid (DNA) microarray technologies have provided new perspectives on the exercise induced molecular events that orchestrate adaptation. Current understanding suggest that the molecular signals that occur in response to endurance and resistance-training are distinct, with each mode of exercise activating specific subsets of genes and cellular signalling pathways (Atherton *et al.*, 2005). It is believed the intramuscular signals during and following an acute bout of endurance and resistance–training are responsible for longer term adaptations. In this regard, two signalling pathways regulate endurance and resistance-training adaptation. Following endurance exercise adenosine monophosphate-activated kinase-peroxisome proliferator activated receptor gamma coactivator-1 (AMPK-PGC-1) becomes up regulated. Whereas, following resistance-exercise the Akt/protein kinase B-mammalian target of rapamycin-p70 S6 kinase

(Akt- mTOR-S6K) pathways become up regulated. These intramuscular processes become up regulated following the onset of exercise and can be active for up to 72 hours following training (Cunningham *et al.*, 2006). However, it has been reported that these contrasting molecular profiles are incompatible (Hawley, 2009). Figure 3 describes how the interaction between these unique signalling pathways may help to explain why interference in strength related adaptation has been observed following a concurrent-training programme. When AMPK-PGC-1α pathway is up regulated in response to an endurance stimulus, the mTOR pathway can become repressed via the AMPK trichosanthin (TCS) 1/2 pathway (Cunningham *et al*., 2007). This indicates that combining diverse contractile activity may interfere with the distinct molecular profiles and likely suppress or limit the specificity of the adaptive response (Hawley, 2009).

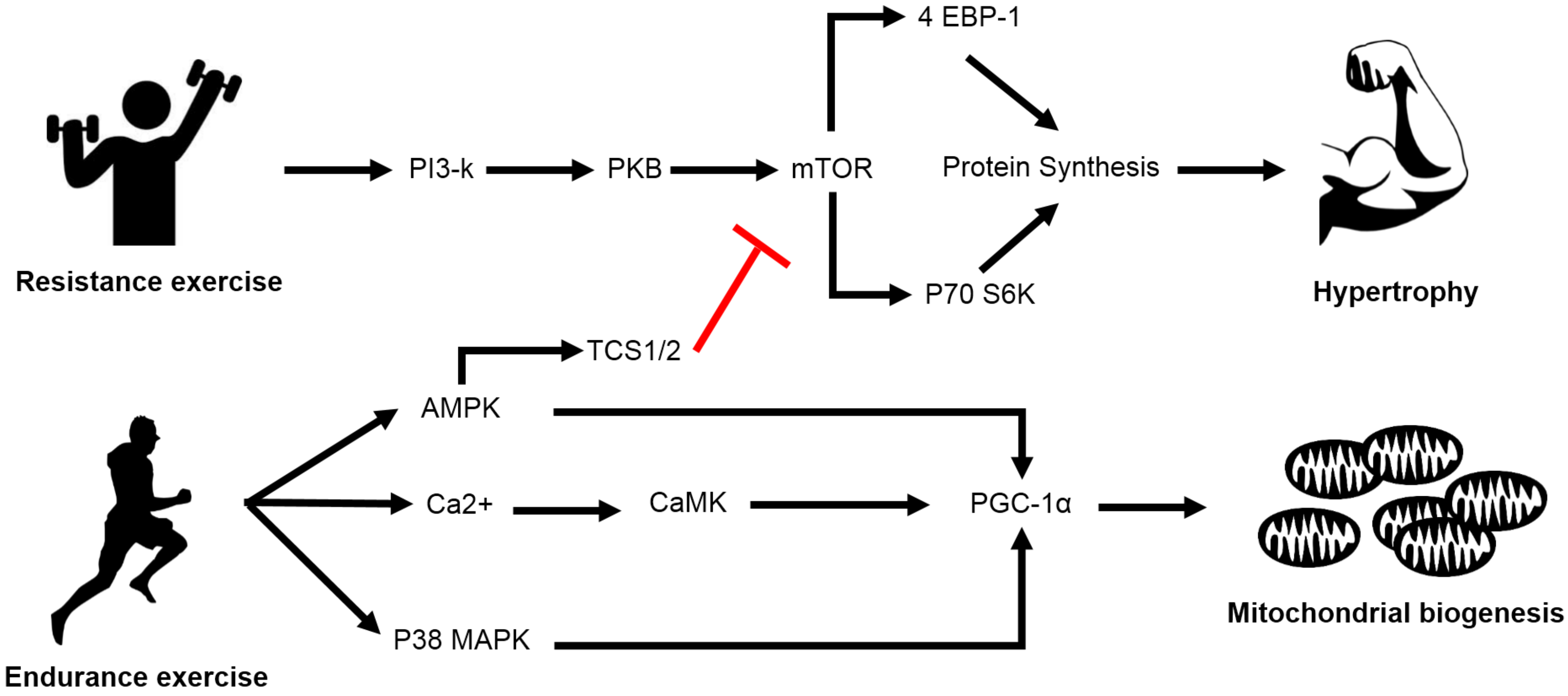

Figure 3: Intracellular signalling pathways mediating exercise-induced muscle adaptations following resistance and endurance-training [Modified from Hawley, 2009 p. 357] ***Endurance exercise;*** *AMPK = 5' adenosine monophosphate-activated protein kinase; TSC1/2 = tuberous sclerosis complex 1/2; Ca2+ = calcium; CaMK = calmodulin-dependent kinase; p38 MAPK = p38 mitogen-activated protein kinases; PGC-1α = peroxisome proliferator activated receptor γ co-activator-1α;* ***Resistance exercise;*** *PI3K = phosphatidylinositol-3-OH kinase; pKB = Protein Kinase B; mTOR = mammaliantarget of rapamycin; 4E-BP1 = eukaryotic initiation factor 4E-binding protein; p70S6K = p70S6 kinase*

The distinct molecular responses associated with endurance and resistance-training provide a mechanistic hypothesis that could explain the interference phenomenon. Furthermore, the acute time-course of signalling processes in response to exercise also suggest that interference may be exacerbated by the way the concurrent-training stimulus is delivered (i.e. the sequence and recovery time between training bouts) (Coffey *et al*., 2006, Coffey and Hawley, 2006). Understanding the molecular responses to concurrent-training protocols may aid our understanding of how to organise training in the applied setting. In this regard Coffey and colleagues have investigated the molecular responses to different concurrent-training protocols. In 2009 the research group investigated the acute molecular responses in consecutive bouts of resistance and endurance-exercise. Eight healthy male participants performed 30 min of cycling at 70% of $\dot{V}O_2$ max followed by 5 x 8RM leg extensions or vice versa. Muscle biopsies were taken before exercise, 15 min after each exercise bout, and after 3 h of passive recovery. Results showed that an anabolic signal associated with mTOR pathway (IGF-1) was supressed when endurance-exercise preceded resistance-exercise. Whereas, the anabolic pathways (muscle ring finger mRNA and hexokinase II mRNA) were elevated when endurance-exercise was undertaken after resistance-exercise. It was concluded that exercise order modified the acute molecular response (Coffey *et al*., 2009b). In a similar study, the same research group found greater molecular interference when sprint exercise was performed immediately before and after a resistance-exercise protocol (Coffey *et al*., 2009a). Therefore, the research group suggested that to minimise molecular interference sprint-activities should be isolated from resistance-training and ideally be performed on a separate training day. The authors also hypothesised that not only the sequence but the recovery time between training bouts could further exacerbate acute "interference". The findings from Coffey's laboratory have indicated that the sequence of concurrent-training the proximity of training bouts and the intensity of training can interfere with acute intramuscular signalling processes associated with adaptation. However, without follow up training studies, it was unclear if these acute observations would interfere with long term strength related adaptation.

In order to test the hypothesis that increased recovery time may reduce acute and chronic interference, Lundberg *et al*. (2012) carried out a series of comparable studies, with a 6 hour recovery period between exercise bouts. This repeated measures design study, required 9 participants to perform 45 min of one leg cycle ergometry followed by 4 x 7 maximal concentric and eccentric knee extensions 6 hours later (condition 1), or an isolated bout of resistance-exercise (condition 2). Subsequent biopsies revealed that signals associated with protein synthesis and mitochondrial biogenesis were elevated in condition 1 compared to condition 2 (Lundberg *et al*., 2012). The researchers followed up this acute study with a 5-week training study using the same training protocols. The results demonstrated support for their previous findings, demonstrating increased aerobic capacity and increased muscle size following training (Lundberg *et al*., 2013). These data demonstrate that the acute molecular interference can be influenced by the sequence of training and the proximity of each exercise bout. However, it is not apparent if combining the training protocols used by football players would provide similar order effects.

Typically, elite footballers participate in concurrent high intensity sport-specific training (e.g. small sided games) and high-load, low repetition resistance-training. To the authors knowledge no research groups have investigated the intramuscular responses to the training performed by football players. Therefore, future research could investigate the molecular responses to football-specific concurrent-training methods. This may have practical implications for football teams who routinely perform concurrent-training.

2.4 THE ROLE OF NUTRITION AND EXERCISE INDUCED ADAPTATION

The following section will discuss the role of nutrition in regulating intramuscular processes that have shown to be correlated with long term muscle adaptation (e.g. myofibrillar protein synthesis). This section will discuss the evidence in the context of isolated resistance-training, isolated endurance-training and combined resistance and endurance-training (i.e. concurrent training).

2.4.1 Resistance-training

Resistance-training stimulates myofibrillar protein synthesis and breakdown, the balance of which determines the degree of muscle hypertrophy (Spiering, Kraemer et al. 2008). Appropriate nutritional strategies can have a synergistic effect upon intramuscular processes associated with muscle adaptation (for review see; Tipton and Witard 2007). The 'Pathway of Adaptation Model' (Figure 4) proposed by Volek et al., (2006) highlights the interaction between the availability of key nutrients and the metabolic/intramuscular processes that orchestrate end point muscle adaptations. The model highlights that nutrient quality, quantity and the timing in nutritional intake (i.e., before, during and after exercise) is important to elicit the acute response necessary for adaptation.

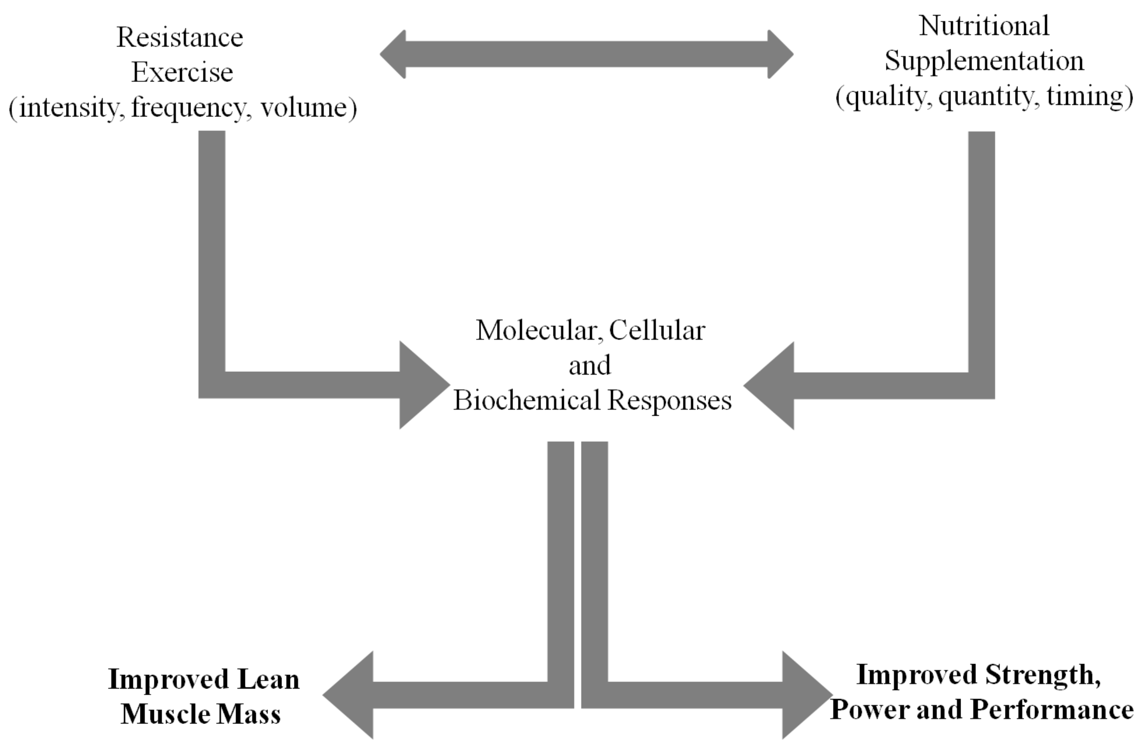

Figure 4: Pathway of Adaptation Model first described by Volek et al., (1997) (above is presented as presented by Bird et al., 2007 (Pg 82).

The 'Pathway of Adaptation Model' is supported by a number of articles that have shown specific nutritional strategies to enhance intramuscular processes associated with training induced muscle adaptations. for example; Rasmussen and colleagues (2000) demonstrated that ingesting 6 g of essential amino acids and 35 g sucrose 1 or 3 h after a bout of resistance exercise led to a >400% increase in pre-exercise myofibular protein synthesis compared to no supplementation (Rasmussen, Tipton et al. 2000). Consumption of this same protein and carbohydrate supplement immediately before exercise also increased amino acid delivery to the muscle and improve net muscle protein balance (Tipton and Wolfe 2001). These findings (amongst others) highlight that the timing of carbohydrate and protein intake can influence the intramuscular events responsible for muscle adaptation (Hawley and Burke 2010). The quantity and type of protein has also been shown to influence acute intramuscular events associated with longer term muscle adaptation. Previously, Hawley *et al.*, (2013) and Philips *et al*., (2012) have compared the effect of small (10g) and larger quantities (25g) of whey, soy or animal proteins taken at different times throughout the day on whole-body protein turnover. The findings from these studies highlighted that individuals should aim to include 0.25g ▪ kg/bw of whey protein every 3 hours to enhance lean body mass. Collectively, data pertaining from these studies has highlighted that the acute pattern, the total amount, and the type of protein consumed should be considered when designing nutritional strategies to support resistance-training programmes.

2.4.2 Endurance-training

Investigations have shown that increasing carbohydrate intake prior to an endurance event can enhance performance of prolonged events (>1hr) such as cycling, distance running and football (Karlsson and Saltin 1971). Therefore, when training for sports in which carbohydrate is the most heavily metabolized fuel, it is recommended that athletes should consume a diet rich in carbohydrate (Jeukendrup 2004). Carbohydrate supplementation before, during, and after a training bout can attenuate the rate of muscle glycogen depletion during exercise and speed the rate of glycogen resynthesis after exercise. Together these adaptations may enhance performance. This effect on glycogen is most likely achieved by increasing glucose availability and by affecting hormones such as insulin, which may activate important steps involved in glycogen re-synthesis during future exercise bouts. Muscle performance is also increased through enhanced muscle glycogen sparing, preventing low blood glucose concentration and stimulating the central nervous system (for review see Jukendrup et al., 2011). It is evident that carbohydrate availability is desirable in competition or during training which requires a high level of skill and or effort (Zeederberg, Leach et al. 1996). Recent evidence has suggested that participating in endurance exercise with low muscle glycogen stores may have a beneficial effect on adaptations associated with endurance performance (Hawley, 2013). Enhanced transcriptional activation of enzymes capable of altering Adenosine 5 monophosphate AMP activated protein kinase [5-AMPK], hexokinase, and the pyruvate dehydrogenase [PDH] complex have been observed in the 'fasted state' (Hawley and Burke 2010). Although, additional research is warranted to validate if 'fasted' endurance exercise can translate to chronic muscle adaptations which directly influence muscle performance. Therefore, it has been suggested that competitive athletes who manipulate carbohydrate availability before, during, or after selected training sessions should do so in line with a long-term periodized training-nutrition plan which has the end goal to promote metabolic training adaptations which translate to improvements in performance (Hawley and Burke 2010).

2.4.3 Concurrent endurance and strength-training

Elite athletes are typically required to train multiple times each day (Goto, Ishii et al. 2007). These training sessions can have diverse mechanical demands (e.g. resistance-training and endurance-training) and therefore can lead to significant metabolic stress on the body. In 2000 Greg Haff and his co-workers highlighted the importance of nutritional strategies when multiple training sessions are performed on the same day. This research group specifically examined the effect of carbohydrate supplementation or placebo on the ability to perform multiple sets of the squat exercise. To ensure the subjects were in a ‘glycogen depleted’ state each person performed 15 sets of various squat exercises, then 4-hours later subjects were required to squat to exhaustion (sets of 10 repetitions at 55% of 1RM). When compared to placebo, carbohydrate supplementation significantly improved the number of sets, number of repetitions, and duration of exercise (Haff, Koch et al. 2000). Similar observations have also been found when athletes perform multiple aerobic-training sessions on the same day without adequate nutritional supplementation (Rico-Sanz, Zehnder et al. 1999). Tesch et al., (1998) found that muscle glycogen content was reduced by ~40% following a bout of running exercise. The authors highlighted that this reduction was more prominent in Type II muscle fibers and that this change could diminish performance during secondary high volume, high-intensity or high skill training (Tesch, Colliander et al. 1986) (Tesch *et al*., 1998). Therefore, it can be concluded that when multiple diverse training bouts are performed on the same day adequate provision of specific nutrients before, between and following each training bout is necessary to maintain muscle performance and recovery.

Whilst, these studies have demonstrated the importance of carbohydrate availability when athletes perform multiple training sessions in one day, at present, no research group has specifically investigated the effects of nutritional interventions on the training process whilst concurrently training for strength and aerobic parameters. Considering that the availability of carbohydrate and protein sources before, during, and after training can impact number of biochemical and molecular responses associated with chronic adaptation and acute muscle performance (Hawley, Hargreaves et al. 2006) careful consideration of nutrient timing, quality, and quantity particularly when concurrent-training sessions performed in the same day is required. Matching the nutritional demands to periodised concurrent-training programs may be particularly important for football players who routinely perform diverse contractile activity such as; strength, aerobic, anaerobic and power training. The timing of 'session specific nutrients' to match the unique demands of each workout or phase of training in relation to each individual athlete may enhance adaptations to training (Hawley, Tipton et al. 2006).

At present no nutritional recommendations currently exist for football players who train both aerobic and strength variables on the same day. Concurrent strength and aerobic-training represents a specific period where nutrient status becomes compromised because of increased training volume. Therefore, nutrient ingestion before after and perhaps during each exercise bout may be particularly important for muscle recovery and the adaptive processes. Future research should investigate how nutritional interventions can influence muscle performance, recovery and adaptation in elite football players who routinely perform concurrent training programmes.

2.5 CONCLUSION

During a competitive game, football players cover large distances through high-intensity running and sprinting (Bradley *et al*., 2009). In addition, players engage in explosive movements including jumping and tackling (Bangsbo *et al*., 2006). In order to be competitive at the highest level, players require high levels of aerobic and anaerobic capacity, and muscular strength and power. Consequently, concurrent-training methods are often employed to improve aerobic capacity and muscle strength simultaneously. However, since the initial observations by Hickson in 1980, numerous studies have demonstrated that strength and power adaptation can become compromised following a concurrent-training programme. Across the past thirty years scientists have provided a number of methodological and mechanistic explanations for this interference. As these explanations are interrelated, they can be grouped into two categories (i) the acute fatigue hypothesis or (ii) the chronic hypothesis. Both hypotheses are directly affected by the organisation of training (i.e. the training sequence and the recovery time between training bouts). Considering that football teams often concurrently train on the same day, the organisation of training may be of particular importance. However, few long term studies have directly investigated the effect of concurrent-training sequence. As a result, it is difficult at this time to make clear recommendations as to the most effective way to deliver the concurrent-training stimulus.

Recent advances in sample processing and deoxyribonucleic acid (DNA) microarray technologies provide new perspectives on the molecular signals which occur in response to exercise and training. Molecular responses to concurrent-training has emerged as contender to potentially explain the interference phenomenon. Indeed, it has been demonstrated that the sequence and recovery time between concurrent exercise bouts can play a significant role in the acute molecular responses that orchestrate end-point adaptations. It is not known if these findings would translate to elite football players and the training methods they routinely engage in. Few studies have directly investigated the effects of concurrent-training in elite football players. Future research is required to investigate the effects of concurrent-training, training sequence and recovery duration in elite football players. A comprehensive investigation of the concurrent-training practices performed by football teams could permit the development of practical recommendations that may reduce interference and improve adaptation. This understanding could advocate the design of more effective training strategies, which could ultimately translate to improvements in match-related performance.

CHAPTER THREE

PILOT STUDY

AN OBSERVATION OF THE ORGANISATION OF CONCURRENT-TRAINING WITHIN AN ELITE FOOTBALL TEAM.

STUDY 1: ABSTRACT

AN OBSERVATIONAL STUDY OF THE TRAINING PATTERNS WITHIN AN ELITE FOOTBALL TEAM.

Purpose: The aim of this study was to investigate the concurrent-training practices at a professional football club. Specifically, the frequency, organisation and training-load of all training and games completed by a professional team across a 10 week period were examined. **Methods:** 21 professional football players competing in the English 'nPower championship' participated in this observational study (mean ± SD 26 ± 4 yrs, stature, 1.84 ± 0.1 m, body mass, 83 ± 7 kg). Training was categorised into football-training (FT), Games, resistance-training (RT) and recovery days. Training load parameters observed included, rating of perceived exertion training load (RPE-TL), GPS indices and Heart rate measurements and volume load (VL). on concurrent-training days the training sequence, recovery time and the nutritional intake around training was documented. **Results:** The average weekly RPE-TL for each sub component of training and GPS and Heart rate data was significantly higher in the initial 3 weeks of the observational phase. There were no significant difference in total training load or GPS and Heart rate data across the remaining 7 weeks. Players performed concurrent-training on 17 occasions. The structure of training, recovery time and nutrition around training was unsystematic. **Conclusion:** The findings show that the training load during the 'pre-season' may not have been sustained long enough to produce the desired training response. Considering that training frequency and training-load was not significantly different across the remaining 7 weeks, monotony may have occurred and been sub-optimal for muscle adaptation. The secondary findings from this study demonstrate that the organisation (recovery time, sequence) of concurrent-training was unsystematic and therefore could have affected the long term adaptive process. Although, at present, the long term effect of the concurrent-training protocols observed in this study are not known. Future research could investigate the effect of the concurrent-training protocols used by football players.

Key Words: Training-load, Concurrent-training, Training-organisation

3.0 INTRODUCTION

A large number of studies have evaluated the physical demands of match-play and training within elite football (Mohr *et al*., 2003, Impellizzeri *et al*., 2006, Rampinini *et al*., 2007a, Bradley *et al*., 2009). In order to compete at the highest level, it is fundamental that football players develop the ability to repeatedly perform intense intermittent exercise for extended periods (Drust *et al*., 2007). This outcome can be achieved using training drills that incorporate the ball. This is often the preferred training method as it allows players to develop technical skills under match-like conditions. Therefore, small sided games (SSGs) and other drills are used by teams on a daily basis to improve and maintain physiological goals deemed important for match-play performance (Hill-Haas *et al*., 2011). In addition to sports-specific conditioning, research supporting the use of resistance-training has become increasingly prevalent (McGuigan *et al*., 2012). Muscular strength is the underpinning physical quality that influences powerful movement (Cormie *et al*., 2011a, Cormie *et al*., 2011b). Indeed, research in elite football players has shown a high correlation (r = 0.94) between lower limb strength and sprint performance (Wisloff *et al*., 2004). This, accompanied by the reduced incidence of 'soft-tissue' injury (Mjolsnes *et al*., 2004) supports the utility of structured resistance-training to improve aspects of performance and increase playing availability in elite football players.

Traditionally, football teams aim to develop football-specific fitness and maximal strength during the 'pre-season' period and then maintain both elements as the focus turns towards competition during the 'in-season' period (Hoff and Helgerud, 2004b). However, the already complex task of planning and implementing periodised training within applied environments can become increasingly challenging when training time is restricted because of other ‘coach led’ technical and tactical elements of training (Ronnestad *et al*., 2011b). The delivery of training intensity and volume affect acute molecular (Coffey *et al*., 2009b) and metabolic (Goto *et al*., 2005) responses associated with adaptation. If training is delivered in an unsystematic way the long-term adaptation may be negatively affected. Few studies have attempted a comprehensive analysis of the training organisation within professional football. Such data has the potential to identify difficulties in planning that may limit the successful outcome of the adaptive process. This type of evidence would seem to be important for the organisation of effective training programmes.

Therefore the purpose of this study was to investigate the training and nutritional practices at a professional football club. Specifically, the frequency and organisation of all training and games completed by a professional team across a 10 week period were examined. We hypothesised that when multiple training bouts were performed on the same day, the acute organisation of exercise sequence, nutritional availability and recovery time between training sessions would be unsystematic.

3.1 METHODOLOGY

3.1.1 Experimental design

Training completed by a men's senior football team competing in the English 'nPower Championship' was recorded across a 10 week period. The first 5 weeks were in the 'pre-season' period whereas the second 5-weeks were in the 'in-season' (July, August and September) period. The weekly training programme was categorised into 4 sub-components; 'football-training', 'resistance-training', 'games' and 'recovery-days'. Football-training was defined as a 'coach-lead' technical and tactical training session which typically involved a variety of 'small-sided games' and running drills with and without the football. Resistance-training was categorised as a training session in the gymnasium involving body-weight and free-weight resistance-exercises. Games were defined as a competitive game which took place within the 'nPower Championship' or the 'Capital one Cup'. Recovery-days were considered as a day off away from the training facility.

Training and competition took place across 4, 6 or 7 days each week with some days involving two training sessions. In total there were 48, 'football-training sessions', 11, 'games', 17 'resistance-training sessions' and 5 days off. In the 'pre-season' (weeks 1-5) 'friendly' games were arranged. one game was performed in weeks 2, 3 and 5 and 2 'friendly games were arranged in week 4. During the 'in-season' period (weeks 6-10), players were involved in one game in week 6, and week 10 and two games in week 7 and week 8. Week 9 was designated as an 'international week' therefore, *n* = 12 players trained and played for their respective countries. Subsequently no training or playing data was recorded for these players during this week. The frequency of training prescribed by the coaching staff is presented below in Table 2 (i.e. the amount of sessions available).

Table 2: The frequency of football-training, games, resistance-training and recovery-days prescribed by the coaches across the observational period.

Week	FT	Game	RT	OFF	Total
1	6	0	5	1	11
2	5	1	3	0	9
3	5	1	3	0	9
4	4	2	1	0	7
5	6	1	1	0	8
6	4	1	1	1	6
7	5	2	0	1	7
8	4	2	1	1	7
9	4	0	1	2	5
10	5	1	1	1	7
Total	48	11	17	7	

Table key: FT; football-training, Match; competitive game, RT; resistance-training, OFF; recovery-day

In order to accurately investigate the total training-load across the observational period, the 'total weekly training-load' for each training session and game was calculated using the rating of perceived exertion training-load (RPE-TL) method (Impellizzeri *et al*., 2004). Weekly football-training intensity and volume was also recorded by heart-rate and global positioning satellite (GPS) monitoring data. Weekly resistance-training volume and intensity was recorded using the repetition maximum (RM) (e.g. players lifted 6RM) and the 'volume-load' completed during each session respectively (McBride *et al*., 2009). The acute organisation of training was recorded using the concurrent-training sequence (e.g. resistance-football sequence or football-resistance sequence). The duration from the end of the first training session to the start of the secondary session was recorded as the 'recovery time'. Finally, the nutritional intake before and after each workout was also recorded. An Accredited Strength-and-Conditioning Coach (ASCC) from the United Kingdom Strength-and-Conditioning Association (UKSCA) and member of the football clubs sports science support staff watched all training sessions and recorded training data throughout the observational period. on occasions players did not participate in training due to ‘acute muscular strains’ (1-2 days) and international commitments (e.g. week 4) therefore these players were removed from the analysis during these time-points. The participants demographic and fitness data is presented below in Table 3.

Table 3: Participant demographic and fitness data (n = 21)

Physical Characteristics	Mean ± SD
Age (y)	26 ± 4
Stature (m)	1.84 ± 0.1
Body mass (kg)	83 ± 7
$\dot{V}O_2$ max (ml·kg^{-1}·min^{-1})	58 ± 3

Before providing written informed consent, all participants were informed of the nature of the study, of all associated risks, and of their right to withdraw at any time. This investigation followed the guidelines of the World Medical Assembly and was approved by the university’s research ethics committee.

3.1.1.1Total training-load

Total training-load for football-training, resistance-training and games was calculated using the RPE-TL method. Thirty minutes following each exercise bout players were asked to rate the intensity of the session using the 10-point RPE scale (Siegl and Schultz, 1984). The RPE training-load (RPE-TL) was then calculated by multiplying the RPE score by the duration of the training session (in minutes) to provide an index of the total training-load. The duration of all training sessions was recorded using a stopwatch (Casio, Japan). Football-training, resistance-training and game RPE load was then added together to equate the 'weekly training-load' data. The validity of this approach in assessing training-load in elite football players has been previously established (Impellizzeri *et al*., 2004).

3.1.1.2 Football-training volume and intensity

Football-training intensity was evaluated using a heart-rate monitor (Polar, Kempele, Finland). Heart rate was continually recorded throughout each training session and game. Heart rate is commonly used to assess exercise intensity in football (Karvonen and Vuorimaa, 1988). As average heart rate data fails to reflect the physiological demands of intermittent team sports, the amount of time spent in different heart rate zones is typically used to indicate exercise intensity (Stagno *et al*., 2007). for the purpose of this study the time distribution between 85-100% of HR_{max} (RZ) was used to represent exercise intensity during football-training (Stolen *et al*. 2005). In addition to a heart rate monitor players also wore a global positioning system (GPS) monitoring device during each football-training session (Statsports, Ireland, Ltd). Data for overall distance (OD), sprint distance (SD) (> 7m.s-1) and high speed distance (HS) (>5.5m.s-1) was recorded for further analysis. Heart rate and GPS training data was downloaded immediately following each training session and stored on a database for later analysis.

3.1.1.3 Resistance-training volume and intensity

Resistance-training programmes involve a number of different acute programme variables (e.g. repetitions, sets, relative intensity and contraction speed). Quantifying multiple training volume and intensity variables can be difficult. for this reason the 'volume load' (VL) method has been used to quantify 'total resistance-training-load' (Peterson, Pistilli *et al*. 2011). This method involves multiplying the reps, sets and weight lifted by each participant to reach one arbitrary unit for comparison. This VL method has been used to compare resistance-training prescription in experimental conditions (Kok *et al*. 2009; Tran *et al*. 2006) and when monitoring training in athletes (Haff *et al*., 2008). for the purpose of this study VL was recorded and used as a marker of resistance-training volume. Resistance-training intensity was also indicated using the repetition maximum (RM) the players were lifting during each training session (e.g. 8RM or 4RM). All gym based data was recorded by the principle investigator during each resistance-training session.

3.1.1.4 Acute organisation of training

When multiple training bouts were performed on the same day descriptive information was collected by the principle investigator. Data indicated the sequence of training (e.g. football-football, resistance-football and football-resistance) and each training start and end time. As the recovery duration between exercises can effect both acute peripheral fatigue (Docherty and Sporer, 2000) and acute metabolic responses to training (Goto *et al*., 2005) the time between exercise bouts was also recorded in minutes using a stopwatch (Casio, Japan). Furthermore, as the availability of key nutrients such as protein and carbohydrate can affect acute cellular signalling cascades associated with adaptation (Tipton and Ferrando, 2008) the nutritional availability around training was recorded. Nutritional intake was recorded as before the first training session, between training bouts and after the second training session. The type of nutrition consumed by the athletes was categorised as a meal (breakfast or lunch with protein source like eggs or meat) or a nutritional sports product that included a whey protein and carbohydrate source.

3.1.2 Statistical analysis

Statistical analysis was carried out using the statistical package 'IBM SPSS Statistics' (version 17.0). The average weekly training duration, training volume and training intensity and training-loads were compared across weeks 1 to week 5 using a general linear model with repeated measures. Estimated marginal means for the repeated analysis were corrected using Bonferrioni confidence intervals. Descriptive data is presented regarding the acute organisation of training. This included the sequence of training, the nutritional availability around training bouts and the recovery time allocated between training sessions. The statistical significance (*P*) was set at ≤ 0.05 and all information is presented as means ± standard deviations (M ± SD).

3.2 RESULTS

3.2.1 Frequency of training

Player adherence to each subcomponent of training during the observational phase is presented in Figure 4. No players completed all training and games across the 10-week period. on average the participants completed 74% of all football-training sessions, 60% of games and 60% of resistance-training sessions. Statistical analysis revealed significantly higher frequency of football-training compared to any other form of training ($P < 0.05$).

Table 4: Frequency of football, resistance-training matches and days off

	FT	RT	Match	Total	off
Week 1	4.9 ± 0.6	4.5 ± 0.8	0 ± 0	9.5 ± 1.2	1.0 ± 0
Week 2	5.1 ± 0.3	2.9 ± 0.3	1.0 ± 0	8.6 ± 1.8	0 ± 0
Week 3	5.0 ± 0	2.7 ± 0.5	1.0 ± 0	8.6 ± 0.7	0 ± 0
Week 4	4.0 ± 0	1.0 ± 0	1.8 ± 0.4	6.5 ± 0.7	2.0 ± 0
Week 5	5.4 ± 0.5	1.0 ± 0	1.0 ± 0	6.9 ± 0.3	1.0 ± 0
Week 6	4.4 ± 0.6	1.0 ± 0	1.0 ± 0	5.8 ± 0.8	1.0 ± 0
Week 7	4.7 ± 0.9	0 ± 0	1.8 ± 0.4	6.0 ± 0	0 ± 0
Week 8	4.8 ± 0.6	1.0 ± 0	102 ± 0.4	6.7 ± 0.4	1.0 ± 0
Week 9	4.0 ± 0	1.0 ± 0	0 ± 0	4.8 ± 0.4	3.0 ± 0
Week 10	4.4 ± 0.6	1.0 ± 0	1.0 ± 0	5.7 ± 0.7	0 ± 0

Key: FT; football-training, Match; competitive game, RT; resistance-training, Day off; ‘recovery-day’

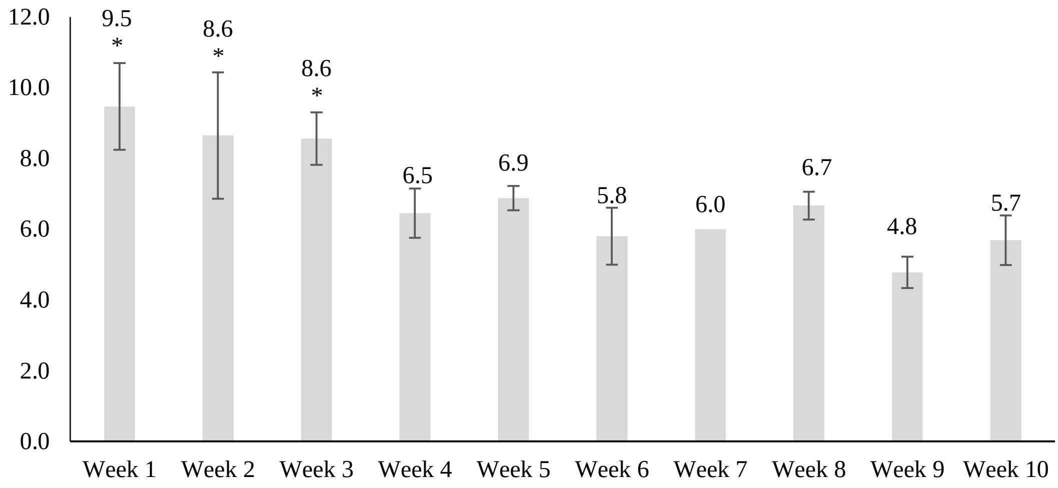

Figure 5: Total number of training sessions and games completed

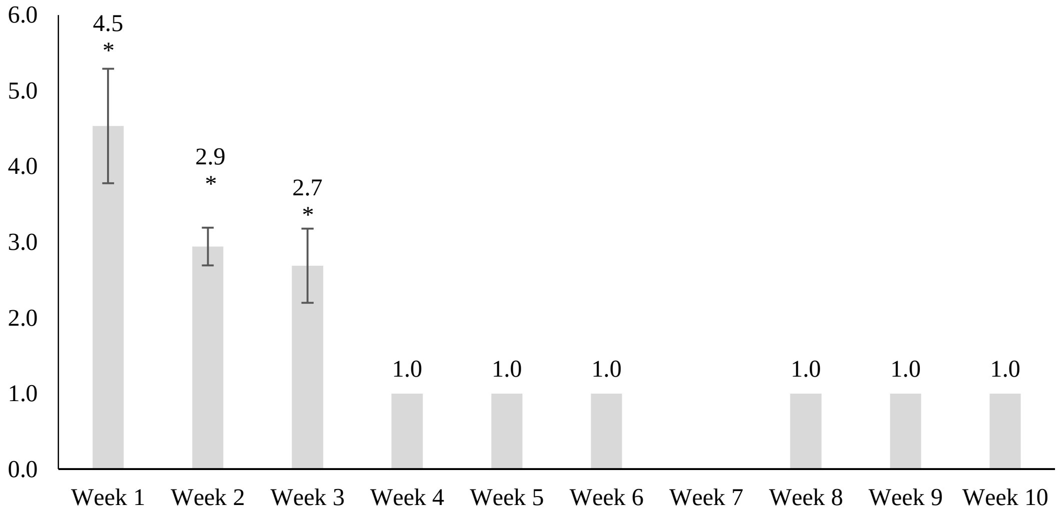

Figure 6: Total number of resistance-training sessions completed

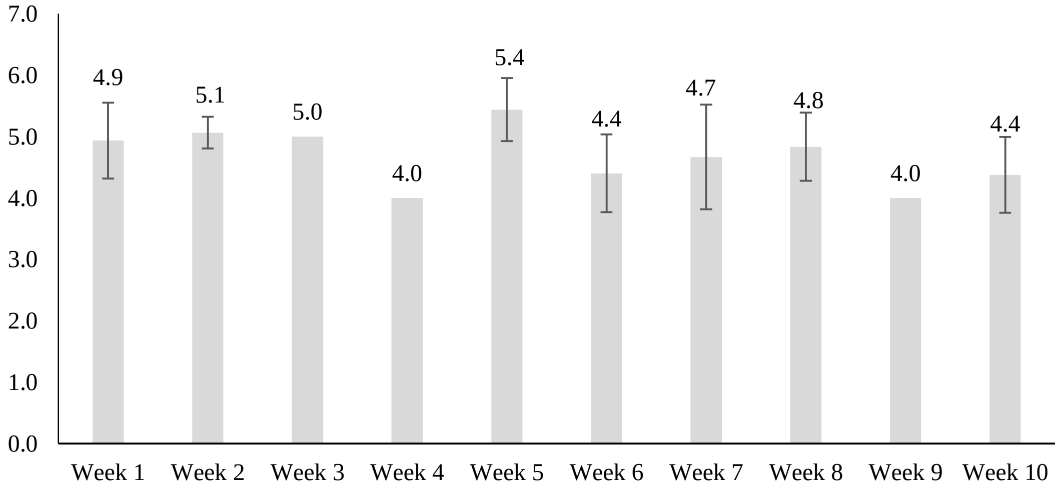

Figure 7: Total number of football training sessions completed

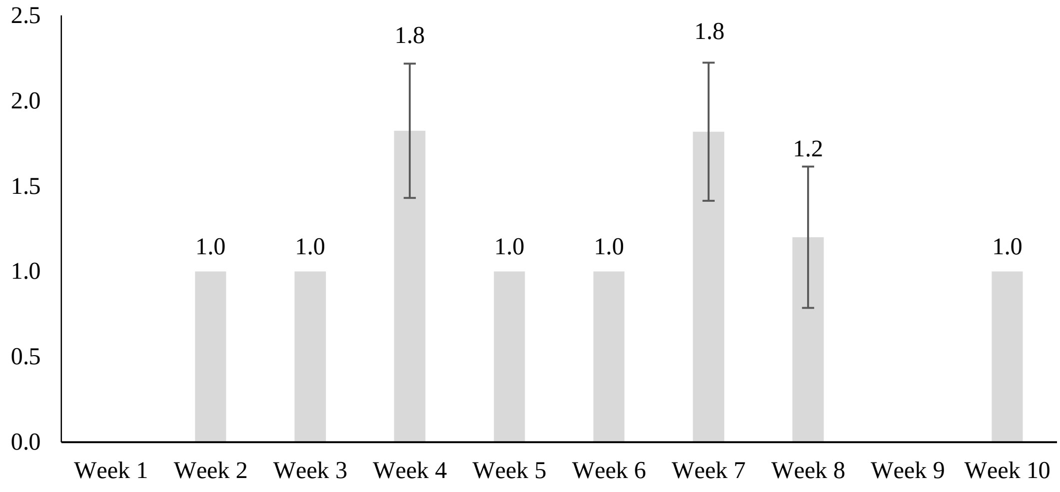

Figure 8: Total number of matches played

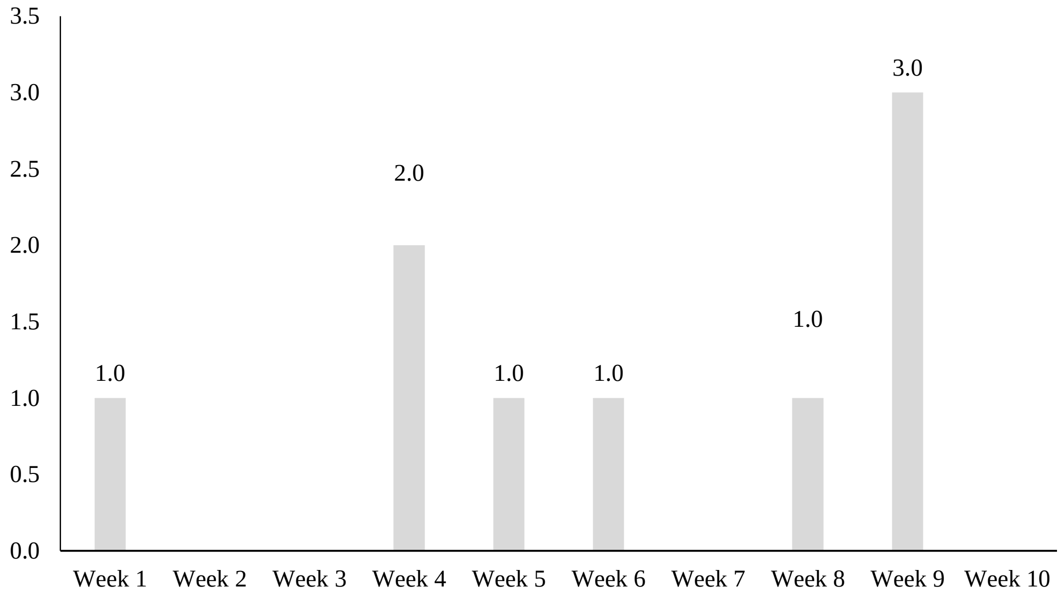

Figure 9: Total number of 'days off'

3.2.2 Rating of perceived exertion training-load (RPE-TL)

Descriptive information for the RPE-TL for each subcomponent of training is presented below in Figure 10 and Table 5. The average duration of a football-training session was 71 ± 8 (min). Perceived intensity of football-training was 6 ± 1 (AU). The average RPE-TL for football training was 1775 ± 484 (Table 5). The average length of match playing time during across the 10-week observational period was 91 ± 41 (min). Rating of perceived exertion for games was 7 ± 1 (AU). The average weekly RPE-TL for games was 712 ± 334 (AU). The average daily length of a resistance-training session 51 ± 7 (min). Rating of perceived exertion was 6 ± 1 (AU). The average weekly RPE-TL for resistance-training was 312 ± 98 (AU). The total RPE-TL included combined data from football-training, resistance-training and games across the observational period (Figure 5). The highest training-load occurred in week 1 (4558 ± 643 AU). The lowest training-load occurred in week 9 (1898 ± 562 AU). Repeated measures analysis revealed that the RPE-TL for week's 1, 2 and 3 were significantly higher when compared to weeks 4, 5, 6, 7, 8 9 and 10 ($P < 0.05$).

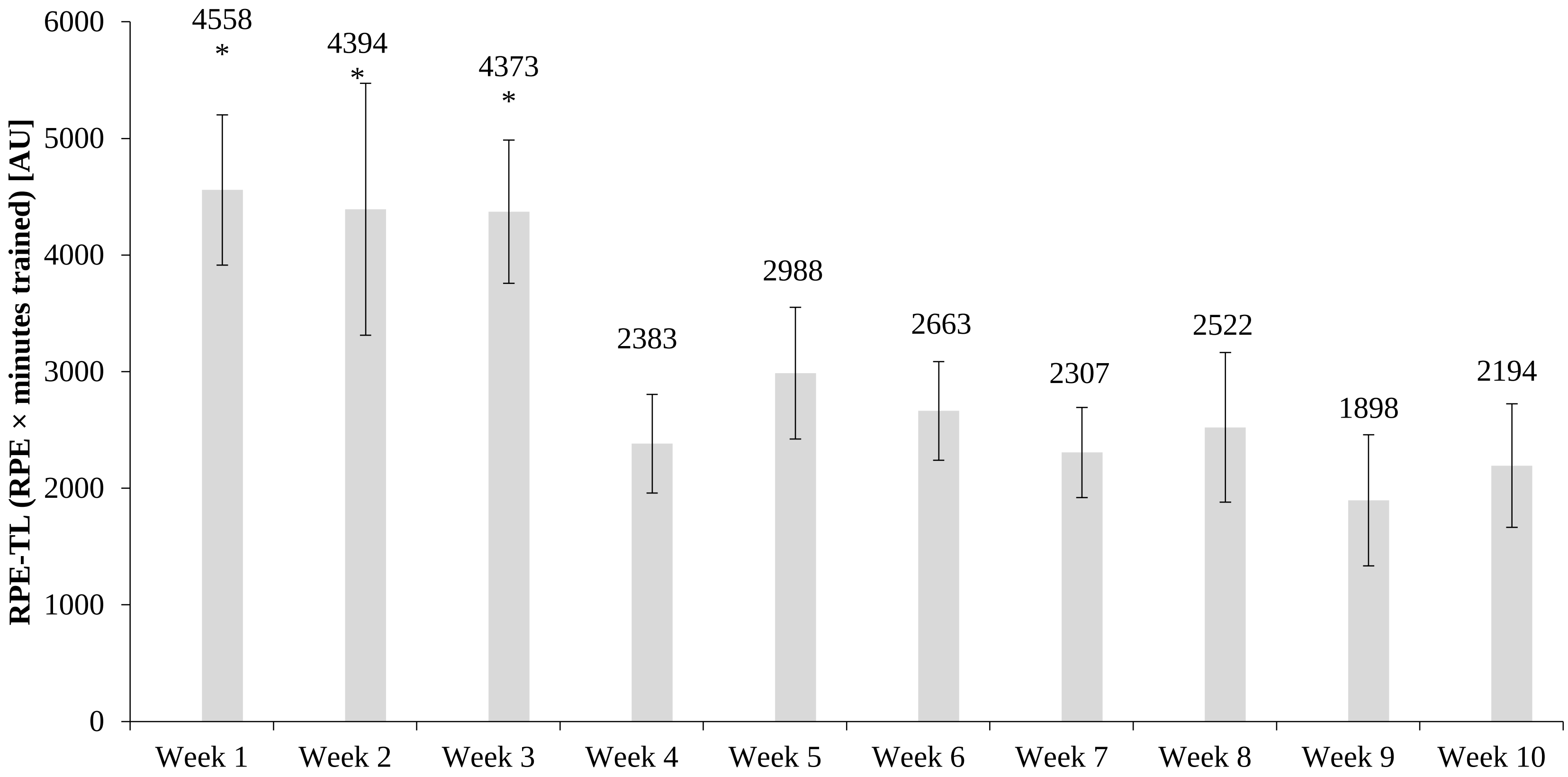

Figure 10: the total RPE-TL completed across the 10-week observational period.

Table 5: Average weekly RPE-TL for football-training, resistance-training, games and the total RPE-TL completed during the 10-week observational period. Data is presented as mean ± SD

	Week 1		**Week 2**		**Week 3**		**Week 4**		**Week 5**		**Average**
FT [AU]	2821 ± 387	(*n* = 15)	3251 ± 160	(*n* = 16)	2997 ± 384	(*n* = 16)	1504 ± 303	(*n* = 20)	2174 ± 407	(*n* = 16)	2549 ± 707
Match [AU]			264 ± 28	(*n* = 16)	251 ± 29	(*n* = 14)	637 ± 273	(*n* = 17)	833 ± 269	(*n* = 8)	496 ± 287
RT [AU]	1738 ± 317	(*n* = 15)	1085 ± 280	(*n* = 17)	1157 ± 250	(*n* = 16)	397 ± 114	(*n* = 17)	424 ± 58	(*n* = 15)	960 ± 562
Total	4558 ± 643	(*n* = 15)	4394 ± 1080	(*n* = 17)	4373 ± 614	(*n* = 16)	2383 ± 423	(*n* = 20)	2988 ± 565	(*n* = 16)	3739 ± 988

	Week 6		**Week 7**		**Week 8**		**Week 9**		**Week 10**		**Average**
FT [AU]	2033 ± 326	(*n* = 15)	1648 ± 585	(*n* = 15)	1775 ± 476	(*n* = 18)	1804 ± 654	(*n* = 9)	1633 ± 342	(*n* = 16)	1775 ± 484
Match [AU]	544 ± 234	(*n* = 7)	899 ± 458	(*n* = 11)	654 ± 193	(*n* = 15)	0	(*n* = 0)	510 ± 250	(*n* = 9)	712 ± 334
RT [AU]	369 ± 66	(*n* = 14)	0	(*n* = 0)	243 ± 47	(*n* = 15)	210 ± 20	(*n* = 4)	365 ± 113	(*n* = 12)	312 ± 98
Total	2663 ± 423	(*n* = 15)	2307 ± 286	(*n* = 15)	2522 ± 642	(*n* = 18)	1898 ± 562	(*n* = 9)	2195 ± 531	(*n* = 16)	2358 ± 560

Table key: FT: football-training, Match: competitive game, RT: resistance-training, Total RPE-TL; total rating of perceived exertion training-load (AU)

3.2.3 Football-training volume and intensity

During the observational phase distance covered (avg. 29367 ± 5984 m), sprint distance (avg. 189 ± 69 m) and time distribution in heart rate zone 85–100% of HR_{max}, (avg. 96 ± 48 min) was statistically different between weeks 1, 2 and 3 and the remaining 7 weeks of training (Table 5). High speed distance completed during week 4 was significantly higher than HSD completed in weeks 6, 8 and 10 but not statistically different to week 7 (Table 5).

Table 6: Average football-training intensity and volume completed during the 10-week observational period

	Week 1 (***n*** **= 18)**	**Week 2** (***n*** **= 16)**	**Week 3** (***n*** **= 17)**	**Week 4** (***n*** **= 15)**	**Week 5** (***n*** **= 16)**
OD [m]	33233 ± 8901*	39594 ± 2883*	35012 ± 4828*	28146 ± 5931	19882 ± 3464
HSD [m]	376 ± 362*	1399 ± 301	2019 ± 278*	1142 ± 357	434 ± 127
SD [m]	84 ± 48	160 ± 71*	202 ± 72*	187 ± 119*	54 ± 29
RZ [min]	106 ± 92*	87 ± 53	78 ± 38	86 ± 55	28 ± 16
	Week 6 (***n*** **= 15)**	**Week 7** (***n*** **= 15)**	**Week 8** (***n*** **= 18)**	**Week 9** (***n*** **= 9)**	**Week 10** (***n*** **= 16)**
OD [m]	25188 ± 5541	28540 ± 5139	23719 ± 5031	26532 ± 7165	23348 ± 7564
HSD [m]	878 ± 258	1062 ± 447	902 ± 309	*1459 ± 330	767 ± 331
SD [m]	184 ± 91	223 ± 118	137 ± 62	83 ± 73	157 ± 74
RZ [min]	63 ± 35	88 ± 40	66 ± 33	83 ± 87	62 ± 42

Table Key: Overall distance (OD), high speed distance (HSD) (>5.5m.s^{-1}), sprint distance (SD) (> 7m.s^{-1}) and time at > 85% HR_{max} (RZ)

3.2.4 Resistance-training volume and intensity

One resistance-training session was performed 5 times in the first week, three times in weeks 2 and 3 and once each week for the remainder of the observational period with the exception of week 2. Mean ± SD volume loads completed by the team are presented in Figure 6. Volume load was significantly highest in weeks 1 2 and 3. The intensity of resistance-training as indicated by the repetition maximum (RM) performed during each training session ranged from 4 to 8 RM (90 – 80 5 of 1RM) during the observational period.

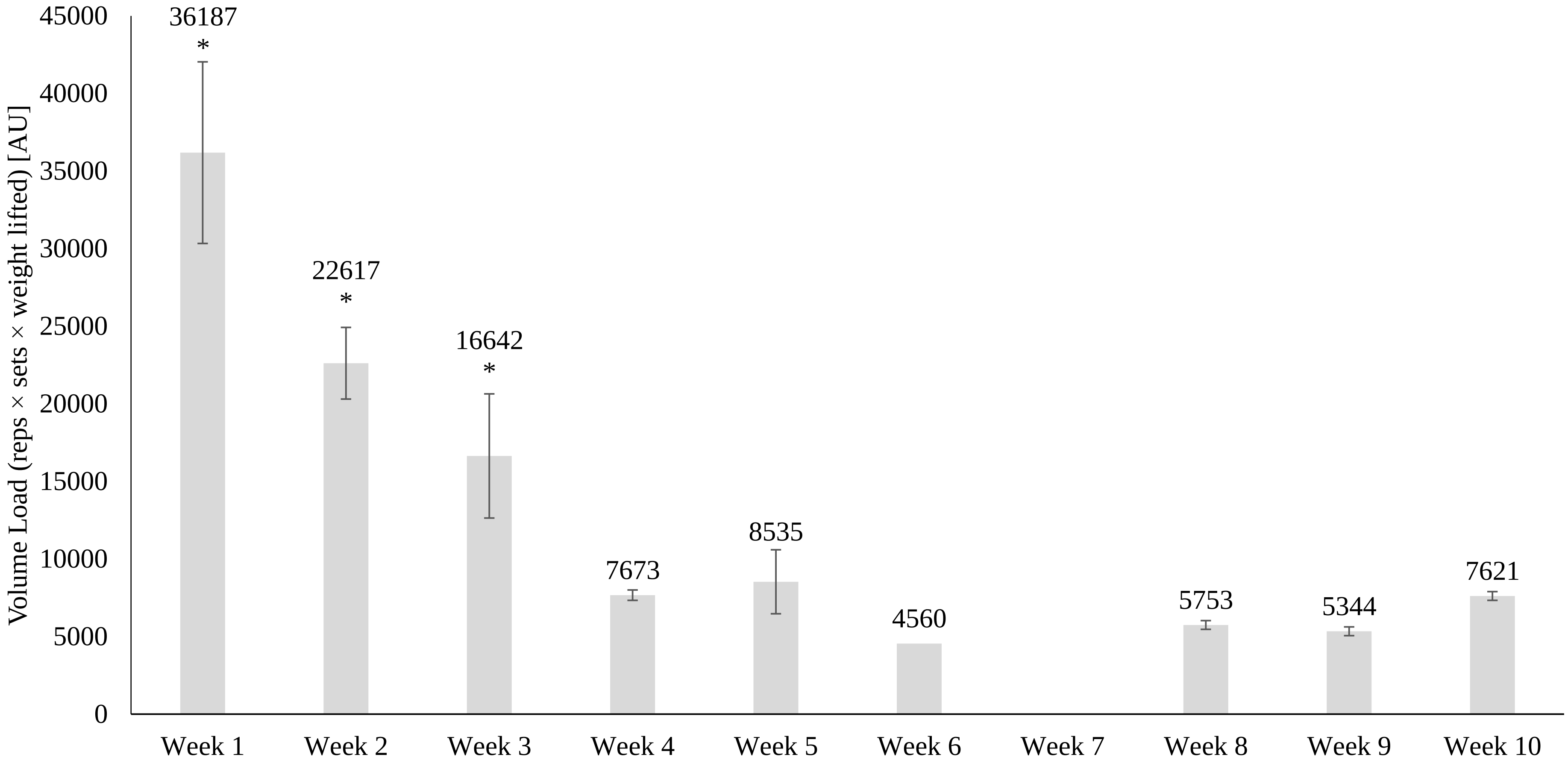

Figure 11: Average weekly resistance-training volume load (reps × sets × weight lifted) [AU] completed during the ten week observational phase.

3.2.5 Acute organisation of training.

on seventeen occasion's football and resistance-training were performed on the same day. The 'sequence' or 'order' in which resistance and football-training was not consistent. Resistance-training was performed before football-training on 5 occasion, whilst football-training was performed before resistance-training on 12 occasions (Figure 7).

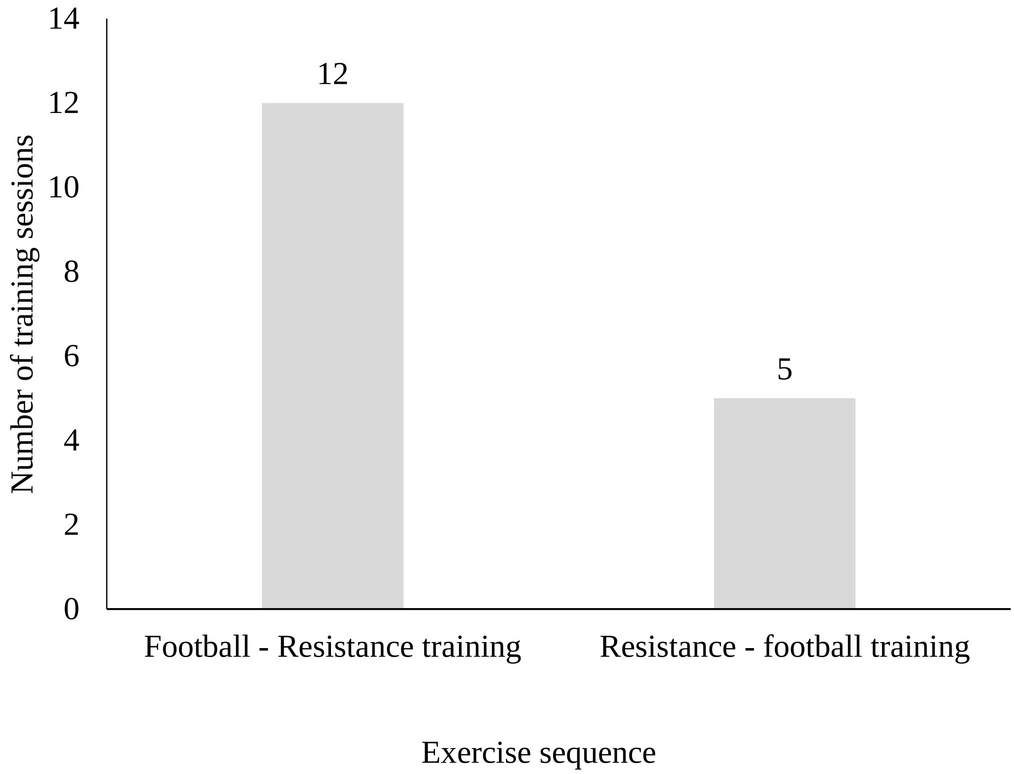

Figure 12: Number of times resistance-training was performed before and after football-training during observational period.

The frequency of upper and lower body resistance-training performed across the observational period is presented in Table 6. The recovery time between football and resistance-training was unsystematic across the observational period. When resistance-training was performed before football-training the recovery time between exercise bouts was between 30 and 60 minutes. When resistance-training was performed after football-training recovery time ranged from 35 to 60 minutes (Table

6). When resistance-training was performed before football-training both the football-training RPE and RZ (mins) were significantly higher ($P > 0.05$).

Table 7: Descriptive information concerning the exercise intensity, exercise sequence and nutritional arrangements on concurrent-training days

	Football - Resistance Sequence	Resistance - Football Sequence
Frequency of sequence	12	5
Recovery period (Mean ±)	75 ± 48	60 ± 5
Recovery period (range)	35 to 60 min	30 to 60 min
Nutrition		
Nutrition Before session 1	12 × Breakfast	no nutrition provided
Nutrition Between bouts	12 × Lunch	5 × Breakfast
Nutrition after session 2	12 × Protein shake	5 × Lunch
Resistance-Training		
Upper body RT	6	0
Lower body RT	3	0
Upper and Lower Body RT	3	5
8RM (80% of 1 RM)	10	0
5RM (87% of 1 RM)	2	4
4RM (90% of 1 RM)	0	1
Average RPE	6 ± 1	6 ± 1
Football-Training		
Distance	5942 ± 1057	6213 ± 958
85 – 100% HR_{max} (min)	5 ± 12	11
Average RPE	6 ± 1	7 ± 1

The nutritional availability before session 1, between exercise bouts and following session 2 is presented in Table 6. When resistance-training was performed before football-training players had no nutrition provided prior to resistance-training. on the remaining concurrent-training days players consumed a meal or nutritional product which included a protein source before, between and following each training session (Table 6). All meals consumed were recorded using photographs. Example meals including breakdown of macro nutrients are presented in the table below.

Table 8: example meals and breakdown of macro nutrients consumed during the observational period

	Protein	Carbohydrate	Fat	Calories
Breakfast 3 scrambled eggs, 2 slices of whole meal bread, spinach	33.9g	37.6	19.3	464
Lunch 1 Chicken breast, Pasta, cheese, Side Salad or Veg	47.9g	67.4g	13.9	593
Evening Meal (*not controlled) e.g. Lamb, Potatoes, Veg	61.6	83.8	18.8	766
Protein shake	25g	13g	0.5	220

3.3 DISSCUSSION

The aim of this study was to investigate the concurrent-training practices at a professional football club. The study had two specific aims; (1) to describe the training frequency and training-load completed by the team across a 10-week training period (2) to describe the acute organisation of same day football and resistance-training. The findings show that training frequency and training-load was significantly higher during the first three weeks of the observational period. It was thought that this may have been explained by the fact that this three week period was during the ‘pre-season’ training phase. Typically elite football teams engage in a 6 to 8 week ‘pre-season’ prior to the competitive phase (Reilly, 2003), therefore this relatively short ‘pre-season’ may have not been optimal to improve the players fitness (Bangsbo, 2006). The secondary findings from this study demonstrate that the organisation of concurrent-training was unsystematic. Furthermore, in some cases athletes trained without adequate nutrition prior to commencing training. This approach to training may not be optimal for acute muscle protein synthesis rates, longer-term muscle adaptation and indeed for muscle performance during the secondary training session. However, without additional experimental data these conclusions remain speculative. Therefore, the effect of different concurrent-training methodologies require further attention. This may lead to practical guidelines for teams who typically perform concurrent resistance and football-training on the same day.

The average weekly training RPE-TL described in this study (‘pre-season’; 3739 ± 988, ‘in-season’; 2358 ± 560) are similar to data previously reported for the ‘pre-season’ and ‘in-season’ period by Wrigley *et al*., (2012); 3948 ± 222 AU, and Impellizzeri *et al*., (2006) 2798 ± 322 AU respectively. However, our data is higher to that reported by Jeong and colleagues (2011); 1703 ± 173 AU. It is thought that this discrepancy may be explained by comparably lower football and resistance-training frequency reported in this study.

When weekly average total RPE-TL was compared across weeks significant differences were evident. Weeks 1, 2 and 3 were significantly higher when compared to weeks 4, 5, 6, 7, 8, 9, and 10. This may be explained by the periodisation approach used by the team across the observational phase. The first 5 weeks of the observational were categorised as the ‘pre-season’. This phase of the season is typically devoted to increasing player fitness following the ‘off-season’ when detraining may have occurred (Reilly, 2006). Although it is acknowledged that the ‘pre-season’ preparatory phase is typically 6 to 8 weeks. A longer ‘pre-season’ can allow for a linear progression of intensity and volume and thus reducing the likely hood of injury occurrence (Krustrup et al., 2005). Therefore is it not clear from this study why the intensity and volume was increased significantly during the first week of training following the ‘off-season’ period. It is also not apparent from this study why the increased training stress was only carried out for 3 weeks. The above factors may have increased the risk of injury to the players and been less optimal when compared to a longer ‘pre-season’ with a linear approach to training intensity and volume.

During the remaining 7 weeks of the observational period there were no significant differences in training load. This may have been due to the use of non-linear periodisation typically observed during the ‘in-season’ period in team sports. In team sports where the competition schedule is frequent, non-linear periodisation is typically used due to the reduced time to recover and prepare for competition (Fleck and Kraemer 2004). This training methodology is typically used to maintain fitness gained following an intensive ‘pre-season’ period and allows for variations in training intensity and volume between each training session (Stone *et al*., 1999b, Stone *et al*., 1999a, Gamble, 2006). Therefore, whilst there may have been fluctuation in training-load between days there was no differences between weekly training-load. However, considering the short pre-season period the increased training monotony (weeks 4 to 10) may not have been optimal for maintaining fitness. Previously monotonous training loads have been associated with increases in athlete fatigue and reduced performance gains (Smith, 2003, Kentta and Hassmen, 1998). Therefore, the absence of training-load fluctuation across weeks may not have been optimal for the athletes involved in this study. Although, few studies have investigated the acute and chronic effect of training-load in elite football players. Future research could investigate the effect of training-load on muscle fatigue and long-term performance in elite football players.

The sequence of concurrent football and resistance-training was not consistent throughout the observational period. Players performed resistance-training before and after football-training with different recovery durations between exercise bouts. Few studies have investigated the long-term effects of performing concurrent-training in different sequences, therefore it is difficult to say if this training strategy may be detrimental to muscle adaptation. The available evidence that investigates the acute molecular responses to training suggest that even slight alterations in the organisation of training could have profound effects upon long-term adaptation (Coffey et a., 2006). for example; when resistance-training is performed 6 hours after aerobic-exercise signals inside the muscle associated with improvements in aerobic and strength related performance become amplified (Wang *et al*., 2011, Lundberg *et* *al*., 2012). Whereas, when resistance-exercise and aerobic-exercise is performed with little recovery time between exercise bouts the molecular responses can become blunted (Coffey *et al*., 2009b). This suggests that both the exercise sequence and the amount of recovery time allocated between exercise bouts could have an effect on the intended adaptation. However, the acute or chronic responses to different concurrent-training protocols used by football players has not yet been elucidated especially in a "real world" setting. Therefore, future research could investigate the effects of performing different concurrent-training protocols in elite football players. This may have practical relevance to football players who perform these diverse types of training on the same day.

It is well documented that in order to maximise the anabolic potential during and following resistance-training, adequate carbohydrate and protein should be available before and after training (for reviews see; Jeukendrup, 2004, Tipton and Wolfe, 2004). This may be particularly important for athletes who are completing multiple training sessions each day (Jeukendrup and Jentjens, 2000). In the present study resistance-training and football-training were performed directly after each other with little nutrient provision between exercise bouts. It has been documented that low glycogen availability can influence a number of key signalling cascades responsible for adaptation (e.g. AMPK, mTOR) (Xu *et al*., 2012). Therefore, the reduced nutritional availability during the secondary training session may have inadvertently modulated the intended training response. Although, few data exist concerning the effect of concurrent-training in the 'fasted' and 'fed' states in trained athletes. More research concerning the effects of nutrient availability in concurrently training athletes is warranted. This may provide useful information for football teams who perform concurrent-training programmes

3.4 CONCLUSION

The aim of this study was to describe the concurrent-training practices at a professional football club. The greater training frequency and training-load observed in weeks 1, 2 and 3 could be explained by the fact that this period was during the 'pre-season' phase. Although, the relatively short duration of this 'pre-season' phase may not have been long enough to produce optimal training effects. Following the 'off-season' phase when player fitness has declined, football teams typically engage in a 6 to 8 week 'pre-season' period to regain physical capacity prior to the competitive phase (Reilly, 2003). In addition to the reduced length of the 'pre-season' period monotonous weekly training loads were observed across weeks 4 to 10. This lack of training fluctuation may also not have been optimal for longer term muscle adaptation and recovery. Collectively, the reduced pre-season period (i.e. 3 weeks) and the lack of fluctuation in training volume and intensity from weeks 4 to 10 may not be optimal for longer-term muscle performance (Fleck, 1999).

The second aim of this study was to observe acute organisation of concurrent resistance and football-training. It was found that players performed resistance-training before and after football-training with various recovery periods and nutritional intake. The longer-term training adaptations associated with the training and nutritional strategies observed in this study are not known. Future experimental research is required to understand the effectiveness of the training programmes used in this applied exercise setting. Specifically, investigating the effect of concurrent-training sequence, the recovery time between exercise bouts and the nutritional intake around training may be of particular importance. This type of research may provide information of significance to practitioners who aim to maximise the effectiveness of their training programmes.

CHAPTER FOUR

METHODOLOGY

THE RELIABILITY OF METHODOLOGICAL PROCEDURES DESIGNED TO INVESTIGATE A RANGE OF MUSCLE ADAPTATIONS FOLLOWING A CONCURRENT TRAINING PROGRAMME

4.0 METHODOLOGY

4.1 Experimental procedures

The battery of assessments was designed to measure muscle performance and muscle morphology. Muscle performance tests included strength and power assessments. Strength tests included a one-repetition maximum (1-RM) for the half-back squat exercise, peak isokinetic force of the dominant quadriceps/hamstring muscle groups and maximal isometric voluntary contraction (MIVC) for the quadriceps. Muscular power was measured using quadriceps MIVC rate of force development, vertical jump height and the fastest 10 and 30 metre sprinting time. Muscle morphology of the thigh was measured using ultrasonography. Morphology indices included muscle thickness and muscle architecture (vastus lateralis fascicule angle of penneation and length).

4.1.1 Reliability

In order to reduce the likelihood of systematic bias the following methodological measures were followed. Participants took part in three familiarisation sessions, which involved both sub maximal and maximal practices on each test, one each week for three weeks prior to formal testing. Testing days were always preceded by a 48h period where no physical exercise was carried out. Paired t-tests revealed systematic bias between trials was non-significant ($P > 0.05$). In order to minimise the random error participants always completed standardised protocols at the same time of day.

4.1.2.1 Isokinetic assessment overview

Measurements of isokinetic strength were assessed using an isokinetic dynamometer (Kin.com, Harrison Tennessee, U.S). Each participant visited the laboratory at the same time-of-day on three occasions separated by one week. Day one involved a familiarisation session whilst days two and three were used as experimental trials. These two trials served to provide the data for the test-retest analysis. on each day individuals performed a standardised warm-up prior to testing. This involved 10 minutes cycling (>70 RPM) followed by 5 minutes of dynamic stretching. Participants also performed a test specific warm-up on the isokinetic dynamometer (described below). To avoid inter-tester variability all measurements were conducted by the same experimenter.

4.1.2.2 Isokinetic set up

To allow accurate duplication of testing procedures, the isokinetic dynamometer positions specific to each individual were documented and replicated at each testing session. The initial setup involved aligning the rotational axis of the dynamometer with the posterior aspect of the participants' lateral femoral condoyle (Iga *et al.*, 2006). At this position the leaver arm length, dynamometer height and seat position was recorded and replicated upon return to the laboratory. Gravitation torque was not determined at the position of maximal gravitational effect, (i.e. zero degrees of knee flexion) as forces may become overestimated as a result of passive or active muscle components (Westing and Seger, 1989). Therefore, to minimise underestimation of knee extensor peak torque and overestimation of knee flexor peak torque, gravitational torque of the 'limb-lever system' was directly measured at 14 degrees of knee flexion on each testing occasion.

4.1.2.3 Familiarisation

The familiarisation process involved a series of submaximal and maximal efforts at the relevant angular velocities and muscle actions on 3 separate occasions separated by one week. Using the quadriceps and hamstrings, participants performed concentric repetitions at 60% 80% 90% and 100% of perceived maximum effort at 60 and 180 degrees per second. Individuals also performed eccentric repetitions at 60% 80% 90% and 100% of perceived maximum effort, at 120 degrees per second (Morton *et al*., 2005).

4.1.2.4 Isokinetic assessments

The two ‘experimental sessions’ were separated by a 7 day recovery period. Prior to the test, participants were allowed an isokinetic specific warm-up containing three sub-maximal and one maximal effort at 60, 120 and $180^0 \cdot s^{-1}$. This was followed by the assessment of peak concentric and eccentric strength of the quadriceps and hamstrings. Each assessment involved bidirectional movements of the knee (extension & flexion) at 60, 120 and $180^0 \cdot s^{-1}$.and was performed throughout 90^0 to 10^0 of knee extension & flexion (where 0^0 is full extension). Slower angular velocity actions were performed before higher velocity tests to promote learning effects and reduce the risk of an injury. During each maximal repetition, the participants were instructed to hold the side of the seat whilst pushing as hard and as fast as they could. Standardised visual feedback using on screen graphs and verbal encouragement was given throughout the test (Morton *et al*., 2005). To avoid any unwanted involvement from other muscle groups, stabilisation straps were placed across the trunk, pelvis and engaged leg (Iga *et al*., 2006) Participants performed between 3 to 5 maximal efforts at each speed. A rest period of 30 seconds was allocated between consecutive bidirectional movements and 3 minutes was allocated between each angular velocity.

Hamstring : Quadriceps ratios'

Subsequent data was used to calculate the functional $HAMSTRING_{ECCENTRIC}$: $QUADRICEPTS_{CONCENTRIC}$ (H_{ECC}:Q_{CON}) and $HAMSTRING_{ECCENTRIC}$: $QUADRICEPTS_{CONCENTRIC}$ (H_{ECC}:Q_{CON}) at $60^{o}\cdot s^{-1}$ and $180^{o}\cdot s^{-1}$ (Iga *et al*., 2006)

4.1.2.5 Maximal Isometric Voluntary Contraction (MIVC), Isometric Loading Rate (ILR)

To ensure each contraction was isometric (no movement), the participants were required to preload the force cell in the direction of the MIVC (with approximately 80 Newton's) for a period of three seconds before each MIVC. Each participant was allowed 3 maximal efforts with 2 minutes recovery between each trial. Data with a reduction in torque prior to MIVC were regarded as not isometric and were subsequently removed from the analysis. The peak force (N) without a subsequent reduction in torque was recorded. All three efforts were plotted on the same graph. The effort with the steepest gradient was used in the analysis of the isometric loading rate (ILR). The isometric loading rate (ILR) was calculated using the equation below in Figure 8. Moment $_{70}$ and Moment $_{20}$ represent 70% and 20% of peak torque (Nm) respectively. Time $_{70}$ and Time $_{20}$ represent the time at which each value was achieved (Woodard *et al*., 1999).

$$\text{ILR} = \frac{(\text{Moment}_{70} - \text{Moment}_{20})}{(\text{Time}_{70} - \text{Time}_{20})}$$

Figure 13: Method previously described by Woodard, James *et al*., (1999) for the estimation of rate of force development.

4.1.3 Muscle power-related variables

4.1.3.1 Vertical jump-height, sprinting speed and 1-repetition for the half back-squat

The vertical jump, 10 and 30 metre sprint and half back-squat one repetition maximum (1-RM) were all assessed on the same day, on two separate occasions, separated by one week. Each test commenced at the same time-of-day, and was carried out by the same experimenter(s). Vertical jump testing began at approximately 09:30 am with the sprint test following at approximately 10:30hrs. The 'back-squat strength test' was performed at 14:00hrs on each occasion. Prior to formal testing all participants took part in a familiarisation day. Familiarisation involved both verbal and visual instruction on all test procedures and an opportunity for all participants to practice each test. Practice involved a series of submaximal and maximal efforts during this session.

Before all tests, participants completed a standardised dynamic warm-up. Vertical jump height was measured using a jump mat (FLSelectronics, Cookstown, Northern Ireland). Participants were instructed to complete 2-3 maximal efforts in both the squat jump (SJ) and the countermovement jump (CMJ). Participants stood with feet shoulder width apart with their hands placed on their hips throughout each movement. Three minutes was allocated between each effort for recovery. The highest countermovement and squat jump was recorded for analysis. Following the vertical jump testing, participants completed 3 maximal 30 metre sprints on an outdoor grass surface. Between each sprint participants were allowed a 3 to 5 minute recovery period (Earle and Baechle, 2004). The fastest sprint time was recorded for analysis.

The half back-squat 1-RM was assessed using free-weights and a squatting rack (Ivanko, San Pedro, California, U.S). Participants performed back-squat specific warm-up repetitions of around 50%, 70%, 80% and 90% of a previous or self-estimated 1-RM score. This was followed by a series of maximal repetitions each separated by 3-5 minute rest periods. The maximum weight in kilograms lifted for a repetition that was performed to a knee angle of 90 degrees between the participants' femur and tibia was recorded for analysis. (for more information regarding the 1-RM protocol used in this thesis please refer to Earle and Baechle, 2004). All the participants involved in this study had a minimum of 2 years of resistance-training experience and had completed numerous 1-repetition maximum testing sessions as part of their training programme.

4.1.4 Muscle morphology

4.1.4.1 Muscle architecture variables (muscle thickness, fascicule length & fascicule angle of pennation)

Following a recovery day after the field-testing each participant visited the laboratory at the same time-of-day on two separate test occasions separated by one week. Upon arrival, landmarks were placed on each individual's dominant leg at a distance of 50% between the lateral femoral condyle and the greater trochanter using a 1 metre measuring tape and a felt tip pen. Landmarks were measured and marked in the standing position by an experienced investigator (Rutherford and Jones, 1992). Participants were then seated on the edge of a seat with hips and knees at right angles. Using a high resolution B-mode ultrasound scanner (12 MHz) (LOGIQ-e, Fairfield, Connecticut, U.S), images were taken at the designated landmark. Acoustic gel was placed over the probe head (40mm linear-array transducer) to aid acoustic coupling during measurement. Three sagittal images at the mid-point of the thigh were saved for retrospective analysis. Upon arrival on the second testing occasion, landmarks' were re-marked onto the participants' dominant leg (using the procedures described above). Images were captured for retrospective analysis using exactly the same approach to that of the first.

4.1.4.1.1 Image analysis

Images were digitally analysed using 'LOGIQ-e software' (built into ultrasound scanner) to determine whole muscle thickness (WMT), fascicle length (FL), and fascicle angle of penneation (AoP). The built-in image software allowed the experimenter to accurately calculate distances and angles using a moving a cursor between designated points (Figure 9). To avoid inter-tester variability all measurements and image interpretation was conducted by the same experimenter.

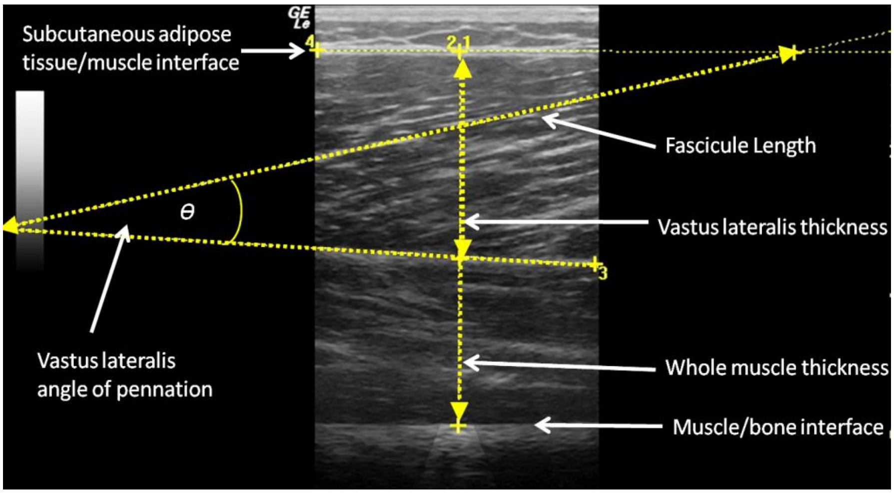

Figure 14: Ultrasound image of the vastus lateralis (VL) and vastus intermedius (VI) muscles, vastus lateralis fibre angle of penneation (AoP), vastus lateralis fascicle length (FL) and whole muscle thickness (WM-T).

Table 9: Test re-test reliability data (mean ±), t-test (P) (systematic bias), 95% ratio limits of agreement (LoA), coefficient of variation (CV) (%), CV *1.96 (%) for muscle strength indices and isokinetic functional reciprocal muscle group ratios (Dominant leg

	Test 1	**Test 2**	***t*-test (*P*)**	**95% ratio LoA**	**CV (%)**	**CV *1.96 (%)**	**SEM**	**SEM *1.96**	**TEM**	**TEM (%)**
Quadriceps										
Concentric *60° • s* $^{-1}$	236 ± 41	235 ± 39	0.85	0.98 × / ÷ 1.17	5.7	11.2	13.4	26.2	12.4	2.6
Concentric *180° • s* $^{-1}$	216 ± 36	216 ± 37	0.59	1.00 × / ÷ 1.09	3.1	6.2	6.8	13.3	6.4	1.5
Eccentric *120° • s* $^{-1}$	295 ± 41	294 ± 47	0.57	0.99 × / ÷ 1.11	4.0	7.8	11.7	22.9	10.6	1.8
Hamstrings										
Concentric *60° • s* $^{-1}$	130 ± 25	130 ± 22	0.71	1.00 × / ÷ 1.18	5.8	11.3	7.5	14.8	7.3	2.8
Concentric *180° • s* $^{-1}$	135 ± 25	140 ± 28	0.18	1.03 × / ÷ 1.26	12.4	24.3	12.4	24.3	12.5	4.5
Eccentric *120° • s* $^{-1}$	184 ± 36	191 ± 35	0.57	1.04 × / ÷ 1.19	10.6	20.9	10.6	20.9	11.3	3.0
H: Q Ratio										
$H_{CON}^{60} : Q_{CON}^{60}$	0.55 ± 0.10	0.55 ± 0.09	0.77	1.02 × / ÷ 1.27	8.9	17.5	0.05	0.10	0.04	4.1
$H_{ECC}^{120} : Q_{CON}^{60}$	0.79 ± 0.19	0.82 ± 0.17	0.21	1.05 × / ÷ 1.28	8.4	16.5	0.07	0.13	0.07	4.1
$H_{ECC}^{120} : Q_{CON}^{180}$	0.86 ± 0.16	0.90 ± 0.17	0.06	1.04 × / ÷ 1.19	5.7	11.1	0.05	0.10	0.05	3.0
Squat 1RM (kg)	107 ± 15	108 ± 15	0.16	1.02 × / ÷ 1.04	1.6	3.2	1.74	3.4	1.82	0.85

Table 10: Test re-test reliability data (mean ±), t-test (P) (systematic bias), 95 %

ratio limits of agreement (LoA), coefficient of variation (CV) (%), CV *1.96 (%) for muscle power indices (n = 17).

	Test 1	**Test 2**	***t*-test (*P*)**	**95% ratio LoA**	**CV (%)**	**CV *1.96 (%)**	**SEM**	**SEM *1.96**	**TEM**	**TEM (%)**
SJ (cm)	38.7 ± 4.3	39.0 ± 3.5	0.54	1.01 × / ÷ 1.13	3.6	7.1	1.4	2.8	1.4	1.8
CMJ (cm)	40.8 ± 4.2	41.4 ± 3.5	0.27	1.03 × / ÷ 1.16	4.1	8.1	1.7	3.32	1.7	2.0
10m Sprint (s)	1.71 ± 0.08	1.72 ± 0.06	0.48	1.00 × / ÷ 1.06	2.1	4.1	0.04	0.07	0.04	1.0
30m Sprint (s)	4.37 ± 0.24	4.35 ± 0.21	0.62	0.98 × / ÷ 1.07	1.9	3.6	0.08	0.16	0.08	0.9
ILR	1185 ± 316	1163 ± 268	0.7	1.00 × / ÷ 1.15	4.0	7.9	47.2	92.5	45.8	1.9
MIVC (N)	691 ± 148	671 ± 130	0.34	0.95 × / ÷ 1.06	4.1	8.0	27.2	54.3	29.0	2.1

Table key: MIVC; Maximal Isometric Voluntary Contraction ILR; Isometric Loading Rate.

Table 11: Test re-test reliability data (mean ±), t-test (P) (systematic bias), 95% ratio limits of agreement (LoA), coefficient of variation (CV) (%), CV *1.96 (%) for muscle morphology indices (n = 17).

	Test 1	**Test 2**	***t*-test (*P*)**	**95% ratio LoA**	**CV (%)**	**CV *1.96 (%)**	**SEM**	**SEM *1.96**	**TEM**	**TEM (%)**
VL^{θ} (o)	16.0 ± 2.4	15.5 ± 2.5	0.24	0.93 × / ÷ 1.15	7.5	14.7	1.2	2.3	1.2	3.8
ℓ_F (cm)	10.5 ± 1.2	10.4 ± 1.3	0.67	1.00 × / ÷ 1.17	5.1	9.9	0.53	1.04	0.51	2.5
MT (mid) (cm)	6.1 ± 0.4	5.0 ± 0.4	0.18	0.97 × / ÷ 1.06	1.8	3.5	0.09	0.17	0.09	0.9
MT (Distal) (cm)	4.71 ± 0.41	4.67 ± 0.42	0.09	0.95 × / ÷ 1.07	2.2	4.3	0.10	0.20	0.12	1.3

Table key: VL $^{\theta}$; Vastus lateralis fascicule angle of pennation (^{0}), ℓF; Fascicle Length (cm), MT; Vastus lateralis and vastus intermedius muscle thickness

CHAPTER FIVE

MUSCLE ADAPTATIONS FOLLOWING FIVE WEEKS OF CONCURRENT FOOTBALL AND RESISTANCE-TRAINING IN PROFESSIONAL YOUTH FOOTBALL PLAYERS

STUDY 3: ABSTRACT

MUSCLE ADAPTATIONS FOLLOWING FIVE WEEKS OF CONCURRENT FOOTBALL AND RESISTANCE-TRAINING IN PROFESSIONAL YOUTH FOOTBALL PLAYERS.

Purpose: The aim of this study was to describe the changes in indicators of muscular performance and adaptations in muscle morphology following 5-weeks of concurrent-training in professional youth football players. **Methods:** Seventeen professional male football players from an English Premier League Academy volunteered to participate in this study (mean ± SD 17.0 ± 0.5 yrs, stature, 180 ± 5.3 cm, body mass, 76.5 ± 7.5 kg). Participants were assigned to a condition where football-specific endurance-training (E) was performed at 10:30h prior to strength (S) training at 14:00h (E+S) Concurrent-training was performed for 5-weeks and consisted of five to six football-specific endurance-training sessions plus one competitive game and 2 strength-training sessions each week. Before and following training participants muscle strength, muscle power related variables and muscle morphology was measured. **Results:** Following training significant time effects were observed for muscle strength parameters; half-back squat ↑11.5%, P = 0.04, Quadriceps 180^{o}·s^{-1} CON; ↑17%, P = 0.02, Hamstring 120^{o}·s^{-1} ECC; ↑14%, P = 0.05, 10 meter sprinting time ↓ 6%, P = 0.04, Yo-Yo distance (m) ↑ 23%, P = 0.02. Vastus lateralis fascicule angle of pennation ↑ 13%, P = 0.01. **Conclusion:** The findings demonstrate that both sports-specific aerobic fitness and muscular strength can be improved simultaneously. Our data suggest that improvements in muscular strength can be attributed to architectural and neuromuscular adaptation and less so to increases in muscle hypertrophy.

Keywords: Football, Resistance-training concurrent-training, muscle architecture

5.0 INTRODUCTION

In professional football several physical fitness components are required for successful performance (Stolen *et al*., 2005). Elite players possess high levels of sports-specific endurance, speed, agility, and muscle strength (Bangsbo *et al*., 2006). As a result, a variety of diverse training interventions are implemented simultaneously by football teams (Bishop *et al*., 2011). for example aerobic fitness is trained using field-based sessions such as small-sided games (SSGs), while gym-based resistance-training programmes are employed to maximize muscle strength (Rampinini *et al*., 2007c, Chelly *et al*., 2009). The findings from our initial observational investigation (Chapter 3) highlight that footballers often perform multiple training bouts on the same day. This situation can be attributed to the demands of the competition schedule and the subsequent reduced available training time. Our data demonstrated that elite football players perform football training using SSGs in the morning (10:30 hr) and resistance-training either in the early morning (08:30 hr) or in the early afternoon (14:00 hr). At present the long-term physiological responses associated with either training structure are not understood. This is largely due to the present lack of published articles investigating the effect of concurrent-training sequence in professional football players. Therefore, future research is required to quantify the adaptations following a concurrent-training cycle using the training methods used in football.

To interpret the effectiveness of concurrent-training programmes in the forthcoming experiments it is necessary to initially quantify the 'margin of error' associated with our chosen experimental protocols. The reliability of field and laboratory assessments are calculated using a 'test re-test' reliability study. During this analysis the participants perform each assessment on two separate occasions in a controlled manner. To calculate the ‘margin of error’, the data collected form each trial is then compared using appropriate statistical methods (Atkinson and Nevill, 1998). It is important that prior to each reliability study the ‘learning effects’ associated with each test is removed using a familiarisation process. To ensure that muscle fatigue is minimised it is necessary that sufficient recovery time is allocated between tests (Hopkins, 2000).

This chapter had two specific objectives (1) to quantify the reliability of a battery of tests designed to interpret indices specific to concurrent-training programmes used by elite football players and (2) to describe the changes in indicators of muscular performance and adaptations in muscle morphology following 5-weeks of concurrent-training in professional youth football players. As statistical methods to calculate the ‘margins of error’ vary considerably, this chapter employed a range of reliability statistics for each measurement tool (Atkinson and Nevill, 1998).

5.1 METHODOLOGY

5.1.1 Participants

Seventeen professional male football players from an English Premier League Academy volunteered to participate in this study (Table 12). After receiving oral and written information concerning any possible risks associated with the training and testing protocols, all participants gave their written informed consent to participate in the study. The study conformed to the code of ethics of the World Medical Association and was approved by the Ethics Committee of Liverpool John Moores University.

Table 12: Participant demographic and fitness data (n = 17)

Physical Characteristics	Mean ± SD
Age (y)	17 ± 1
Stature (m)	1.81 ± 0.05
Body mass (kg)	75.4 ± 5.9
$\dot{V}O_2$ max ($ml \cdot kg^{-1} \cdot min^{-1}$)	58.5 ± 5.0

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5.1.2 Experimental design

Participants performed a 5-week block of training in which football-specific endurance-training was followed by strength-training (E+S, n = 16). In the week before and after the 5-week training block, participants were assessed for measures of muscle strength, power-related variables and muscle morphology. Previously, in order to quantify the margins of error associated with each experimental procedure all participants completed familiarisation and a test re-test 3 weeks prior to the experimental phase. Reliability statistics are presented in chapter 4. The inclusion criterion for the study was ≥ 80% adherence to training sessions. Eight players did not adhere to these criteria (due to injury and variations in the club training schedule) and as such, data are presented hereafter for the remaining eight players who met all inclusion criteria for this study.

5.1.2.1 The organisation of pre and post training testing protocols

The week prior to, and the week following the intervention period, training volume and intensity was reduced and resistance-training was removed from the programme. This allowed additional time to complete the battery of physiological assessments and also reduced the likelihood of fatigue. The schedule of testing is presented in Figure 10 below. Following a recovery day muscle architecture and body composition were measured on ‘Day 1’ (9-11am). on ‘Day 2’ following two consecutive days of rest vertical jump height, (9am) sprint speed (10am) and 1RM squat strength (12pm) was measured on ‘Day 2’. Isometric and isokinetic strength were measured on ‘Day 4’ following a recovery day (i.e. ‘Day 3’). The Yo-Yo test was performed on the morning of ‘Day 5’ at 10.30am. Individuals performed isometric and isokinetic testing at randomised timeslots between 9am and 4pm. To minimise ‘time-of-day effects’ testing times were replicated for each individual at the later testing time-point.

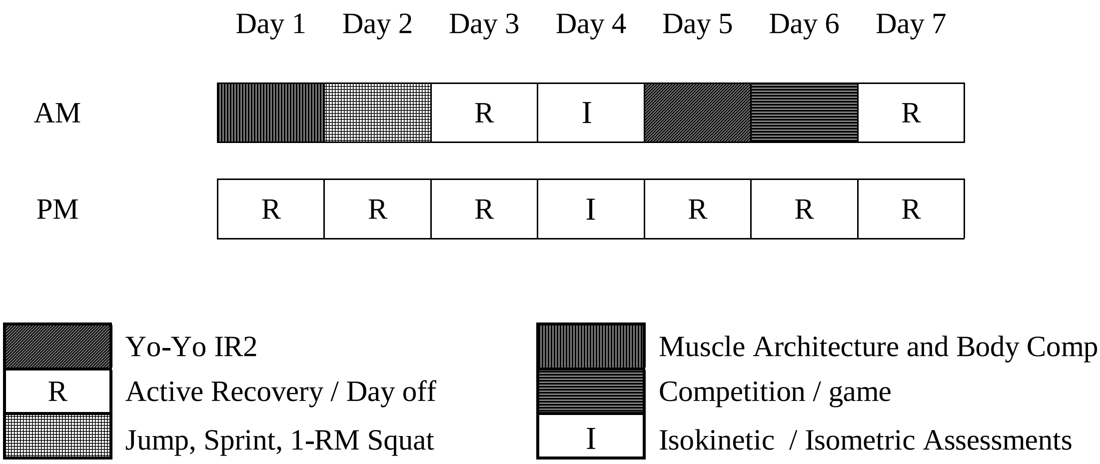


Figure 15: The organisation of physiological testing before and after the intervention period.

5.1.3.1 The training programme

During the intervention participants completed 8 training sessions each week. This consisted of two football-specific endurance-training sessions using small-sided games (SSGs) (E), two resistance-training sessions (S), three technical and tactical training sessions plus one competitive game. on Mondays and Thursdays, football-specific endurance-training sessions was completed at 1030 h followed by resistance-training at 1400 h. Technical and tactical training took place on Tuesdays (1030 h / 1400 h) and Fridays (1030 h), whilst competitive games took place at 1100 h on Saturday. The training intervention was carried out in the first five weeks of the competitive season (August/ September).

	Mon	Tues	Wed	Thur	Fri	Sat	Sun
Am	SSG & tech	Tech & tact	Rest	SSG & tech	Tech & tact	Game	Rest
Pm	RT	Tech & tact	Rest	RT	Rest	Rest	Rest

Key; RT; resistance-training, SSG, Small-sided games (4 v 4, 4 min at 90-95% HR^{max}, 3 min active recovery x 4), Tech; Technical skills training, Tact; tactical awareness training.

Figure 16: The organisation of endurance conditioning, football training resistance-training, games and rest days throughout the intervention period.

Football-specific endurance-training (E) consisted of small-sided games, involving a 4 verses 4, possession format. Each game lasted 4 minutes and was performed at around at 90-95% HR^{max}. Three min of active recovery was allocated between each game. Games were performed on a 37 m x 27 m pitch (for more detail on this game format and reliability statistics the reader is directed to the following articles; Little and Williams, 2007, Hill-Haas *et al*., 2008a, Hill-Haas *et al*., 2008b) All SSGs were conducted as part of training, and were performed immediately following an initial warm-up. Technical and tactical training sessions were designed by the team coach and included a variety of skills drills and tactical plays. Games represented competitive fixtures in the Barclays U18 Premier league.

The present experimental chapter incorporated 4 sets of 6 maximal repetitions (6 RM) of the following lower limb resistance based exercises: half-back squat, dead-lift, stiff-leg dead-lift and front-lunge. Participants also completed 3 sets of 8 repetitions of the Nordic hamstring exercise. The above resistance-training protocols were replicated from the training programmes previously observed in Chapter 3. Previously, authors have demonstrated that increased body mass following resistance-training can have detrimental effects upon aerobic performance in elite football players (McMillen et al., 2006). Therefore, the present resistance-training programme was designed to increase muscle strength via neural and architectural adaptations (Hoff et al., 2002). Lower limb multi-joint exercises were utilised to promote the likelihood of force transfer to functional movements that may be beneficial to football performance (e.g. jumping and sprinting) (Wisloff et al., 2003). The 'eccentric Nordic hamstring exercise' was incorporated in order to mitigate the risk of hamstring injury (Mjolsens, 2006). These resistance-training strategies follow the acute programme guidelines put forward by the American College of Sports Medicine (ACSM) to improve muscular strength (Kraemer *et al*., 2002b, Kraemer *et al*., 2002a).

During the ‘pre-season’ each participant performed the above resistance-training exercises progressively from 65 to 75 % of estimated 6RM once per week for the first 3-weeks and twice per week in the following two weeks of 'pre-season'. The aim of this training phase was to familiarise the players to the resistance-training protocols and to minimise the possibility of delayed onset of muscle soreness (DOMS) during the intervention period. The research group acknowledged that the possibility of injury would be increased if the participants returned from the 'off-season' period and completed the concurrent-training protocols prescribed in the present investigation. Therefore, the participants completed the resistance-training protocols during the first 5 weeks of the 'in-season' period.

An Accredited Strength-and-Conditioning Coach (ASCC) from the United Kingdom Strength-and-Conditioning Association (UKSCA) designed and supervised the strength-training sessions. The training compliance and individual workout data (weight lifted, number of sets and repetitions completed), was also recorded (for a more detailed view of the training load for each experimental group refer to Table 13). It is well documented that in order to maximise the anabolic potential during and following resistance-training, adequate carbohydrate and protein should be available before and after training (for reviews see; Jeukendrup, 2004, Tipton and Wolfe, 2004). for this reason nutritional support was provided before, between and after training. This nutritional arrangement previously described in Chapter 3 was used in the present study and is described below in Figure 12.

Table 13: Summary of the training load completed across the 5-week training period

Football-specific training (E)	**Week 1**	**Week 2**	**Week 3**	**Week 4**	**Week 5**
Frequency	6	6	7	6	6
Average Duration (min)	82 ± 33	80 ± 34	93 ± 27	82 ± 32	78 ± 30
time > 85% HR ^{MAX} (min)	00:15:39 ± 00:10:28	00:38:45 ± 00:08:48	00:34:49 ± 00:02:06	00:22:34 ± 00:09:45	00:19:42 ± 00:03:48
Avg. Training Load (Borg Scale x min)	746 ± 258	684 ± 277	559 ± 189	690 ± 222	657 ± 249
Strength-training (S)	**Week 1**	**Week 2**	**Week 3**	**Week 4**	**Week 5**
Frequency	2	2	1	2	2
Duration (min)	35 ± 0	37 ± 7.5	32 ± 5.9	30 ± 5.1	32 ± 2.5
Avg. Training Load (Borg Scale x min)	218 ± 44	246.4 ± 52	200 ± 33	215 ± 43	232 ± 35
Volume Load (AU) (kg x reps x sets)	11148 ± 1633	11798 ± 2128	6013 ± 647	10600 ± 2975	13229 ± 1505
Total Training Load (Borg Scale x min)	2968 ± 597	30154 ± 248	3268 ± 345	2881 ± 380	2749 ± 261

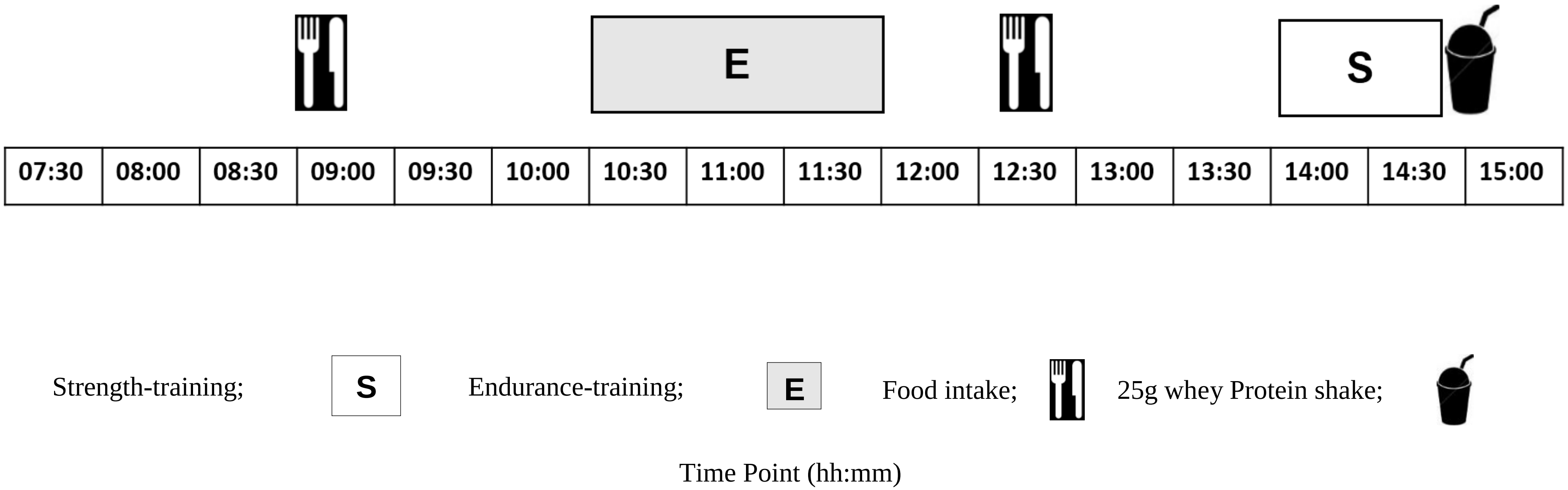


Figure 17: The organisation of nutrition and exercise carried out across the 5-week training period.

5.1.3.2 Dietary Controls

on concurrent-training days, a standardised breakfast was consumed 0900 h (~464 calories: 37.6 g carbohydrate, 33.9 g protein and 19.3 g fat). All players also consumed a standardised lunch at 1230 h (593 calories; 67.4 g carbohydrate, 47.9 g protein and 13.9 g fat). Finally, all players consumed a standardised protein shake upon completion of strength-training (~220 kcals: 25 g protein, 13 g CHO, 0.5 g fat, Multipower, UK). This dietary protocol ensured that all players were provided with comparable total energy content for the hours in which the players were physically present at the football club. Although this study did not consider nutritional intake relative to body mass this nutritional feeding pattern represented a typical scenario which occurred often within the club.

5.1.4 Statistical analysis

The software package SPSS (Version 17.0 SPSS inc. Chicago, IL) was used for statistical analysis. The reliability of each experimental procedure was calculated using the following statistical procedures. Primarily a paired t-test was calculated to detect learning effect bias between testing occasions. Before calculating absolute reliability Pearson's correlation coefficient was assessed using the mean and the absolute difference between each test occasion to assess the presence or absence of heteroscedasticity. If R^2 was between 0 and 0.1 the data was considered homoscedastic. If R^2 was greater than 0.1 the data was considered to be heteroscedastic. Positive relations (0.31 ± 0.16) revealed the presence of heteroscedasticity. Consequently the ratio limits of agreement were calculated for heteroscedastic data after logarithmic transformation. The statistical packages SPSS

(Version 17.0 SPSS inc. Chicago, IL) and Microsoft Excel (2007) were used for data analysis. Statistical significance was set at $P \leq 0.05$. In order to determine if muscle strength, muscle power-related variables and morphology changed following the intervention period a student's t-test was employed. All data in text, figures and tables are presented as means ± SD and $P \leq 0.05$ is indicative of statistical significance (*denotes significant effect for time). Effect sizes (ES) were calculated as the difference between the means divided by the pooled standard deviation, with values of 0.2, 0.5, and above 0.8 considered to represent small, medium, and large differences, respectively (Cohen, 1988).

5.2 RESULTS

5.2.1 Muscle Strength

Changes in muscle strength following the training period are described in Table 3. Following training there was a significant improvement in the isokinetic strength of the hamstring muscle group. This occurred in the concentric measurement at 180° • s^{-1} (*P* = 0.02; 17% increase) and in the eccentric measurement at 120° • s^{-1} (*P* = 0.05; 14% increase). The 1-RM for the half back squat exercise increased significantly (*P* = 0.04) (11.5% increase). Training induced non-significant increases in other isokinetic parameters including isokinetic concentric torque of the quadriceps at 60 • s^{-1} (*P* = 0.15; 9% increase); concentric torque of the hamstrings at 60 • s^{-1} (*P* = 0.31; 7 % increase) and eccentric torque of the quadriceps at 120 • s^{-1} (*P* = 0.11; 9% increase).

Table 14: Muscle strength data pre- and post- training, concentric and eccentric peak torque (Nm) of the quadriceps and hamstring muscle and 1RM half back squat (kg)

	Test 1	Test 2	% Δ	*P*	*ES*
Quadriceps					
Concentric *60° • s* $^{-1}$	221 ± 32	240 ± 48	9%	0.15	-0.46
Concentric *180° • s* $^{-1}$	210 ± 27	208 ± 28	-1%	0.74	0.072
Eccentric *120° • s* $^{-1}$	283 ± 32	309 ± 54	9%	0.11	-0.58
Hamstrings					
Concentric *60° • s* $^{-1}$	129 ± 41	138 ± 34	7%	0.31	-0.23
Concentric *180° • s* $^{-1}$	118 ± 27	138 ± 30	17%	0.02*	-0.70
Eccentric *120° • s* $^{-1}$	169 ± 39	192 ± 32	14%	0.05*	-0.64
IMVC (N)	651 ± 210	670 ± 123	2.9%	0.19	-0.11
IMVC Loading Rate (AU)	1018 ± 356	1110 ± 234	9.0%	0.19	-0.30
Squat 1RM (kg)	127 ± 31	141 ± 26	11.5%	0.04*	0.80

The data derived from the isokinetic peak torque data was subsequently used to calculate the 'hamstring : quadriceps ratios'. Whilst there was no significant improvements in any of the hamstring to quadriceps ratios, the $H_{ECC}^{120} : Q_{CON}^{180}$ ratio improved by 15% and showed a trend towards statistical significance (*P* = 0.08). The convention H/Q ratio (i.e. the ratio of concentric peak concentric hamstring to concentric quadriceps torque at 60 • s $^{-1}$) and the functional H/Q ratio (i.e. the peak eccentric hamstring torque at 120 • s $^{-1}$ to peak concentric quadriceps torque 180 • s $^{-1}$) did not significantly change following the training period (*P* = 0.57; *P* = 0.90 respectively) (see Table 4).

Table 15: Muscle strength data before and after training for functional reciprocal muscle group ratios (Dominant leg)

H : Q Ratio	**Test 1**	**Test 2**	% Δ	***P***	***ES***
$H_{CON}^{60} : Q_{CON}^{60}$	0.58 ± 0.17	0.58 ± 0.10	1%	0.90	0
$H_{ECC}^{120} : Q_{CON}^{60}$	0.77 ± 0.16	0.81 ± 0.08	5%	0.57	-0.31
$H_{ECC}^{120} : Q_{CON}^{180}$	0.81 ± 0.17	0.93 ± 0.12	15%	0.08	-0.81

5.2.2 Muscle power-related properties

Changes in muscle power-related properties following the training period are described in Table 5 Following the training period a 6% reduction in sprint time over 10 m was observed (P = 0.04). Following training, 30 m sprint time did not change (P = 0.11) (see Table 3). The squat jump and countermovement jumps did not significantly improve with training (P > 0.05), although CMJ showed a trend towards statistical significance (P = 0.08).

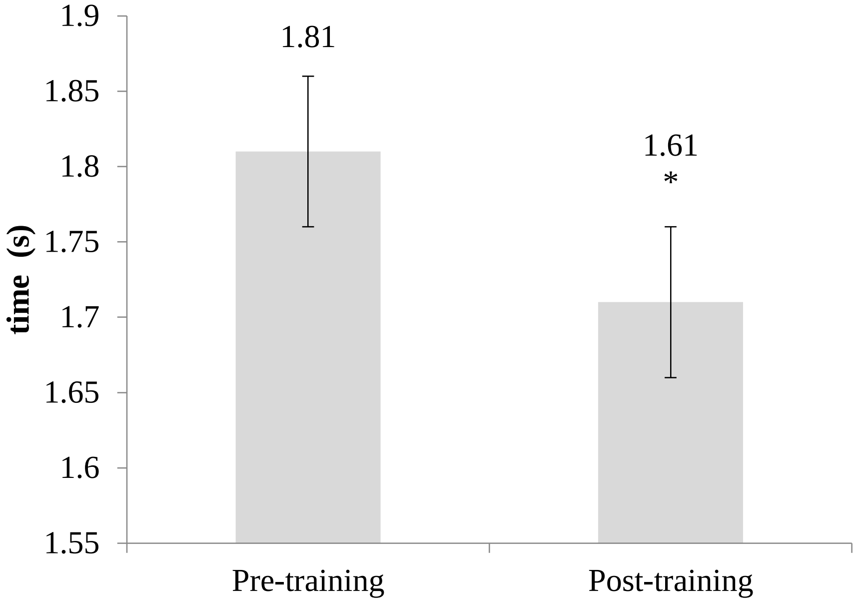


Figure 18: 10 meter sprint times before and following the training phase

Table 16: Muscle power-related properties and football-specific anaerobic fitness before and after training:

	Test 1	**Test 2**	% Δ	***P***	***ES***
SJ (cm)	41.2 ± 6.4	42.3 ± 7.3	2%	0.37	-0.16
CMJ (cm)	41.4 ± 5.0	42.5 ± 6.1	3%	0.08	-0.19
EUR (AU)	1.0 ± 0.01	1.0 ± 0.01	0%	0.89	0
10 m Sprint (s)	1.81 ± 0.07	1.71 ± 0.05	-6%	0.04*	1.64
30 m Sprint (s)	4.49 ± 0.19	4.30 ± 0.10	-4%	0.11	1.25
Yo-Yo IR-II (m)	838 ± 168	1015 ± 165	23%	0.02*	-1.06

Table key; squat jump (SJ) (cm), countermovement jump (CMJ) (cm), and fastest 10 m and 30 m sprint time (s), and Yo-Yo intermittent recovery test level 2 distance (IRT2) (m), Eccentric Utilisation Ratio (EUR) (AU)

*denotes significant effect for time (P < 0.05)

5.2.3 Muscle Morphology Variables

Changes in muscle morphology before and after training are displayed in Table 6. No significant changes were observed for whole muscle thickness at the mid location of the vastus lateralis (P = 0.99) or fascicule length (P = 0.82) with training. Fascicule angle of pennation increased by 13% following training and was statistically significant (P = 0.01).

Table 17: Muscle morphology values before and after training (mean ±)

	Pre	Mid	Post	% Δ	*P*	*ES*
VL θ (^{0})	12.8 ± 0.8	13.8 ± 1.0	14.40 ± 0.8	13%	0.01*	-1.10
ℓ_F (cm)	10.14 ± 0.62	10.26 ± 1.33	9.95 ± 1.78	-2%	0.82	-0.11
MT (cm)	4.94 ± 0.23	4.94 ± 0.21	4.94 ± 0.45	0%	0.99	0

Table key: VL θ; Vastus lateralis angle of penneation (^{0}), ℓ_F; Fascicle Length (cm), MT; Vastus lateralis and vastus intermedius muscle thickness (cm)

5.2.4 Body composition

Changes in body composition are presented below in Table 18. Following the 5-week concurrent-training period there were no significant changes in body mass, 'sum-of 8 skinfold' sites or body fat or muscle mass for either group.

Table 18: Body composition before and following the intervention phase

Body Composition	Pre	Post	% Δ	*P*	*ES*
Body mass (kg)	75.4 ± 4.3	76 ± 5.6	0.8%	0.31	-0.12
Sum of 8 skinfolds	56.3 ± 7.9	57.7 ± 10.9	1.9%	0.34	-0.28
Body Fat % (Reilly, 2006)	9.9 ± 0.6	10.1 ± 1.0	1.3%	0.35	-0.24
Muscle Mass (%)	60.0 ± 2.6	59.5 ± 3.1	-0.9%	0.33	0.17

5.3 DISCUSSION

The purpose of this study was to investigate of the training protocols observed in Chapter 3 could serve as a sufficient stimulus to improve muscle strength and football-specific fitness following a 5-week training period. The results of this study demonstrate that short-term concurrent-training can improve aerobic and strength capacities in elite football players. Following training 1-RM half back-squat and 10 meter sprinting speed improved significantly. These increases could have a positive impact upon power-related tasks during match-play (e.g. accelerating, turning and jumping). After the intervention period improvements in sports-specific aerobic fitness (Yo-Yo IR2) were also observed. This training effect may enhance the players' capacity to perform high-intensity running during match-play. Collectively, the results of this study support that elite football players who participate in a structured concurrent-training programme can improve physical parameters that may enhance match-play performance.

Following the intervention period improvements in both isokinetic and 1RM half back squat were observed, although the magnitude of strength improvement was less than other studies that have investigated the effects of strength-training in elite football players (Ronnestad *et al*., 2008, Chelly *et al*., 2009, Wong *et al*., 2010, Helgerud *et al*., 2011, Christou *et al*., 2006). This could be attributed to the fact that these studies used older subjects (21–31years old) and longer training periods (8-weeks to 16-weeks). However, when compared to other studies that have used football players of similar age and training history, improvements in the literature are still considerably more than observed in the present study (35% & 39% vs. 11.5%) (Christou *et al*., 2006, Chelly *et al*., 2009). The acute hypothesis Craig proposed by

Craig *et al*., 1991 states that "interference is caused by residual fatigue from the endurance component of concurrent-training resulting in the inability to effectively develop tension during the strength element of concurrent-training". Therefore, it is possible that the way in which the concurrent-training programme was delivered in the present study caused acute fatigue during resistance-training component of the training programme. Indeed both Christou *et al*., (2006) and Chelly *et al*., (2009) employed a training design where the athletes performed resistance-training immediately prior to football-specific training. Whereas, in the present study participants performed resistance-training after football-specific practice. This suggests that, during the present resistance-training session, players may have been tired and subsequently not as able to train at high intensity in the resistance-training session (i.e. acute interference) (Craig *et al*., 1991). Although, it is acknowledged that without either acute information regarding the muscle recovery or a direct comparison of the effect of performing resistance-training before football training it is difficult to make this conclusion. Therefore, future research could investigate the effects of performing resistance-training before and after sports-specific training in elite football players. A better understanding of the effects of performing different concurrent-training protocols may allow practitioners to make more informed decisions when prescribing concurrent-training programmes to athletes.

Muscle hypertrophy was not observed following the intervention period. This may have been due to the design of the resistance-training programme. Increases in muscle size are typically observed using high volume resistance-training programmes (3-5 sets of 6–12 repetitions), completed on 3 days per week for 6 to 16-weeks (Folland and Williams, 2007a). Therefore, the lack of hypertrophy could be due to the frequency of resistance-training and the length of the training phase completed by participants in this study.

The frequency of aerobic-training could have also effected the athletes' ability to adapt to the strength-training programme. Recent evidence indicate that the frequency of aerobic-training can influence the degree of interference in hypertrophy and strength related adaptation (Wilson *et al*., 2012). When the aerobic stimulus is performed on more than 3 days per week interference in strength related adaptation and hypertrophy is significantly increased (Wilson *et al*., 2012). The athletes in the present study completed endurance-exercise on 6 days of the week. Therefore, in addition to the resistance-training design the present endurance-training frequency may also explain the lack of hypertrophy observed here. At present, it is not clear if including additional resistance-training sessions or reducing the frequency of football training sessions may influence the training response in elite football players. Therefore, future research could investigate the effect of training frequency upon the interference phenomenon.

As muscle hypertrophy did not occur following training it is thought that the present improvements in strength could be explained by architectural and neuromuscular adaptation. Following training the vastus lateralis fascicule angle of pennation increased by 13%. This increase is in line with previous authors who have reported muscle architecture adaptation following a concurrent-training programme (Blazevich and Jenkins, 1998, Blazevich and Jenkins, 2002, Blazevich *et al*., 2003, Blazevich *et al*., 2007). The geometry of each fascicule is directly linked to the muscles capacity to produce force (for review see; Blazevich, 2006b). Increases in fascicule angle have also been associated with an increase in sprint times in elite athletes (Kumagai *et al*., 2000). Therefore the increase in fascicule angle of pennation could provide a mechanistic explanation for the improvements in sprint time observed in this study.

At present it is not apparent if muscle architecture variables are negatively affected by a concurrent-training stimulus. Considering that opposing fascicule angle adaptations are observed following chronic periods of endurance and resistance-training it is possible that muscle architecture adaptation is compromised during concurrent-training (Blazevich, 2006b). Without controlled studies investigating the effects of concurrent-training on muscle architecture it is not possible to conclude this at present. Therefore, future research could investigate the chronic architectural responses to concurrent-training performed in different sequences.

In addition to architectural adaptation, the improvements in isometric rate of force development observed (9%, P = 0.09) may also help to explain strength improvements following training. The rate of force development (RFD) can be defined as the rate of increase in muscle force following the onset of muscle contraction (Aagaard *et al*., 2002). The rate at which force increases has important significance for functional movement during football match-play. for example, sprinting, typically involves contraction times of between ~50 and ~250 ms (Earle and Baechle, 2004). This short contraction time may not allow peak force to be achieved. Consequently, improving the muscles capacity to contract quickly may be important as it allows a higher muscle force earlier in the contraction phase (e.g. 100–200 ms). Indeed the improvements in RFD in the present study also corresponded to an improvement in the 10m sprint time and isokinetic strength in faster contractions. This improvement in acceleration capacity may have a direct significant to competitive engagements during match-play.

5.4 CONCLUSION

The aim of this study was to describe the adaptations associated with a 5-week concurrent-training programme in elite football players. The findings demonstrate that both sports-specific aerobic fitness and muscular strength can be improved simultaneously. Our data suggest that improvements in muscular strength can be attributed to architectural and neuromuscular adaptation and less so to increases in muscle hypertrophy. Other authors have reported greater improvements in muscular strength following concurrent-training in elite football players. However, in these studies athletes performed resistance-training immediately before the aerobic stimulus. Therefore, the concurrent-training sequence used in this study may have led to peripheral fatigue and blunted strength related adaptation. Future research could investigate the effect of concurrent-training sequence in elite football players. This research could offer practical solutions to mitigate the interference effect associated with concurrent-training and may be important for athletes who regularly perform concurrent-training.

CHAPTER SIX

THE EFFECT OF CONCURRENT FOOTBALL AND RESISTANCE-TRAINING SEQUENCE ON MUSCLE STRENGTH AND MORPHOLOGY IN ELITE FOOTBALL PLAYERS

STUDY 4: ABSTRACT

THE EFFECT OF CONCURRENT FOOTBALL AND RESISTANCE-TRAINING SEQUENCE ON MUSCLE STRENGTH AND MORPHOLOGY IN ELITE FOOTBALL PLAYERS

Purpose: To test the hypothesis that training sequence of concurrent-training can modulate the magnitude of training-induced changes in muscle strength, power and morphology in professional football players. **Methods:** In a matched group design, fifteen elite football players (age: 17 ± 2 years; height, 1.82 m ± 0.06 m; body mass, 77.0 ± 7.3 kg; $\dot{V}O_{2\,max}$, 62.0 ± 4.7 $ml^{-1}.kg^{-1}.min^{-1}$) were assigned to a condition where football-specific endurance-training (E) was performed prior to strength (S) training (E+S, n = 7) or alternatively, where S preceded E (S+E, n = 8). Concurrent-training was performed for 5-weeks and consisted of five x E sessions and 2 x S sessions per week. **Results:** Factorial ANOVA (designs) indicated significant interaction effects for training time on half-back squat (H-BS) (S+E, 9.6%: E+S 19.6%; $P \leq 0.05$), fascicule angle of pennation (vastus lateralis) (AoP) (S+E, 7.9%: E+S 14.4%; $P \leq 0.05$), 10m sprinting time (S+E, -0.1%: E+S, -6.0% $P \leq 0.05$). Significant main effects for time were observed in H-BS ($P \leq 0.05$); isomeric loading rate ($P \leq 0.05$); isokinetic hamstring strength ($60^{o}{\cdot}s^{-1}$ CON, S+E, 12.2%: E+S, 19.2%; $180^{o}{\cdot}s^{-1}$ CON, S+E, 9.5%: E+S, 11.2%; $120^{o}{\cdot}s^{-1}$ ECC, S+E, 23.3%: E+S, 16.8%; $P \leq 0.05$); isokinetic quadriceps strength ($180^{o}{\cdot}s^{-1}$ CON, S+E 13.2%: E+S 2.5%), squat jumping height (S+E, 8.1%: E+S, 4.4%; $P \leq 0.05$). **Conclusion:** Data demonstrate that performing E after S training (with a feed between sessions) attenuates the magnitude of improvement in muscle strength, power and morphology during short-term concurrent-training. Professional football players may therefore benefit from performing strength-training several hours after endurance-training (i.e. in the afternoon) so as maximise concurrent-training adaptations.

Keywords: Concurrent-training, strength-training, football, muscle architecture

6.0 INTRODUCTION

Since the pioneering work of Hickson (1980), it has been well documented that training to simultaneously improve muscular strength and endurance results in compromised strength adaptations (Baar, 2006). The way in which the concurrent-training stimulus is delivered can impact acute biological and molecular responses to the exercise bouts and could potentially cause acute and (or) chronic interference (Hawley, 2009). Therefore, understanding the optimal way to organise training may be beneficial to athletes who perform concurrent strength and endurance-training on the same day.

The challenge of how to organise training each week is particularly important for elite football players who are required to train these diverse fitness components (e.g. aerobic capacity and muscular strength). Furthermore, the training time available to these athletes is often limited owing to the competitive schedule where players play in excess of 40 games per season (Bangsbo *et al*., 2006). As such, football players routinely engage in concurrent-training in which diverse types of training are performed within close proximity and sometimes in unsystematic exercise orders. Understanding the training responses to concurrent-training practices commonly used in football may lead to a consensus regarding the organisation of training.

Previously, it was thought that performing resistance-training in a non-fatigued state (i.e. first) would avoid acute interference and aid strength related adaptations (Craig *et al*., 1991). However, recent molecular and training study evidence suggests that performing endurance-training first may be more beneficial (Lundberg *et al*. 2012, Lundberg *et al*. 2013). The optimal training sequence to simultaneously train for muscle strength and aerobic endurance therefore remains a contentious issue (Coffey *et al*. 2009). At present, the chronic effects of concurrent exercise sequence has not been investigated in elite football players.

Findings from Chapter 5 demonstrate that muscle strength and power related variables (e.g. sprinting) can be improved following a 5 week 'in-season' period of concurrent sports-specific endurance and high-load, low-repetition resistance-training. Although, the training effect was significantly lower to that previously observed when strength-training is performed before endurance-training. With this in mind, the aim of the present study was to investigate if the sequence of concurrent-training could alter the extent of training adaptations induced in professional football players. To this end, we employed a matched group design whereby two groups of athletes performed five weeks of concurrent-training in which football-specific endurance-training preceded resistance-training (or vice versa). Training-induced changes in skeletal muscle strength, power and morphology were monitored before and following the intervention phase.

6.1 METHODOLOGY

6.1.1 Subjects

Twenty professional male football players (academy level) from an English FA Premier League Club volunteered to participate in this study. Demographic and fitness information is presented below in Table 19. After receiving oral and written information concerning any possible risks associated with the training and testing protocols, all participants gave their written informed consent to participate in the study. The study conformed to the code of ethics of the World Medical Association and was approved by the Ethics Committee of Liverpool John Moores University.

Table 19: Participant demographic and physiological information (n = 15)

Physical Characteristics	Mean ± SD		
	Sample (*n* = 15)	S+E (*n* = 8)	E+S (*n*=7)
Age (yr)	17 ± 0.5	16.9 ± 0.4	16.8 ± 0.5
Body mass (kg)	76.5 ± 7.5	79.5 ± 8.0	75.1 ± 8.7
Stature (cm)	180 ± 5.3	182.2 ± 5.4	181.0 ± 5.6
Body Fat % (Reilly, 2009)	10.7 ±1.3	9.95 ± 0.69	10.63 ± 1.25
Sum of 8 skinfolds (mm)	64.8 ± 17.4	55.0 ± 8.85	62.0 ± 12.20
Yo-Yo IRT2 (m)	896 ± 187	826 ± 174	970 ± 220
$\dot{V}O_2$ max (ml·kg^{-1}·min^{-1})	62.3 ± 4.38	59.38 ± 3.1	65.38 ± 1.84

6.1.2 Overview of Experimental Design

In a matched group design, subjects were randomly allocated to a training group who performed a 5 week block of training in which football-specific endurance-training was followed by resistance-training (E+S, n=10) or alternatively, a training structure where resistance-training preceded football-specific endurance-training (S+E, n=10). An overview of both training situations is shown below in Figure 13.

In the week before and after the 5-week training block, subjects were assessed for measures of muscle strength, power and muscle morphology. The end-point inclusion criterion for the study was ≥ 90% adherence to training sessions. Five players did not adhere to this criteria (due to injury and varied schedule associated with playing for the clubs' senior teams) and as such, data are presented hereafter for the 15 players who completed the study (E+S, n = 7; S+E, n = 8).

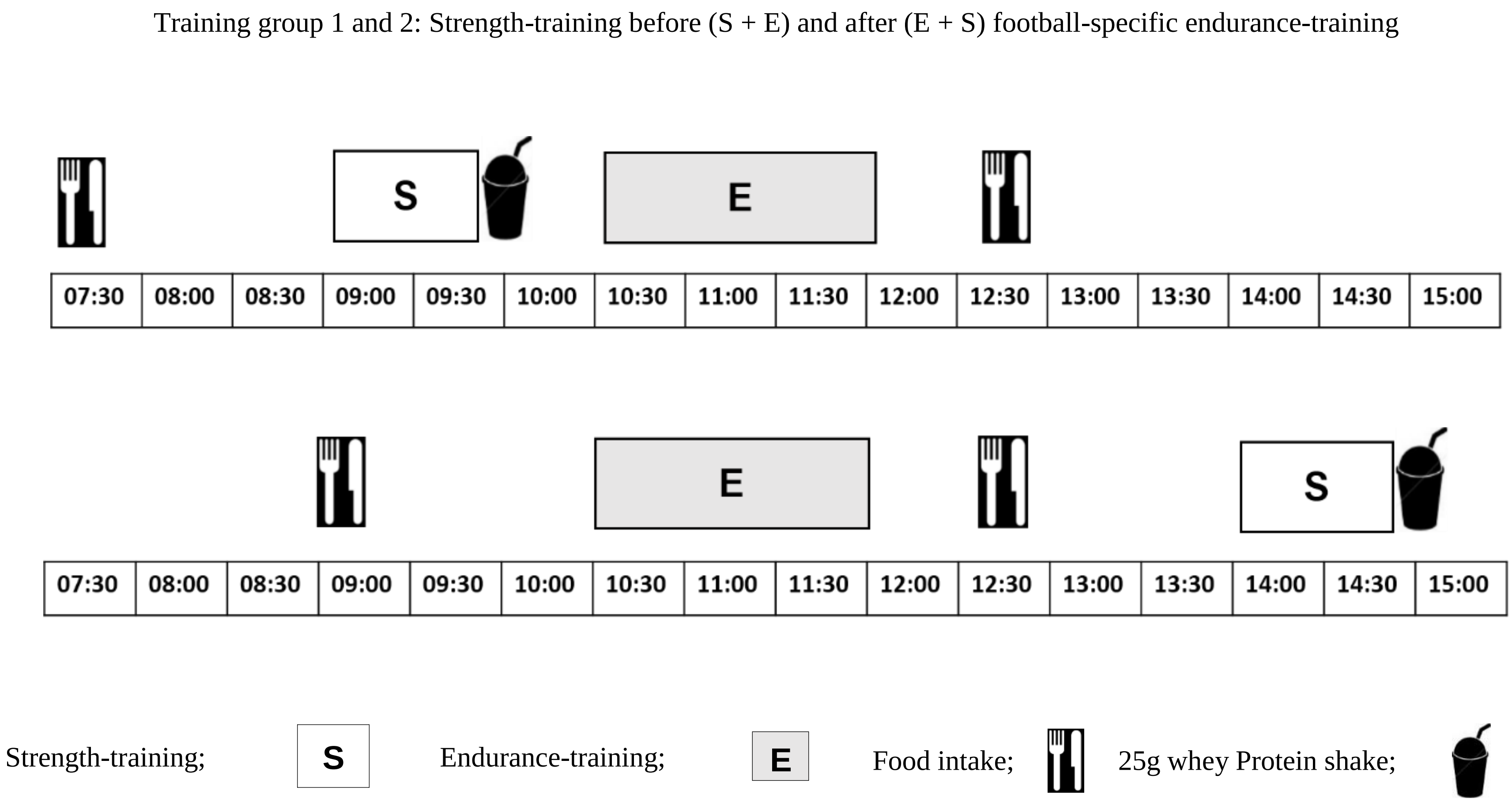


Figure 19: Exercise and nutritional protocols for the S+E and E+S training groups.

6.1.3 Experimental procedures

The methodology for each experimental procedure is presented in greater detail in Chapter 4. Below is a brief overview of the methodological procedures performed before and after the intervention period.

The battery of assessments used in the present study was designed to measure muscle strength (peak isokinetic force of the dominant quadriceps and hamstring muscle groups, maximal isometric voluntary contraction (MIVC) for the quadriceps and 1-repetition maximum (1-RM) for the half-back squat exercise), power (MIVC rate of force development, vertical jump height, the 10 and 30 m sprinting time) and muscle morphology (muscle thickness, fascicule angle of pennation and fascicule length). The week prior to and the week following the intervention period training volume and intensity was reduced and resistance-training was removed from the programme. This allowed additional time to conduct each physiological test and also reduced the likelihood of fatigue. The schedule of testing is presented in Chapter 4 in greater detail and was as follows; muscle architecture and body composition were measured on Monday (9-11am). on Tuesday following two consecutive days of rest (i.e. Sunday and Monday) vertical jump height, (9am) sprint speed (10am) and 1RM squat strength (12pm) was measured. Isometric and isokinetic strength were measured on Thursday following a recovery day (i.e. Wednesday). Individuals performed isometric and isokinetic testing at randomised timeslots between 9am and 4pm. To minimise 'time-of-day effects' testing times were replicated for each individual at the later testing time-point.

All players had previously been familiarised with the performance tests (at the beginning of the pre-season period) and test-retest reliability (performed 5-7 days apart) data is shown in Chapter 4. Participants refrained from intense physical activity in the 24–hour period before each testing session. All evaluations were conducted at the same time-of-day and by the same investigator.

6.1.3.1 Training Interventions

The training intervention was carried out in the first five weeks of the competitive season (August/September). During each week, all subjects completed 8 sessions. Two football-specific endurance-training sessions using small-sided games (SSGs) (E), two resistance-training sessions (S), three technical and tactical training sessions plus one competitive game. on Mondays and Thursdays football-specific endurance-training sessions was completed at 1030 h followed by resistance-training at 1400 h. Technical and tactical training took place on Tuesdsay (1030 h / 1400 h) and Fridays (1030 h), whilst competitive games took place at 1100 h on Saturdays.

Football-specific endurance-training (E) consisted of small-sided games. These games involved a 4 verses 4, possession format. Each game lasted 4 minutes at 90-95% HRmax. Between each game 3 min of active recovery was allocated. Games were performed on a 37m x 27m pitch (for more detail on this game format and reliability statistics please refer to Little & Williams 2007 and Hill-Haas *et al*., 2008 respectively). All SSGs were conducted as part of training, performed immediately following an initial warm-up. The resistance-training programme consisted of 4 sets of 6 maximal repetitions of the same resistance-exercised previously described in

Chapter 5 (half-back squat, dead-lift, stiff-leg dead-lift and front-lunge). Participants also completed 3 sets of 8 repetitions of the Nordic hamstring exercise. Technical and tactical training sessions were designed by the team coach and included a variety of skills drills and tactical plays. Games represented competitive fixtures in the Barclays U18 Premier league.

For those subjects allocated to the S+E groups, resistance-training was performed at 0845 h ± 15 min and as such, E preceded S training and commenced at 1030 h. In contrast, for subjects in the E+S group, S training was commenced at 1400 h ± 15min. Whilst this design is not precisely balanced in terms of alternative timing of sessions, this experimental design was deliberately chosen, as it is common practice in professional football clubs for concurrent-training to be performed in the morning such that both sessions are completed by 1200 h. In contrast, it is unusual for football players to perform ‘double sessions’ where consecutive training sessions are interspersed with a deliberate recovery period as would be the case by completing training sessions before and after a lunch period. Detailed training load data for each experimental group is presented below in table 20.

Table 20: Training load completed by the strength - endurance (S + E) training group

Week	No of Sessions	Duration (mins)	Average Minutes > 85% HR Max	Strength Volume Load	RPE Load (RPE*Min)
Week 1	6	490	00:32:20	13251 ± 236	2400
Week 2	6	633	00:28:56	15758 ± 8626	3504.9
Week 3	6	532	00:28:52	9330 ± 4823	2704.3
Week 4	6	487	00:23:36	13988 ± 4947	2465.4
Week 5	6	554	00:39:00	14890 ± 4239	3041.9
Mean ± SD	6	539.3 ± 59.6	00:30:33 ± 00:05:40	13443 ± 2485	2823 ± 456
Total	30	2696.5	02:32:44	67217	14116.5

Table 21: training load completed by the endurance - strength (E + S) training group

Week	No of Sessions	Duration (Mins)	Average Minutes > 85% HR Max	Strength Volume Load	RPE Load (RPE*Min)
Week 1	6	490	00:30:53	12217.5 ± 1047	2344
Week 2	6	633	00:35:02	12228 ± 107	3349
Week 3	6	532	00:30:35	10035 ± 4723	2650
Week 4	6	487	00:24:55	14430 ± 3360	2290
Week 5	6	554	00:47:59	12795 ± 4698	2980
Mean ± SD	6	539.3 ± 59.6	00:33:53 ± 00:08:40	12341 ± 1574	2722 ± 445
Total	30	2696.5	02:49:24	61705	13613

6.1.3.2 Dietary Controls

on concurrent-training days, a standardised breakfast was consumed at 0800 and 0900 h for S+E and E+S respectively (~540 Calories: 100 g carbohydrate, 15 g protein and 7 g fat). All players also consumed a standardised lunch at 1230 h (~1000 calories 140 g carbohydrate, 60 g protein and 25 g fat). Finally, all players consumed a standardised recovery shake upon completion of resistance-training so as to ensure nutrient provision prior to E at 1030 h (~220 calories: 25 g protein, 13 g CHO, 0.5 g fat, Multipower, UK). In this way, all players were provided with comparable total energy content for the hours in which the players were physically present at the football club, although we acknowledge that the timing of nutrient intake varied between groups. Nonetheless this represented two scenarios, which occurred often within the club depending on the training schedule.

6.1.4 Statistical analysis

The software package SPSS (Version 17.0 SPSS inc. Chicago, IL) was used for statistical analysis. Following tests for normality (i.e. Shapiro Wilk) and variance assurance (i.e. Levene) a repeated measures two-way General Linear Model was employed to examine the effects of training sequence on changes in muscle strength, power and morphology. Here, the within factor was time (i.e. pre-training versus post-training) and between factor was group (i.e. E+S versus S+E). Where there were significant main effects, Tukey's post-hoc tests were used to locate specific differences. All data in text, figures and tables are presented as means ± SD and $P \leq$

0.05 is indicative of statistical significance (*denotes significant effect for time † denotes a significant interaction between group and time).

6.2 RESULTS

6.2.1 Muscle Strength

Changes in 1-RM for the half back squat are shown in Figure 2. Training increased back squat strength in both groups ($P = 0.01$) where the magnitude of increase was significantly greater ($P = 0.03$) in E+S (19.1% increase) compared with S+E (10.3%). Changes in peak isometric force, isometric loading rate and isokinetic related variables are shown in Table 2. Although training induced increases in isometric peak MVC force ($P = 0.391$), eccentric torque of the quadriceps at 120^{o} ($P = 0.11$) and concentric torque of the quadriceps at 60 ^{o} (P = 0.25), none of these parameters reached statistical significance. Additionally, the ratio of peak eccentric hamstring and quadriceps concentric torque at 60^{o}/s ($P = 0.15$) and 180^{o}/s ($P = 0.23$) was also not significantly changed with training. In contrast, training induced significant increases in isometric loading rate ($P = 0.02$), concentric torque of the hamstrings at 60^{o}/s at 180 ^{o}/s ($P = 0.01$ and 0.03, respectively), concentric torque of the quadriceps at 180^{o}/s ($P = 0.02$), eccentric torque of the hamstrings at 120 ^{o}/s ($P = 0.001$), the ratio of concentric hamstrings to quadriceps torque at 60^{o}/s ($P = 0.01$) and the ratio of the concentric torque of the hamstrings at 60^{o}/s to eccentric torque of the quadriceps at 120^{o}/s ($P = 0.05$). The magnitude of change in the aforementioned parameters was, however, comparable between E+S and S+E ($P > 0.05$ for all variables).

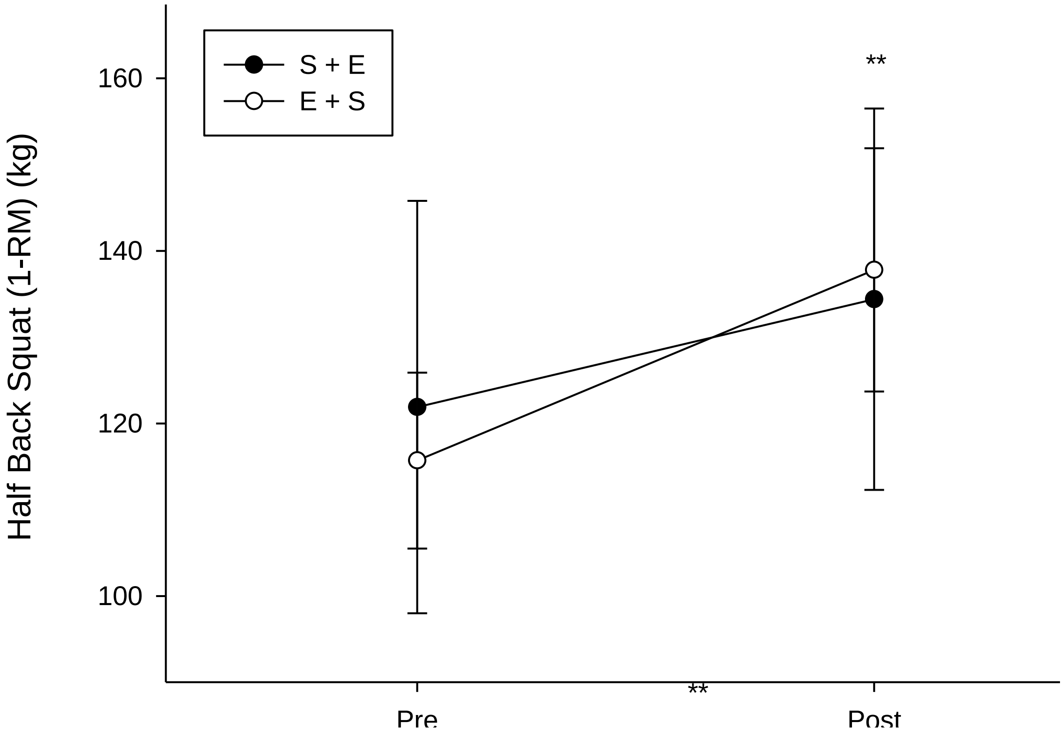


Figure 20: Absolute Changes in Squat Strength following training.

Table 22: Muscle strength data, 1RM half back squat (kg) Isometric peak force and isometric loading rate and concentric and eccentric peak torque (Nm) of the quadriceps for S+E and E+S experimental groups before and after training.

	S+E				E+S			
	Pre	Post	% Δ	*ES*	Pre	Post	% Δ	*ES*
Back Squat 1-RM (kg)	121.9 ± 23.9	134.4 ± 22.10*†	10.3%	-0.54	115.7 ± 10.20	137.8 ± 14.10*	19.1%	-1.79
Isometric MVC Peak force (N)	628 ± 189	631 ± 136	0.6%	-0.01	690 ± 147	721 ± 143	4.4%	-0.21
Isometric MVC Loading Rate	1018 ± 427	1225 ± 389*	20.3%	-0.50	1185 ± 316	1508 ± 295*	27.3%	-1.05
Concentric quadriceps *(60deg/sec)*	218 ± 33	217 ± 31	-0.4%	0.03	217 ± 24	242 ± 32	11.3%	-1.87
Concentric quadriceps (*180degs/sec)*	194 ± 22	199 ± 21*	2.5%	-0.23	203 ± 20	230 ± 15*	13.2%	-1.52
Eccentric quadriceps (*120degs/sec)*	262 ± 47	269 ± 29	2.7%	-0.17	275 ± 47	288 ± 48	4.7%	-0.27
Concentric hamstrings *(60deg/sec)*	108 ± 18	121 ± 22*	12.2%	-0.64	120 ± 23	143 ± 25*	19.2%	-0.95
Concentric hamstrings (*180degs/sec)*	106 ± 20	116 ± 19*	9.5%	-0.51	115 ± 14	128 ± 21*	11.2%	-0.72
Eccentric hamstrings (*120degs/sec)*	133 ± 23	155 ± 32*	16.8%	-0.78	156 ± 21	192 ± 25*	23.3%	-1.55

Table 23: Functional reciprocal muscle group ratios.

	S+E				E+S			
	Pre	Post	% Δ	*ES*	Pre	Post	% Δ	*ES*
H_{CON}:Q_{CON} 60^0·s-1	0.49 ± 0.2	0.56 ± 0.07*	13.24%	-0.46	0.55 ± 0.73	0.59 ± 0.1*	7.95%	-0.07
H_{ECC}:Q_{CON} $60^0 \cdot s^{-1}$	0.62 ± 0.11	0.70 ± 0.13	14.39%	-0.66	0.67 ± 0.14	0.71 ± 0.14	6.54%	-0.28
H_{ECC}:Q_{CON} $180^0 \cdot s^{-1}$	0.69 ± 0.12	0.78 ± 0.21	12.70%	-0.52	0.71 ± 0.14	0.77 ± 0.13	7.04%	-0.44
H_{CON}:Q_{ECC} $180^0 \cdot s^{-1}$	0.41 ± 0.07	0.43 ± 0.50	5.67%	-0.05	0.41 ± 0.03	0.45 ± 0.10	9.88%	-0.54
H_{CON}:Q_{ECC} $60^0 \cdot s^{-1}$	0.41 ± 0.85	0.44 ± 0.06*	7.47%	-0.04	0.43 ± 0.36	0.50 ± 0.12*	16.39%	-0.26

*denotes significant effect for time † denotes a significant interaction between group and time

6.2.2 Muscle power related variables

Sprint time over 10 m showed a significant improvement with training (P = 0.01) whereas 30 m sprint time did not change (P = 0.21). Furthermore, the change in 10 m sprint time was significantly greater (P = 0.02) in E+S compared with S+E (see Table 3). Squat jump also significantly improved with training (P = 0.000), no difference was evident between groups (P = 0.84). In contrast, CMJ showed no significant change in either group as a result of training (P = 0.53).

Table 24: Muscle power properties: Squat Jump (cm), countermovement jump (cm), and fastest 10/30m sprint time (s) before and after the intervention period

	S+E				E+S			
	Pre	Post	% Δ	ES	Pre	Post	% Δ	ES
Squat Jump (cm)	38.9 ± 2.9	41.8 ± 2.4*	4.4%	-1.08	38.0 ± 5.7	41.1 ± 5.2*	8.1%	-0.56
CMJ (cm)	39.2 ± 4.7	39.2 ± 3.3	-0.1%	0	40.7 ± 1.9	41.4 ± 2.8	-1.0%	-0.29
EUR (AU)	1.0 ± 0.1	0.93 ± 0.1	7.1 %	0.69	1.07 ± 0.1	1.0 ± 0.0	7.0 %	0.98
Fastest 10m (s)	1.72 ± 0.65	1.72 ± 0.76	-0.1%	0	1.80 ± 0.36	1.70 ± 0.42†	-5.9%	0.25
Fastest 30m (s)	4.22 ± 0.23	4.21 ± 0.20.2	-0.3%	0.04	4.29 ± 0.73	4.19 ± 0.12	-2.7%	0.19

Table key; squat jump (SJ) (cm), countermovement jump (CMJ) (cm), and fastest 10 m and 30 m sprint time (s), and Eccentric Utilisation Ratio (EUR) (AU)

*denotes significant effect for time † denotes a significant interaction between group and time

6.2.3 Muscle Morphology Variables

Changes in muscle architecture before and after training are displayed in Table 4. No significant changes were observed for whole muscle thickness at either distal (*P* = *0*.15), mid (*P* = *0*.33) or proximal location (*P* = *0*.43) or fascicule length (*P* = *0*.08) with training. Although fascicule angle of pennation increased (*P* = *0*.02) where significantly greater effects were observed in E+S compared with S+E (*P* = *0*.03).

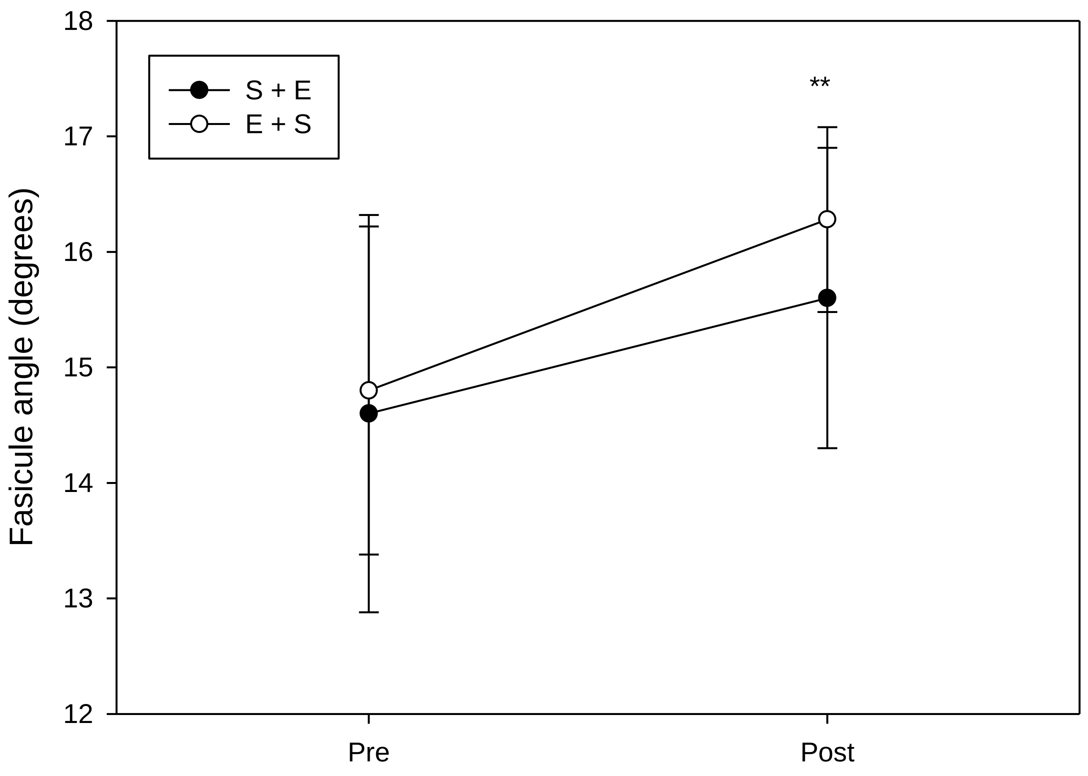


Figure 21: changes in fascicule angle of pennation following training in the E+ S and S +E training groups

Table 25: Mean (±SD) total muscle thickness (cm), angle of pennation (^{0}), fascicule length (cm) before, after 5 resistance-training sessions (mid) and 1 week following intervention training for S+E and E+S

	S+E				E+S			
	Pre	Post	% Δ	*ES*	Pre	Post	% Δ	*ES*
MT-D	4.72 ± 0.16	4.77 ± 0.15	0.88%	-0.32	4.67 ± 0.45	5.08 ± 0.73	8.80%	-0.67
MT-M	4.79 ± 0.50	4.90 ± 0.32	2.48%	-0.26	4.95 ± 0.29	4.98 ± 0.39	0.55%	-0.08
MT-P	3.97 ± 0.39	4.01 ± 0.27	0.88%	-0.65	4.00 ± 0.45	4.07 ± 0.66	1.89%	-0.12
AoP-M	14.60 ± 1.72	15.7 ± 1.3*	7.92%	-0.72	14.18 ± 1.42	16.21 ± 0.80*†	14.31%	-1.76
FL-M	10.34 ± 1.13	9.65 ± 1.21	-6.73%	0.56	11.42 ± 0.89	10.41 ± 1.6	-8.79%	1.57

*denotes significant effect for time † denotes a significant interaction between group and time. Muscle thickness (Distal) (cm), Muscle thickness (Mid) (cm), Muscle thickness (Proximal) (cm), Angle of Pennation (Mid) (°),Fascicule Length (Mid) (cm).

6.3 DISCUSSION

The aim of the present study was to investigate of concurrent-training sequence could significantly alter the extent of training-induced adaptations in muscle function and morphology in professional football players. Using a matched group design (in which both groups completed similar training intensities and volume) and concurrent-training sequences indicative of 'real-world' practices, we provide novel data by demonstrating that performing interval based endurance-training (using small-sided games) immediately after resistance-training (both performed in the morning) can attenuate the extent of improvements in muscle strength (1-RM half back squat), muscle ‘power related variables’ (i.e. 10 m sprint time) and morphology (fascicule angle of pennation). As such, these data demonstrate that when resistance-training is completed after endurance-training with a meal before and after training improvements in parameters associated with physical performances can be made. This finding may advocate the present concurrent-training and nutritional strategy, thus having practical implications for athletes who routinely perform concurrent strength and endurance-training on the same day.

The strength and architectural improvements presented in the current study are thought to be associated with the efficacy of the strength programme design (i.e. multi-joint resistance-training movements, training frequency, effective training load (kg/BM), repetitions, sets and recovery parameters) (Kraemer *et al*., 1998). As both experimental groups completed approximately the same training volume and intensity within the aerobic and strength components of the programme (Table 20), and recorded similar nutritional intake, we suggest that the differences that were observed in both strength and muscle architecture variables could be attributed to the way the training and nutritional stimulus was delivered. This outcome may be a consequence of changes in a number of underlying metabolic processes associated with performing strength-training in the early afternoon with a meal before and after training. for example optimal improvements are typically observed when resistance-training is carried out in the early afternoon (Sedliak *et al*., 2009). Also the intramuscular signalling cascade associated with the resistance-football sequence may have blunted anabolic signalling pathways. Conversely, the intramuscular signalling cascade associated with the football-resistance sequence may have and extended anabolic signalling throughout the evening/night. Furthermore, the timing of nutrient intake around training in the football-resistance-training group may have had synergistic effects on the anabolic environment thus promoting adaptation.

A diurnal effect for metabolic events and human performance is well established (for review see; Hayes *et al*., 2010). Collectively this evidence demonstrates that performance in strength and power related tasks, jumping ability, flexibility and reaction time all show a distinct trend towards improved performance in the evening (16:00 hrs. to 20:00 hrs.) when muscle temperature peaks (Drust *et al*., 2005). Thus suggesting that temporal specificity is important for optimising strength gains (Souissi *et al*., 2002). It is therefore possible that the results of the present study may be as a consequence of circadian effects. However, as resistance-training times in the present study took place at 09:00hrs and 14:00hrs respectively and that experimental research in this area has been conducted significantly earlier (07:00hrs-08:00hrs) and later (17:00hrs-19:00hrs) it is difficult to conclude if time-of-day factors account for the present findings. The lack of a training group performing the same exercise in an isolated fashion is a limitation of the present study. Future research should look to investigate the effects of training sequence but also control for time of day effects.

An alternative explanation for the present results could be that there was an interaction between resistance-training time and the time of strength assessments. Recent evidence suggests that adaptations to resistance-training are greater at the time of day at which training was scheduled when compared to other times of day (Chtourou *et al.*, 2012). The present study employed a 'testing design' which minimised testing times which could discriminate between both training groups. Following the intervention period, maximal strength in the half-back squat exercise was tested at 12:00hrs in both training groups, and isokinetic/isometric assessments were performed in randomised am and pm conditions providing no clear advantage for temporal specific adaptations to either experimental group.

Previous literature has indicated higher 'resistance-training' volume load (expressed as reps · sets · weight lifted) typically results in greater increases in strength when compared to low and moderate volumes (Hanssen *et al.*, 2012). There were no significant differences in volume load between experimental groups. Furthermore as both groups completed the same football training sessions the 'pitch-based' training volume was also similar. It is therefore unlikely that training load factors may account of the changes observed in the present study. This suggests that the intramuscular and/or biological activity in response to each exercise condition may help to explain our data.

Both endurance and resistance-training have unique mechanotransduction pathways, which initiate specific biochemical events that ultimately result in diverse muscle adaptation (Atherton *et al.*, 2005). Performing endurance and resistance-training within close proximity of each other can attenuate the desired mRNA response (Coffey, *et al*. 2009) and influence hormonal secreation (Goto *et al*., 2005, Goto *et al*., 2007a, Goto *et al*., 2007b). Current evidence suggest that performing resistance-training after endurance-training with an extended recovery period can promote signalling cascades and hormonal profiles associated with protein synthesis (Lundberg, *et al*. 2012). These acute responses have been supported by training studies where increases in muscle strength and hypertrophy were observed in those who performed resistance-exercise after aerobic-exercise (Ronnestad *et al*., 2011a, Lundberg *et al*., 2013). There is also evidence to suggest that exercise induced hormonal secretion can influence muscle architecture adaptation (Atkinson *et al*., 2010, Blazevich and Giorgi, 2001). Therefore, the intramuscular signalling and or biological responses to the exercise and nutritional arrangements used within this investigation may help to explain why the E+S training group outperformed the S+E training group. However, at present it cannot be elucidated whether it was the recovery period between training bouts or the sequence of training which caused this interference. Therefore, future control studies could investigate the effects of concurrent-training sequence with different recovery periods. This may help us to gain a better perspective as to what acute programme variables exacerbate the interference phenomenon and assist the design of future concurrent-training programmes.

Nutrient availability can serve as a powerful modulator of many intramuscular events responsible for adaptation (for more information see; Hawley *et al*., 2006). The increased availability of key nutrients before and after the 'resistance-training' session by the E+S group may also provide an explanation for the present findings. The S+E group consumed 100 grams of carbohydrate and 15 grams of protein prior to resistance-training, and a further 25 grams of protein directly after strength-training and approximately 30 minutes prior to football-specific training. The E+S group on the other hand had approximately 140 grams of carbohydrate and 60 grams of protein before resistance-training, followed by an additional 25 grams of protein after resistance-training. As muscle glycogen would have been the principle substrate used during both our training protocols the additional carbohydrate consumed by the E+S group before resistance-training may have facilitated adaptation (Tesch *et al*., 1986) as previous research has substantiated that strength performance is enhanced by carbohydrate supplementation (Haff *et al*., 2003). Furthermore, resistance training with low muscle glycogen can also have a negative effect on the cellular pathway associated with muscle strength (mTOR) (Creer *et al*., 2005, Churchley *et al*., 2007). Thus, it would seem plausible to suggest that the S+E training group did not consume enough carbohydrate prior to consecutive strength and high-intensity endurance-training, and that this may have subsequently impaired adaptation.

In addition to the quantity of nutritional support provided is a difference in the timing and quantity of protein sources available to each group before and after resistance-training. Protein is perhaps the most important nutrient for resistance-training as it is critical for protein accreditation and long-term strength-related adaptation (Tipton and Ferrando, 2008). Recent evidence suggests that resistance-exercise coupled with whey protein ingestion increases activation of the signalling pathways associated with muscle protein synthesis compared with exercise alone (Drummond *et al*., 2009, Farnfield *et al*., 2012). These findings are also supported by chronic training intervention studies that have investigated muscle strength and morphology during and following training. for example, a recent 10-week training study demonstrated that those who supplemented with Essential Amino Acids (EAAs) and saccharose had greater changes in gastrocnemius medialis strength and muscle architecture compared to a placebo group (Vieillevoye *et al*., 2010). Collectively these findings suggest, the additional protein sources consumed by the E+S group prior to resistance-training may also have played a role in the superior adaptations previously described.

The recovery duration between endurance and strength-training was different between exercise trials. The athletes who performed strength-training prior to football training had on average 45 minutes between training bouts, whereas, those who performed strength-training after football training had 120 minutes between bouts. This training design does not allow us to elucidate if recovery time is a mediating factor which could explain the differences observed in chapter 6. Therefore, the discrepancy in recovery duration between experimental conditions is a limitation of this study. Both concurrent-training scenarios (i.e. S + E and E + S) would have created a unique cascade of molecular and biological events. As these intramuscular processes can last from 1 to 8 hours, it is likely that the recovery period in each experimental condition could potentially explain the between group differences observed in the present investigation. Future research investigating the effects of concurrent-training sequence in elite football players should standardise the recovery time between training bouts. This approach would allow for more accurate interpretation of the mediating factors which may exacerbate the 'interference phenomenon'.

6.4 CONCLUSION

In summary, the present study proposes beneficial effects when resistance-training is performed after endurance-training. Following the training period, muscular strength, explosive strength/power, and fascicule angle of pennation was superior in the participants who performed resistance-training after football-specific endurance-training. Indeed, both training groups completed the same exercise volume and intensity regardless of exercise sequence. Investigators have previously suggested that performing resistance-training in a non-fatigued state (i.e. prior to endurance-training) would avoid acute fatigue during the resistance-training component and subsequently reduce the interference phenomena. However, the present findings do not support this ‘acute hypothesis’ proposed by Craig *et al*., 1991. Instead the authors propose that the nutrient availability before and after each training session may have created a ‘synergistic environment’ leading to superior intramuscular signalling and (or) hormonal environment leading to adaptation in the E+S training group. Although it is acknowledged that without control groups performing exercise at the same time of day it cannot be elucidated if the ‘proximity of training’ (i.e. the recovery period between training bouts) or the ‘exercise sequence’ has caused the interference in strength related adaptations observed in this study. More controlled studies investigating the acute and chronic effects of these two exercise and nutritional arrangements are therefore warranted.

CHAPTER SEVEN

THE ACUTE HORMONAL RESPONSES TO TWO CONCURRENT ENDURANCE AND STRENGTH-TRAINING PROGRAMMES IN ELITE FOOTBALL PLAYERS

STUDY 5: ABSTRACT

THE ACUTE HORMONAL RESPONSES TO TWO CONCURRENT ENDURANCE AND STRENGTH-TRAINING PROGRAMMES IN ELITE FOOTBALL PLAYERS

Purpose: The purpose of this study was to describe testosterone (T), cortisol (C), T : C ratio and growth hormone (GH) responses to two concurrent-training sequences commonly used in the football environment. **Methods:** Thirteen elite football players (age: 16.8 ± 0.6 years; height, 1.80.8 cm ± 7.3 cm; body mass, 73.1 ± 5.7 kg; $\dot{V}O_{2max}$, 64.4 ± 4.81ml^{-1}.kg^{-1}.min^{-1}) participated in this In a matched group design. Following familiarisation and 1RM strength testing the participants completed two experimental trails separated by 7 days. Trials involved football followed by resistance-training (E+S) and vice versa (S+E). Venous blood samples were collected at 5 systematic time-points (T1; before RT, T2; after RT/before FT, T3; after FT, T4; before RT & T5; after RT). **Results:** No hormonal differences were observed at rest between trials. Significant time vs. order interaction effects were observed for C (P = 0.02) and GH (P = 0.01). Post-hoc analysis revealed significant differences at T3 for T, GH (T; 27% Δ, P = 0.03; GH; 326% Δ P = 0.05) and at T4 for C (C; 33% Δ, P = 0.01). Significant differences at T4 were also revealed for the T : C ratio (48% Δ, P = 0.04). The E+S exercise condition had a significantly higher AUC for T (P = 0.05) and GH (P = 0.04) **Conclusion:** The results of this study show that by changing the order of concurrent-training, testosterone, cortisol and growth hormone response can become amplified or attenuated. The E+S sequence demonstrated greater relative increases testosterone and growth hormone immediately following football training. The S+E training sequence increased the catabolic hormone cortisol.

Keywords: concurrent-training, resistance-training, football, hormone sequence

7.0 INTRODUCTION

Many athletes complete strength-training in addition to high-intensity intermittent sport-specific training. The findings from our previous investigation (chapter 3) indicate that elite football players perform these diverse forms of contraction in unsystematic exercise orders, with insufficient recovery between sessions and with different combinations of nutritional intake. In some cases players perform strength and sport-specific training consecutively in the morning. Whilst on other days they perform strength-training in the early afternoon period following sport-specific training. Based on the principle that training adaptations are a consequence of acute intramuscular events repeated across time, it could be argued that the introduction of a systematic exercise sequence and nutrient intake could enhance adaptation. The conclusions made in our penultimate study (Chapter 5) reinforce this paradigm. The findings indicate that the strength related adaptation can become blunted when strength-training is performed before endurance-training. Our data suggest that the mechanism which blunted this strength adaptation may be explained by the between group differences in fascicule angle of pennation observed. We hypothesised, that the nutrient timing and intramuscular signalling may help to explain the between group difference in muscle architecture. Although, at present the mediating intramuscular and (or) biological mechanisms responsible for fascicule adaptation has yet to be elucidated and is therefore not well understood. Some evidence suggests that artificial stimulation of specific hormones can influence fascicule adaptation. Blazevich and colleagues (2001) demonstrated that when compared to strength-training alone supplementing testosterone injections increase fascicule angle of pennation without increasing in muscle size resulting in an improvement in muscle function (Blazevich et al., 2001). Although it is not yet known if exercise induced hormonal secretion could have the same effect upon fascicule adaptations. Given that the hormonal profile can be altered by changing the order of strength and endurance exercise bouts (Taipale et al., 2013. Rosa et al., 2012, Cadore et al., 2012), the exercise protocols used in chapter 5 may have augmented the hormonal response and influenced the architectural adaptations observed. Therefore, the purpose of this study was to investigate if exercise induced hormonal secretion could explain the changes in fascicule angle of pennation observed in chapter 5.

7.1 METHODOLOGY

7.1.1 Participants

Thirteen post-adolescent boys (16 to 18 years of age) training in the academy of a club competing in the English Premier League were recruited. Prior to the study, participants were given an information letter to explain the procedures involved in the study. All participants were given an opportunity to ask any questions that are relevant to the study. After receiving oral and written information concerning any possible risks associated with the testing protocols all participants gave their written informed consent to participate in the study. The study conformed to the code of ethics of the World Medical Association (Declaration of Helsinki) and was approved by Liverpool John Moores University ethics committee.

Table 26: Demographic information (n = 13)

Physical Characteristics	Mean ± SD
Age (yr)	17 ± 0.6
Body mass (kg)	73 ± 6
Stature (m)	180 ± 7
$\dot{V}O_2$ max (ml·kg^{-1}·min^{-1})	64 ± 4.8

7.1.2 Overview of experimental procedures

To investigate the effect of manipulating exercise order on the acute hormonal responses to concurrent-training, subjects attended the laboratory on four occasions. on the first day, subjects signed the written consent form and had their anthropometric characteristics evaluated. Participants' six-maximum repetition (6-RM) performance was also evaluated in four 'free weight' exercises. This information was subsequently used to prescribe the strength-training intensity during the experimental trials. on the second visit each individual's maximum heart rate was determined by completing a yo-yo intermittent exercise test. on days three and four participants completed one of two experimental trials; (i) a strength-training session followed by a football-specific endurance-training session or (ii) a football-specific endurance-training session followed by strength-training session. To ensure comparable nutrition between trails, a standardised breakfast, lunch and protein shake was allocated to each athlete. In order to determine the hormonal responses to each exercise sequence, venous blood samples were collected from each participant during 5 sample points in each trial.

7.1.2.1 Days 1 & 2 - Base line testing

one week prior to the first trial each participant reported to the laboratory and completed a 6-repetition maximum (6-RM) strength testing session. The testing session involved the same strength-training exercises previously used in experimental chapters 5 and 6 (half-back squat, stiff leg dead lift, front lunge & the deadlift). Prior to testing participants performed warm-up repetitions of around 60%, 80% and 90% of estimated 6-repetition maximum (based on previous training data).

The warm-up was followed by a series of 6-RM sets each separated by a 3-5 minute rest period. Each time the participant successfully completed the weight was increased by 2.5 or 5kg until the participant could not complete the exercise with correct technique. The maximum weight in kilograms lifted was recorded and used as the training load during experimental trials one and two. on the second visit to the laboratory each participant performed an exercise test to volatile exhaustion (Yo-Yo intermittent recovery test) previously described in Chapter 5 (Wong *et al*., 2011). Prior to the test players were fitted with a heart rate monitor (Polar, Kempele, Finland). Heart rate data was used to compare the training intensity between experimental trials. Maximum heart rate and training intensity data is presented below in Table 27.

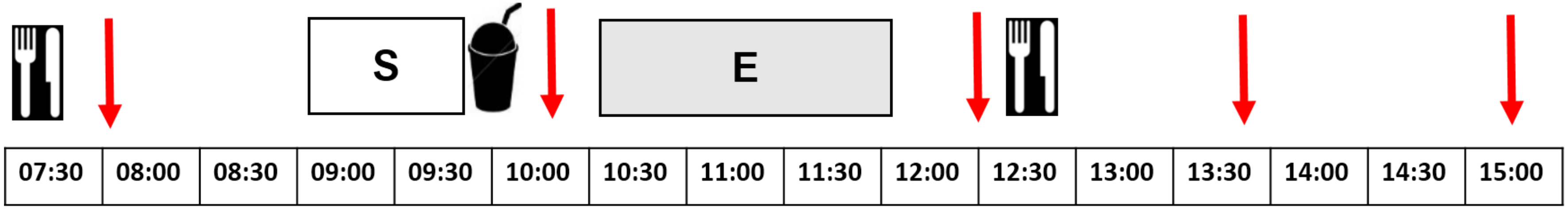
Table 27: Participant training intensity data

Physical Characteristics	Mean ± SD
Heart Rate ^{MAX}	188 ± 9
Half Back Squat 6RM	102 ± 15
SLDL 6RM	82 ± 8
Lunge 6RM	70 ± 5
Deadlift 6RM	80 ± 15

7.1.2.2Days 3 & 4 - Experimental trials

In order to ensure this study had ecological validity the participants replicated the acute training and nutritional arrangements used in our previous training study (Chapter 6). During experimental trial 1 players completed a strength-training session at 9am and then performed a football-specific endurance-training session at 10.30am (S+E). In experimental trial 2 the players completed the same football-specific endurance-training session at 10.30am and the same strength-training session at 2.00pm (E+S) (Figure 16). Throughout each day venous blood samples were collected on 5 occasions before and after exercise and nutrition. Controlled nutrition was provided before, between and after training in both trials.

Trial 1: Strength-training performed before football-specific endurance-training (S+E)



Trial 2: Strength-training performed after football-specific endurance-training (E+S)

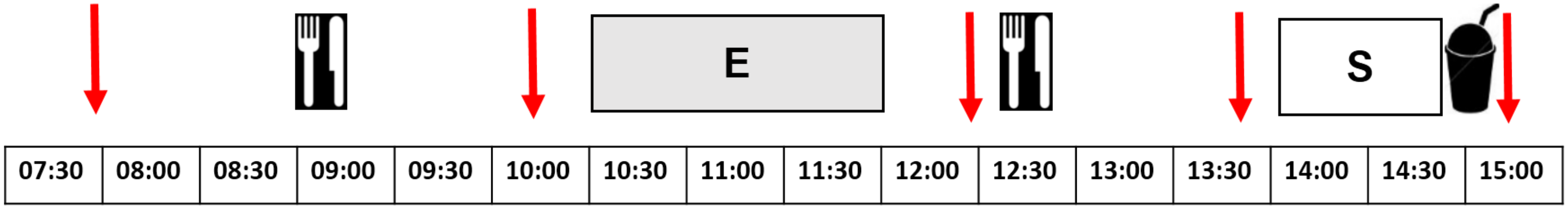


Figure 22: Protocols for exercise, blood sampling with alternate exercise sequences

7.1.2.3 Endurance and strength-training

Participants completed the same strength-training (S) and football-specific endurance-training (E) training sessions at the same exercise intensity on both days. Football-specific endurance-training (E) consisted of the same small-sided games previously prescribed in Chapters 5 and 6. Prior to training players performed a standardised dynamic warm up (~20min) followed by small-sided games (~30min). These games involved a 4 verses 4, possession format. Each game lasted 4 minutes at 90-95% HR max. Between each game 3 min of active recovery was allocated. Games were performed on a 37m x 27m pitch. Following the conditioning component of the session the team coach instructed a variety of technical / tactical plays. The strength-training programme consisted of the same dynamic free-weight exercises previously employed in Chapters 5 & 6 (half-back squat, dead-lift, stiff-leg dead-lift and front-lunge). All strength-training was performed using a squatting rack and Olympic barbell equipment (Ivanko, San Pedro, California, U.S). Using the testing information gained from day 1 the participants completed 4 sets of 6 repetitions on each exercise. Participants also completed 3 sets of 8 repetitions of the 'Nordic hamstring exercise'. A summary of the training completed by the participants during each experimental trail is presented below in Table 27.

Table 28: Endurance and strength-training load summary

	E+S	S+E
Endurance-training (E)		
Distance Covered (m)	6407 ± 985	6582 ± 665
No of high speed runs > 5.5m/s	16 ± 4	19 ± 4
Minutes > 85% HR MAX	8.6 ± 1.3	10.3 ± 3.3
RPE (1-10)	6 ± 1	6 ± 1
Duration (min)	85	90
Strength-training (S)		
Volume (AU) (reps • sets • load)	8000 ± 494	8000 ± 494
RPE (1-10)	8 ± 1	8 ± 1
Duration (min)	40	40

7.1.2.4 Dietary Controls

A standardised breakfast was consumed at 0745 and 0900 h for S+E and E+S respectively (~540 Calories: 100 g carbohydrate, 15 g protein and 7 g fat). All players also consumed a standardised lunch at 1230 h (~1000 calories 140 g carbohydrate, 60 g protein and 25 g fat). Finally, all players consumed a standardised recovery shake upon completion of strength-training (~220 calories: 25 g whey protein, 13 g CHO, 0.5 g fat, Multipower, UK).

7.1.2.5 Blood sampling

Venous blood samples were collected on five occasions by a qualified phlebotomist (8.00-8.15am, 9.45-10.00am, 12:30-12:45pm, 13:45-14:00pm and 15:15-15:30pm) (Figure 16). After each sample was collected, the blood was maintained in ambient temperature for 45 min and then centrifuged for 10 min at 4.000 rpm at 4 degrees. Following separation, serum was removed and frozen at -70ºC for later analysis. Each blood sample was subsequently analysed for concentrations of serum growth hormone (GH) (nmol/L), total testosterone (T) (nmol/L) and cortisol (C) (nmol/L). Testosterone and Cortisol were measured using Cobas 6000 analyzer series radioimmunoassay kits (Hoffmann-La Roche Ltd, Switzerland). Growth hormone was measured using the Access 2 immunoassay System, (Beckman Coulter, USA). To eliminate inter-assay variance, all samples were analysed within the same assay batch, and all intra-assay variances were ≤ 5.0%. Antibody sensitivities were; 0.07 ug/L for GH, 0.7 nmol/L for TT and 1.4 nmol/L for C.

7.1.3 Statistical Analysis

The software package SPSS (Version 17.0 SPSS inc. Chicago, IL) was used for statistical analysis. After normality (i.e Shapiro Wilk) and variance assurance (i.e. Levene) comparisons between different exercise orders were assessed using a two-way analysis of variance (ANOVA) with repeated measures (time v exercise sequence). Hormonal differences at each time point compared between exercise orders using a one-way ANOVA. for each hormone the area under the curve (AUC) was calculated using a trapezoidal method and subsequently analysed used a paired t-test. All data in text, figures and tables are presented as means ± SD. Statistical significance (*P*) was set at ≤ 0.0.5

7.2 RESULTS

Descriptive data for cortisol, total testosterone, growth hormone and the area under the curve (AUC) for each hormone is presented below in Table 28. There were no significant differences in resting hormonal levels between trials.

Table 29: Peak hormonal concentrations at rest and at different time-points before between and after the exercise protocols.

		(1) 08:00h	(2) 09:45h	(3) 12:30h	(4) 13:45h	(5) 15:15h	AUC (· min)
Cort [nmol/L]	E+S	47 ± 6	280 ± 8	32 ± 9	22 ± 7	14 ± 9	4913 ± 1227
	S+E	45 ± 4	31 ± 11	32 ± 9	33 ± 10*	15 ± 4	5455 ± 1505
T [nmol/L]	E+S	18.6 ± 2.9	18.2 ± 3.5	19.2 ± 3.1*	13.3 ± 4.6	13.1 ± 5.5	300 ± 76*
	S+E	19.3 ± 2.9	19.2 ± 4.6	15.1 ± 5.0	13.1 ± 5.6	12.6 ± 6.1	243 ± 81
GH [ug/L]	E+S	0.07 ± 0.09	0.65 ± 1.57	1.21 ± 1.20*	0.09 ± 0.05	1.30 ± 1.86	13.8 ± 10.6*
	S+E	0.03 ± 0.04	1.15 ± 2.10	0.28 ± 0.62	0.05 ± 0.05	0.62 ± 0.56	5.5 ± 9.8

Table Key: Cort; Cortisol, T; total testosterone, GH; Growth hormone, AUC; area under the curve.

7.2.1 Total Testosterone

When strength-training was performed before endurance-training, T decreased by 27% following the endurance-training session (09:45h; 19.2 ± 4.6, 12:30h; 15.1 ± 5.0 mmol/L). When there was no strength session prior to endurance-training, T increased by 5% (09:45h; 18.2 ± 3.5, 12:30h; 19. ± 3.1 mmol/L). A one-way ANOVA revealed between group differences (P = 0.03) after E (i.e. 12:30h) (Figure 17). Therefore, T remained elevated following endurance-training when it was not preceded by strength-training. Using the trapezoidal method the areas under the curve during the E+S trial was significantly higher (P = 0.05) (E+S; 300 ± 76* S+E; 243 ± 81).

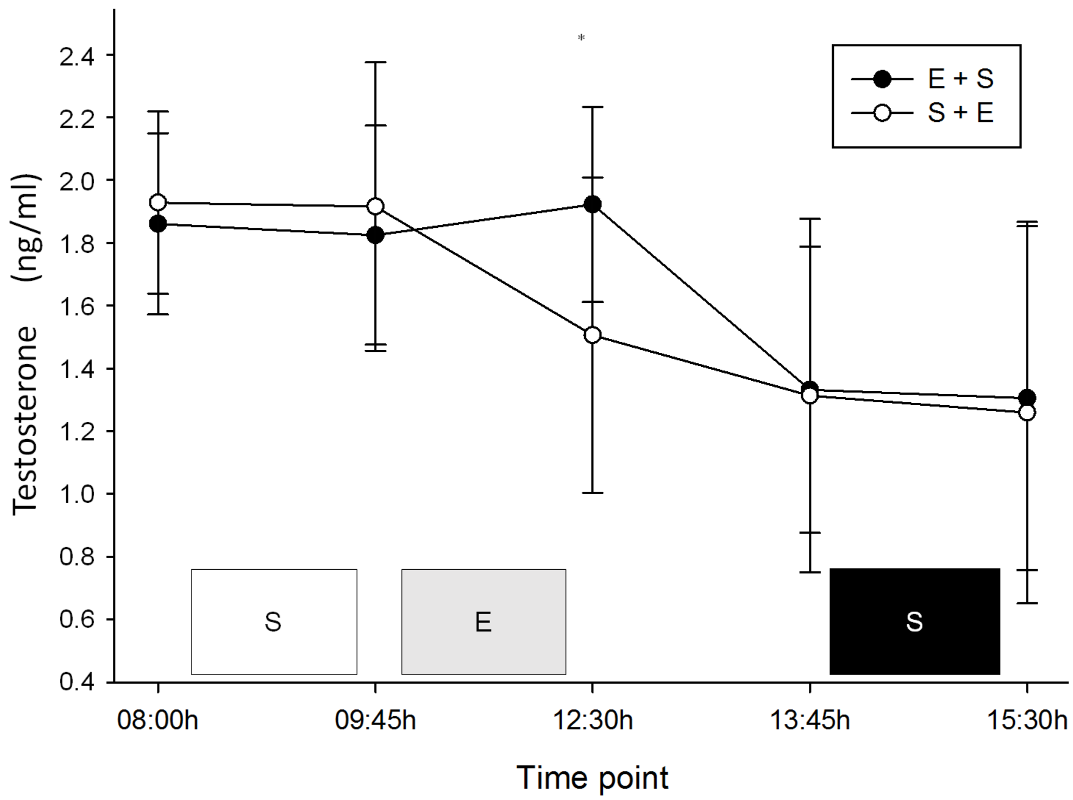


Figure 23: Changes in concentrations of serum total testosterone for each experimental trial. Values are mean ± SE (n = 13). * and ** denote significant differences between trials.

7.2.2 Cortisol

When cortisol at 13:45h was compared between trials, absolute cortisol was significantly higher (*P* = 0.01) in the “strength-endurance" sequence (338.3 ± 105.7 mmol/L verses 225.8 ± 75.0 mmol/L) (Figure 18). The area under the curve for cortisol was not satistically different between trials (E+S; 4913 ± 1227, S+E; 5455 ± 1505)

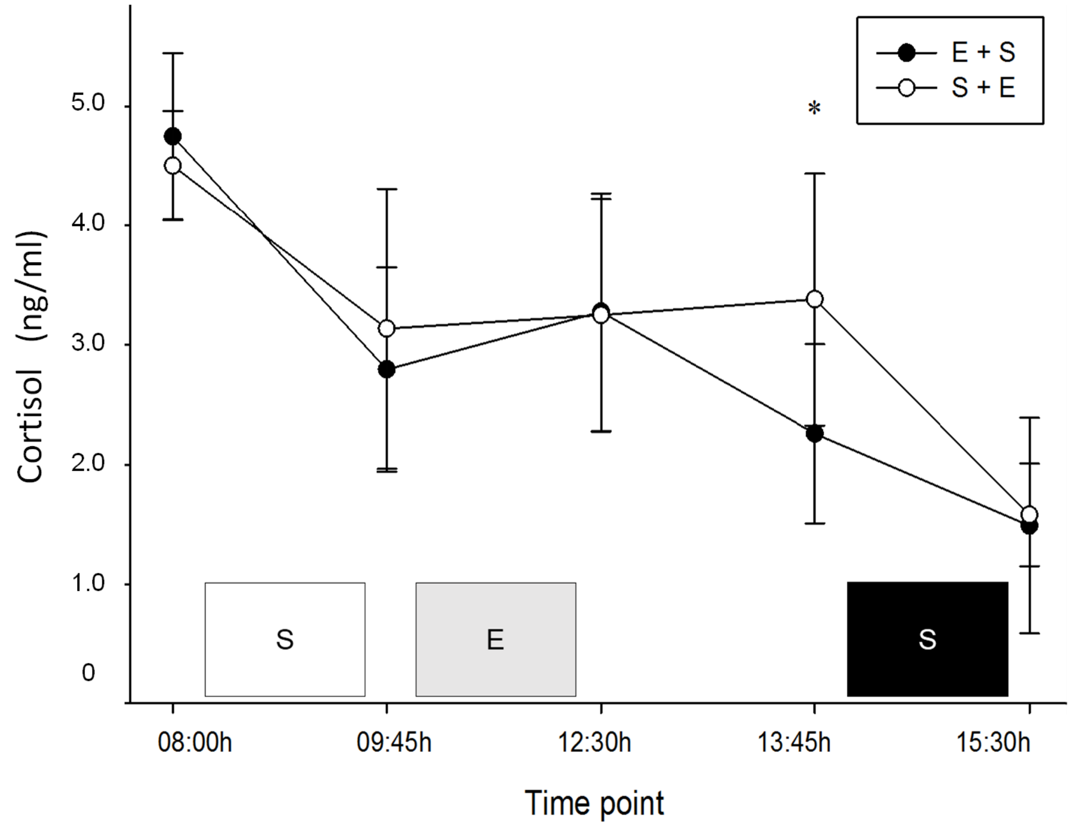


Figure 24: Changes in concentrations of serum total cortisol for each experimental trial. Values are mean ± SE (n = 13). * and ** denote significant differences between trials.

7.2.3 Testosterone : Cortisol ratio

A significant difference between groups at 13:45h was evident (*P* = 0.04) (Table 29). The between group differences was attributed to the significant increase in cortisol observed at this time point in the S+E experimental group.

Table 30: The Testosterone : Cortisol ratio before between and following each exercise sequence: Endurance-Strength (E+S) and Strength-Endurance (S+E)

	(1) 08:00h	(2) 09:45h	(3) 12:30h	(4) 13:45h	(5) 15:15h
E+S	0.04 ± 0.01	0.07 ± 0.02	0.06 ± 0.02	0.06 ± 0.02*	0.10 ± 0.05
S+E	0.04 ± 0.01	0.07 ± 0.03	0.05 ± 0.02	0.04 ± 0.02	0.08 ± 0.04

7.2.4 Growth Hormone

When endurance-training was not preceded by a strength-training session, GH was significantly higher (*P* = 0.05) following endurance-training (12:30h) (1.21 ± 1.2 ug/L) compared to samples collected at 12:30 when strength-training was performed before endurance-training (0.28 ± 0.62 ug/L) (Figure 19). There were significant differences in the area under the curve between experimental conditions (*P* = 0.04) (E+S; 13.8 ± 10.6*, S+E; 5.5 ± 9.8).

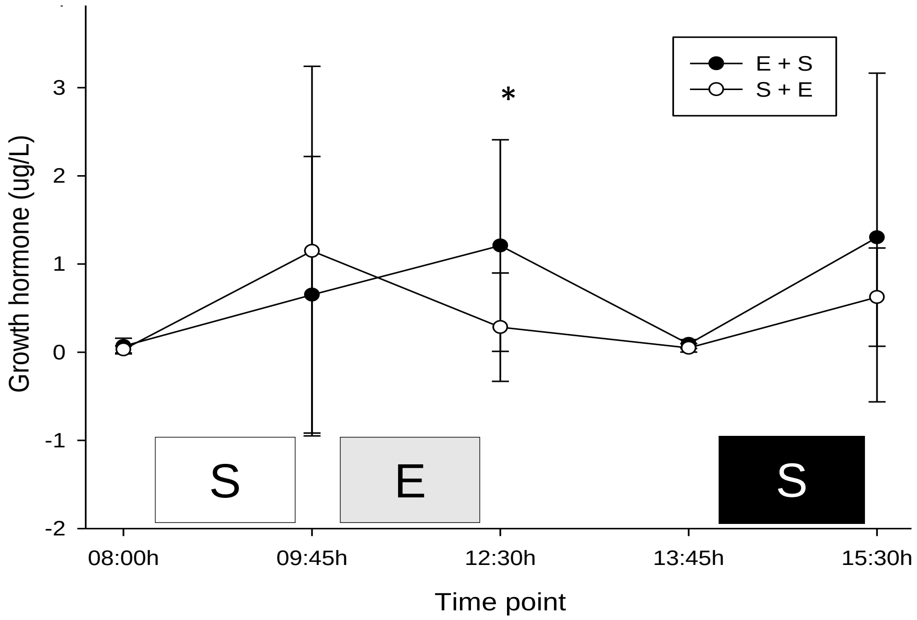


Figure 25: Changes in concentrations of serum Growth hormone for each experimental trial. Values are mean ± SE (n = 13). * and ** denote significant differences between trials

7.3 DISCUSSION

This study aimed to describe the hormonal responses to different concurrent-training scenarios used by elite football players. The findings demonstrate that the recovery period and (or) sequence of concurrent-exercise and nutritional intake around training can modify the acute hormonal response. Taken collectively with the data from our previous training study, the present investigation demonstrates that hormonal responses may be involved in the regulation of muscle architecture variables. The data suggest that performing strength-training after endurance-training may be more beneficial for promoting the 'anabolic' hormones. This was evidenced by the elevated levels of growth hormone and testosterone and cortisol hormones in the "E+S" and "S+E" conditions respectively. This data provides some support for the hormonal hypothesis to explain the interference phenomenon. The findings also offer some mechanistic data which may potentially explain the between group differences observed in the preceding training study (Chapter 6). Collectively, both studies suggest that performing strength-training after football training with adequate nutritional intake and recovery between exercise bouts is more beneficial than condensing multiple training bouts in the morning period without adequate nutrition between exercise bouts. Collectively this information may have practical application for those who prescribe both endurance and strength-training programmes to athletes.

The present findings demonstrate that acute hormonal secretion can be effected when diverse training bouts are performed within close proximity of each other. Our data show support for other investigations that have observed the hormonal responses to concurrent-training. Previously, Goto and colleagues (2005) examined the hormonal responses to isolated and combined bouts of cycling and strength-training. The authors reported attenuated GH when endurance-exercise was performed immediately before strength-training. The same research group also reported reductions in GH when sprinting exercise was performed before strength-exercise. Interestingly, GH was not attenuated when the recovery time was increased to 3 hours. In the present investigation when strength and endurance-exercise were performed with no recovery period anabolic hormones became attenuated following training. Whereas when strength-exercise was performed 2 hours after endurance-exercise GH and T was not attenuated. Although it is not clear if increasing the recovery time would further affect the hormonal responses to training. one limitation of this study is that blood samples were collected immediately before and after training therefore the hormonal secretion rates into the evening is not known. Future research could investigate the hormonal responses to concurrent-training with difference recovery periods across a longer time-course.

The mechanism by which hormonal secretion was influenced at given time points are not entirely understood. Understanding the mechanisms which affect hormones could inform future training and nutritional strategies to reduce concurrent-training interference. Growth hormone was attenuated when strength-exercise was immediately followed by endurance-training. The availability of energy substrates around exercise bouts in each experimental condition may help to explain why GH became attenuated. Previously, it has been documented that free fatty acid (FFA) bioavailability can inhibit the secretion of GH (Goto *et al*., 2005). Similar exercise models to those used in the present study (>90 min) have shown to increase lipolysis and FFA circulation (Romijn *et al*. 1993). In the present study strength and endurance-exercise were performed across a ~3 hour period. This extended training period could have promoted FFAs and subsequently attenuated GH. In contrast during the endurance-strength condition participates had a ~2 hour recovery period between exercise bouts in which a meal was consumed. This situation may have allowed participants to increase carbohydrate availability and subsequently reduced the likelihood of lipolysis. Although it is acknowledged that this hypothesis remains speculative without additional metabolite and hormonal data. Future research could investigate the acute and chronic effect of different nutritional strategies in concurrently training athletes. Findings from this type of research may offer practical guidelines for athletes to minimise the interference phenomenon.

It is acknowledged that investigating other parameters such as gene expression (Bamman *et al*., 2007), microRNA abundance (Davidsen *et al*., 2011), and satellite cell activity (Hanssen *et al*., 2008) may have offered better information to predict long-term muscle adaptation in this population. However, as this study was employed in an applied environment there were limitations. The participants in this study were competing in competition so it was not possible to use invasive techniques such as the muscle biopsy procedure. It is suggested that future research could investigate the effects of football-specific endurance-training and resistance-training in the controlled laboratory setting. This type of research my add more clarity to the conclusions made in this thesis and thus offer a more robust framework for the current understanding of concurrent-training protocols used by elite football players. A further limitation of this study is that it cannot be entirely elucidated if the sequence of training or the recovery period between exercise bouts directly or indirectly effected our results. This was due to the fact that this study was indicative of two 'real-world' training scenarios typically observed at an elite football club. Research is required to elucidate weather the order of concurrent-training or the recovery time can be manipulated to reduce the' interference phenomenon'. The use of a controlled environment and intramuscular techniques may offer more conclusive evidence which could be used to inform future concurrent-training strategies in elite football.

7.4 CONCLUSION

The aim of this study was to investigate the hormonal responses to the concurrent-training protocols used in Chapter 6. The results of this study show that the organisation of concurrent-training can influence acute hormonal responses in elite football players. Performing strength-exercise after endurance-exercise with a ~2 hour recovery period between exercise bouts can promote greater relative increases in T and GH. Conversely, when training is condensed into a morning period anabolic hormones become blunted and catabolic hormones are increased. These observations can in-part be supported by other research groups who have investigated the acute molecular responses to concurrent-training protocols. However, due to limited metabolite and (or) hormonal data the exact mechanisms to explain these acute changes cannot be entirely concluded from this study. None the less the findings from this study do offer some support for the conclusions made in Chapter 6 that performing strength-training after an aerobic stimulus may be a better training strategy than performing strength-training immediately before aerobic-training. It is suggested that the sequence of concurrent-training, the recovery duration between exercise bouts and the substrate availability around each workout are important factors which can influence acute responses associated with adaptation. These findings may have practical application for practitioners who prescribe concurrent-training programmes to athletes.

CHAPTER EIGHT

SYNTHESIS

8.0 SYNTHESIS

The purpose of this chapter is to provide a conceptual interpretation of the present findings in relation to the original aims and objectives of the thesis. This section will also provide practical recommendations in order to minimise the interference effects associated with concurrent-training in this population. This chapter also discusses the limitations and advantages of conducting "real world" research and presents a list of potential areas where future research is warranted.

8.1 Achievement of Aims and Objectives

The aim of this thesis was to investigate the impact of training organisation on the acute and chronic responses to football-specific exercise programmes in elite football players. It was hoped that the conclusions from this thesis would provide practical training recommendations that may help to minimise the interference effects associated with concurrent-training. These aims were achieved via the completion of four objectives.

Objective 1: To characterise the organisation of football-specific concurrent-training at an elite football club.

This objective was addressed via the completion of Study 1 (Chapter 3). Few studies have reported the organisation of training within a professional football club. It was thought that this information could help to identify training scenarios that may limit the adaptive process. Training frequency, training-load and the organisation of training completed by a professional team across the first 10 weeks of the season was recorded. The average weekly RPE-TL of football training, games and resistance-training was only significantly higher across the initial 3 weeks of the observational period ($P > 0.05$). Training intensity (GPS and heart rate data) during football training was also significantly higher across the first 3 weeks (total distance covered; 25827 ± 6107 m, high speed distance; 920 ± 290 m, sprint distance; 147 ± 62 m, heart rate > 85% max; 71 ± 30 min). It was thought that this was because the first 3 weeks of the observational period was during the 'pre-season' preparatory period. and the use of non-linear periodisation commonly used in team sports during the 'in-season' phase (Gamble, 2006). Although as teams typically employ six to eight week 'pre-season' this three week period may not have been enough to significantly improve fitness levels to the desired level where they could be maintained during the in-season period. Although, it is acknowledged that the limitation of this study is that without interviewing the coaching staff it is difficult to ascertain the periodisation approach that the coaches were intending to achieve. Therefore, it is difficult to understand why this training approach was used.

When concurrent-training was observed on the same day it was found that the exercise sequence, nutritional availability and recovery time between training sessions was unsystematic. The players sometimes performed resistance-training in a 'fasted' state, whereas on other occasions players consumed protein and carbohydrate before and after each exercise bout. The players also performed strength-training before football training with no recovery, and after football training with different amounts of recovery time between training bouts. It was thought that this unsystematic approach may have been sub-optimal for long term muscle adaptation. This conclusion is underrepresented with the literature, as few studies have investigated the effects of concurrent-training in the applied football environment. Given that the acute organisation of training and nutrition can affect acute responses (e.g. protein synthesis) which can influence the adaptive process, additional research is required to investigate the effect of the concurrent-training protocols observed in this study.

Objective 2: To evaluate the reliability of a range of sports-specific testing protocols designed to detect changes in fitness parameters following a concurrent-training programme (Study 2)

This objective was addressed via the completion of Study 2 (Chapter 4). In order for to allow for accurate interpretation of future training data, it was necessary to quantify the 'margin of error' associated with our chosen experimental protocols. Following familiarisation and a controlled 'test-re-test', a range of statistical tests were applied to evaluate the reliability of our measurement tools. The resulting data demonstrated that the experimental procedures designed to measure muscle performance and muscle morphology showed good to very good reliability. It was concluded that the protocols designed to evaluate the effectiveness of concurrent-training in elite football players were sensitive to detect change following a training intervention.

Objective 3: To characterise the muscular adaptations following different concurrent-training protocols in elite football players (Study 2 and 3).

This objective was addressed via the completion of Studies 3 and 4 (Chapters 4 and 5). In order to evaluate the effectiveness of the training organisation previously described in Chapter 3, a series of training studies were completed. Here, football players completed the football-specific endurance-training and resistance-training arrangements described in Chapter 3. Players performed resistance-training immediately before football training (S+E) or two hours after football training (E+S) for 5-weeks. Before and after the training intervention muscle strength, muscle power related variables, sports specific fitness and muscle morphology was measured. It was found that when resistance-exercise was performed after football-specific training improvements in muscle strength, muscle 'power related variables' and muscle morphology were more pronounced when compared to performing strength-training immediately before football training; half-back squat (S+E, 9.6%: E+S 19.6%; $P \leq 0.05$), 10 m sprinting time (S+E, -0.1%: E+S, -6.0% $P \leq 0.05$), fascicule angle of pennation (vastus lateralis) (AoP) (S+E, 7.9%: E+S 14.4%; $P \leq 0.05$). As both training groups completed similar training loads it was hypothesised that the recovery period and nutrient timing associated with each training group could have either 'enhanced' or 'blunted' underlying adaptive mechanisms. However, this remains speculative and warrants more research to specifically conclude why interference in strength related adaptation was caused when players performed strength-training immediately before football training.

Objective 4: To investigate the hormonal responses to different patterns of concurrent-training in elite football players.

This aim was met via the completion of Chapter 7. The current literature suggests that systemic factors such as exercise induced hormone secretion do not predict long term muscle hypertrophy. However, few data exist concerning the role of exercise induced hormones in mediating muscle architecture adaptations. Therefore, we aimed to investigate if the acute hormonal response would modified by the concurrent-training protocols used in Chapter 6. We hypothesised that the "anabolic" or "catabolic" environment evident in the E+S and S+E training groups respectively may support findings from our pervious training study. Taken collectively with the data from the previous training study, our findings suggest that hormones may be involved in the regulation of muscle architecture variables. Significant time vs. order interaction effects were observed for Cortisol (C) ($P = 0.02$) and Growth hormone (GH) ($P = 0.01$). Post-hoc analysis revealed significant differences in Testosterone (T) and GH at time-point 3 (12:30 h) (T; 27% Δ, $P = 0.03$; GH; 326% Δ P = 0.05) and at time-point 4 (13:45h) for C (C; 33% Δ, $P = 0.01$). Significant differences at time-point 4 (13:45h) were also revealed for the T : C ratio (48% Δ, P = 0.04). Furthermore, the E+S exercise condition had a significantly higher area under the curve (AUC) for T ($P = 0.05$) and GH ($P = 0.04$). Therefore, peak hormonal responses and calculations of the AUC suggest that the S+E condition created an extended "catabolic" environment, whereas the E+S condition promoted an "anabolic" window across a longer period of the day. The hormonal and training responses associated with each training condition provide evidence that exercise induced endocrine responses may be able to predict longer term training induced adaptations (Kraemer & Ratamess, 2005a). Although, it is acknowledged that this conclusion remains speculative and requires additional research to explain the interaction between endocrine and training responses associated with the E+S and S+E exercise conditions used in this thesis.

8.2 General Discussion

The purpose of training is to prepare players physically, mentally and tactically so that they can cope with the demands of elite level match-play. As each player is unique, it could be argued that these multi-faceted demands require individualised attention. for example, the athlete's training history can significantly affect how they respond to a given training stimulus (Bompa, 2009). As a result, training needs to be individually designed to meet the requirements of each player. Although, the competitive demands and the nature of 'team sports' do not always promote the use of an individualised periodisation strategy. The theory of training periodisation advocates the manipulation of training volume and intensity, which inevitably will influence the player's physiological response to the training stress or load. When the training demands across an extended period are either too high or too low (in relation to the players fitness level), over-training or detraining can occur and could negatively affect match-play performance (Kentta and Hassmen, 1998). Therefore, it is important that the training load is applied in context to the individual and requirements of the competition schedule (Fry *et al*., 1991).

The aim of Chapter 3 was to observe the training periodisation and organisation completed by a professional football team across a 5-week in season meso-cycle. This information helped to demonstrate the current approaches to training used in elite football and to form the basis of future experimental research. The findings of Chapter 3 revealed that training load remained similar across the 5-week observation period. The lack of variation in training load suggests that the physiological stimulus was not varied across the observation period. It could be argued that the training programme was monotonous and therefore could have subsequently influenced the training status of the athletes across the observational period (Smith, 2003). for example, if the athletes are exposed to a high training stimuli too frequently without sufficient time for recovery, the ability to adapt can become compromised and overtraining may occur (Fry *et al*. 2006). Whereas, if the training stimulus is insufficient then a decrease in the physiological benefits already attained can occur (i.e. detraining) (Kentta *et al*., 2001). Therefore, in order to effectively plan for optimum training adaptations it is important the coach understands the physiological demands/responses to each training session (Bompa, 2009). The reason for the lack of periodisation observed in Chapter 3 is unknown but may involve coaching decisions to prioritise recovery between competitions. It is also possible that the coaches' beliefs or his understanding of periodisation may have also influenced the coaching process. for example; the coach might have thought that increased training intensity and volume could increase the risk of injury to his important players. Alternatively, the coach may not have entirely understood how to periodise training or even thought that his periodisation was effective. However, these conclusions remain speculative. Considering that the present data is only representative of one team, it would be of interest to repeat such an investigation across longer periods and at different football clubs to gain a better understanding of the practice of periodisation within professional football.

The second aim of Chapter 3 was to investigate the acute organisation of concurrent-training within this applied environment. As previously mentioned, the congested playing schedule and restricted training time available makes the planning of training within elite football difficult. In this regard, it is common for football players to complete concurrent football and resistance-exercise on the same day. Whilst the interference effects associated with concurrent-training have been well documented (for review see; Doherty *et al*., 2000), many investigations have used untrained subjects and employed training protocols unlike that used by professional football teams. Few studies have directly investigated the effects of concurrent-training in elite football players (McGawley *et al*., 2013). Therefore, at present there are no practical guidelines as how to minimise the interference effect in elite football players. It was thought that this study would highlight the concurrent-training practices used in the applied environment and would provide the basis for future experimental research. It was found that the team had an unsystematic approach to the way nutrition and training was organised and delivered. Training was performed in opposing exercise sequences and with different nutritional provision and recovery periods between exercise bouts. Considering that training and nutritional organisation can influence intramuscular processes that orchestrate end-point adaptations and may also exacerbate the 'interference phenomenon' it was important to investigate the training effects of the concurrent-training programmes observed in Chapter 3.

The interference phenomenon first described by Hickson in 1980, has been investigated extensively (for reviews see; Leveritt, 1999; Nader, 2006, Hamilton *et al* 2013). During the past 30 years authors have attempted to provide a number of theories to explain the interference phenomenon (Craig *et al*., 1991, Bell *et al*., 2000, Docherty and Sporer, 2000, Dudley and Fleck, 1987). Early hypotheses suggested that acute peripheral fatigue following endurance exercise subsequently reduced participants' ability to train at higher intensities in later strength-training sessions and resulted in 'blunted' strength adaptation (Craig *et al*., 1991). The findings of Chapter 6 do not support this hypothesis in that when strength-training was performed after football training, the strength related adaptations were not blunted following a 5-week training period. In fact, the group who performed strength-training in a non-fatigued state prior to football practice showed a reduction in strength related adaptation. As both experimental groups completed similar resistance-training load it was concluded that peripheral fatigue could not explain the between group differences observed. Instead, it was hypothesised that the proximity of training bouts and the nutritional intake around training may have modulated other biological or molecular processes indirectly 'blunting' strength in the 'strength-football' condition.

In a later study (Chapter 7) we attempted to investigate why a 'blunted' strength response occurred when strength-training was performed immediately before football training. Due to the fact that the players were competing in competition, we were unable to use invasive techniques. Therefore, we described the hormonal responses to each concurrent-training scenario. Although the hormonal hypotheses to explain the interference phenomenon remains questionable (West, *et al*., 2009), we observed that hormonal responses were affected by the order in which the concurrent-training stimulus was delivered. It was concluded that the findings from the previous training study could be partly explained by a competing hormonal environment observed during each exercise condition. Although, due to the validity of using hormonal responses as a 'proxy' measurement for anabolism, future research could investigate the acute molecular responses to concurrent-training practices used by elite football players. This may provide a stronger scientific bases for future training recommendations to minimise the interference phenomenon.

It is acknowledged that in order to provide athletes with practical information to minimise the interference phenomenon more controlled research is warranted. To date, most conclusions and hypotheses in the concurrent-training literature have been refined to assumptions based on ‘snap-shot’ observations and ‘end-point’ adaptations without ‘systemic’ mechanistic information. This is demonstrated by the results of acute concurrent-training studies. for example; concurrent-training does not always inhibit anabolic signalling (Apro *et al*., 2013) or protein synthesis (Carrithers *et al*., 2007), yet interference has been reported by the vast majority of chronic training investigations (Wilson *et al*., 2013). Therefore, the interference phenomenon is unlikely to be understood in its entirety through studies describing acute responses to discrete bouts of exercise. In order to understand the evolution of the interference phenomena and comprehend why this process occurs, long-term studies that measure acute training and molecular / biological responses in tandem are warranted.

8.3 Limitations

8.3.1 Study design

The present thesis has investigated the effectiveness of 'real-world' training practices typically performed at a professional football club. Whilst the experimental protocols could be considered 'ecologically valid', they are not without limitation. for example, our design does not allow us to explicitly determine the acute and chronic effect of each training modality in isolation and thus does not allow us to accurately measure the degree of interference caused by concurrent-training. Ideally, participants would have completed each mode of training in isolation and each 'concurrent-training' exercise condition. This type of experiment (randomised cross-over trail) would have allowed for each participant to act as their own 'control' and enhanced the scientific validity of the resulting findings. Although it is acknowledged that this type of experiment is particularly difficult within the applied setting. In order to validate the findings from this thesis future research should investigate the effectiveness of the present concurrent-training in a controlled environment.

8.3.2 Sample Population

A secondary limitation of the present research is that not all studies in this thesis were carried out on the same population. The initial observation study (chapter 3) that formed the basis for the research questions in this thesis was carried out on the senior professional team competing in the English 'n-power championship'. Whereas the remaining experimental research was conducted on the junior athletes at the same professional club. This was because the funding for this research was originally granted to provide training recommendations applicable to the senior team at the football club. Although, the senior athletes were not allowed to train at high-intensity 2-3 days from competition. Therefore, experimental research was carried out on the junior team where participants were allowed to perform strenuous concurrent-training and testing protocols within close proximity of competition. Subsequently, it is acknowledged that the findings of this thesis may not necessarily be applicable to adult professional football players. However, the thesis does provide novel information that strenuous concurrent-training protocols can be employed 2 days from competition during the 'in-season' period to enhance both endurance and strength parameters that may be beneficial to football performance in elite junior athletes.

8.3.3 Recovery period between training bouts

The acute metabolic and intramuscular responses to the present exercise protocols are likely to be specific to the exercise duration, exercise intensity and the work-to-rest ratios used in the endurance and resistance aspects of the program. Moreover, as the intramuscular profile associated with each exercise modality lasts for between 1 and 8hrs following each training bout, the recovery period between each training bout is likely to effect the 'window' of each intramuscular cascade. The recovery duration between endurance and strength-training was different between exercise trials (see figure 19; 'S + E'; ~45 minutes *vs.* 'E + S'; ~120 minutes) and is therefore a further limitation of this thesis. This training design does not allow us to elucidate the mediating factor which could explain the differences observed in chapters 4 and 5. for example the 'concurrent-training exercise sequence' and (or) the 'recovery period' allocated between training bouts could both explain the differences previously observed. Therefore, it is recommended that future experiments investigating the effects of concurrent-training sequence standardise the recovery time between training bouts. The standardisation of the recovery period would allow the intramuscular events associated with each mode of exercise to become up regulated for the same amount of time and would therefore remove this bias allowing for more accurate interpretation of any resultant finding.

8.3.4 Nutritional availability

The importance of nutrient timing on muscle recovery and adaptation has been widely supported (Aragon et al., 2013; Burke et al., 2012, Hawley et al., 2013, Philips et al., 2012). In chapters 5 and 6 each experimental group consumed similar total nutritional intake. However, the ‘timing’ of nutritional intake before and after exercise was not matched in each exercise condition. It is acknowledged that the timing of nutritional intake around training is a limitation of the present experimental design and questions the authors ability to make accurate conclusions. for example the sequence of concurrent-training or the availability of nutrition throughout the day may explain between group differences in chapters 5 and 6. In addition, whilst this nutritional intake was controlled for 3 meals of the day for 7 weeks (i.e. the hours the athletes were present at the football club) we could not control what the participants consumed away from the football club. Between group discrepancies in nutritional intake may have had a significant impact upon the long-term adaptive process in each experimental condition. for example; if 'Player A' consumed an evening meal (~3hrs after leaving the football club) with a whey protein source (~0.25g $\bullet$ kg^{-1}) and a further casein based protein source prior to bed (~3hrs later) it is highly likely that the rise in circulating amino acid levels would be sustained throughout the remainder of the night (Goren et al., 2012). As a result whole body protein turnover and myofibrillar protein synthesis would have been high for an and extended window of approximately 15hrs, thus increasing the potential for adaptation. In contrast if 'Player B' did not consume any food in the evening period or did not consume any or enough protein until the following morning muscle myofibrillar protein synthesis would have become blunted (Titpon et al., 2009). Collectively these two scenarios represent two extreme cases which may have occurred throughout the experimental periods in this thesis and therefore could have also been a mediating factor in the between group differences observed in chapters 4 and 5. It is therefore recommended that future investigations concerning the effectiveness of the concurrent-training protocols used in this thesis should employ a research model where the nutritional intake is controlled across the entire experimental phase.

8.4 Recommendations for future research

Additional research is required to confirm the findings from this thesis. Specifically, more data is needed to investigate the concurrent-training practices used by other football teams and to understand how athletes respond to different training and nutritional arrangements. Furthermore, in order to prescribe training recommendations that could minimise the interference phenomenon in this population, more controlled laboratory studies investigating the effects of football-specific concurrent-training protocols are required. Ultimately, this future research should have the overriding goal of aiding practitioners in the design and delivery of more effective training programmes that increase player performance.

Recommendation 1: Is the approach to periodisation and organisation of concurrent-training unsystematic in the wider community of elite football and if so what are the barriers for coaches and scientists?

The findings from Chapter 3 demonstrate that despite large investment in sports science departments and highly experienced coaches, the application of periodised and well-structured training is not always possible. This may be due to a number of 'barriers' preventing coaches and scientists from applying theory into practice. More research is required to investigate if this observation is prevalent in other football teams. In order to understand these ‘barriers’ in the applied environment it may be necessary to interview coaches and scientists.

Recommendation 2: What are the molecular responses to the concurrent-training protocols used by football teams?

In Chapter 7 we described the hormonal responses to the concurrent-training protocols described previously in Chapter 6. However, it is acknowledged that investigating hormonal responses as a ‘proxy’ measurement to predict long-term adaptation is questionable. Therefore, future research incorporating other techniques such as gene expression (Bamman *et al*., 2007), microRNA abundance (Davidsen *et al*., 2011), and satellite cell activity (Hanssen *et al*., 2012) may provide a mechanistic explanation of our findings and provide further rationale for football teams to adapt the training protocols described in Chapter 6.

Recommendation 3: Does increasing the recovery time between concurrent-training bouts further enhance muscle adaptation?

Chapter 6 demonstrated that strength related adaptations can be enhanced when resistance-exercise is performed 2 hours after football training. However the effect of increasing the recovery duration between training bouts is not yet known. Recent studies investigating the molecular responses to acute concurrent-training suggest that increasing the recovery time between training bouts to >6 h can mitigate molecular interference (Lundberg *et al*., 2013). However, these studies have used steady state cycling protocols in untrained populations, thus highlighting that research is required to understand the relationship between recovery time and the acute and chronic responses to concurrent-training in elite football players.

Recommendation 4: What impact does nutrition have upon acute and chronic responses in different concurrent-training protocols?

At present, few studies have investigated the effects of different nutritional arrangements in concurrently training athletes. Indeed, nutrition is seen as a powerful modulator of intramuscular events responsible for training-induced adaptation (Tipton *et al*., 2004). Acute intramuscular responses associated with aerobic adaptations (e.g. mitochondrial biogenesis) have been shown to improve following endurance-exercise in the fasted state. Whereas, muscle protein synthesis has been shown to be modulated by whey protein intake before and after resistance-training (Hawley *et al*., 2013). Although, the combined interaction of both of these training/nutritional scenarios has not yet been studied. Future research could investigate the effect of different nutritional strategies in concurrent-training protocols used by elite athletes.

8.5 Conclusion

There is a plethora of studies investigating the effects of concurrent-training in untrained populations (Hawley *et al*., 2009). This data has consistently shown that when strength is trained simultaneously with aerobic parameters, strength related adaptations become ‘blunted’. However, the application of this data to elite athletes is questionable with few studies contributing to elucidate the most effective and practical organisation of concurrent-training to minimise the interference phenomenon. This thesis aimed to highlight ecologically valid issues surrounding the application of concurrent-training programmes in the applied environment. To the authors' knowledge, until now, no research groups have categorised how football teams organise and deliver their concurrent-training programmes and nutritional support. The findings from this thesis demonstrate that muscle adaptations can become negatively influenced if the organisation of training and nutrition is unsystematic. It can also be concluded that the way in which the training and nutritional stimulus is delivered can influence acute physiological responses which could potentially influence performance in secondary training bouts and influence longer-term muscle adaptations. Although more work is needed in the laboratory to confirm the findings of this thesis. Additional research is required to elucidate the barriers restricting coaches and sports science practitioners from applying evidenced-based training strategies. This information could eventually lead to a theoretical framework for understanding how to plan and deliver concurrent-training programmes in the applied setting so that the interference phenomenon is minimised.

Reference list

9.0 References

Aagaard, P., Simonsen, E. B., andersen, J. L., Magnusson, P. & Dhre-Poulsen, P. (2002). Increased Rate of force Development and Neural Drive of Human Skeletal Muscle Following Resistance-Training. *Journal of Applied Physiology*, 93, 1318-1326.A

Abernethy, P. J. & Quigley, B. M. (1993). Concurrent Strength and Endurance-Training of The Elbow Extensors. *Journal of Strength & Conditioning Research*, 7, 234-240.

Atherton, P. J., Babraj, J., Smith, K., Singh, J., Rennie, M. J. & Wackerhage, H. (2005). Selective Activation of AMPK-Pgc-1alpha Or Pkb-Tsc2-MTOR Signaling Can Explain Specific Adaptive Responses To Endurance Or Resistance-Training-Like Electrical Muscle Stimulation. Faseb J, 19, 786-8.

Atkinson, G. & Nevill, A. M. (1998). Statistical Methods for Assessing Measurement Error (Reliability) In Variables Relevant To *Sports Medicine*. *Sports Medicine*, 26, 217-238.

Atkinson, R. A., Srinivas-Shankar, U., Roberts, S. A., Connolly, M. J., Adams, J. E., Oldham, J. A., Wu, F. C. W., Seynnes, O. R., Stewart, C. E. H., Maganaris, C. N. & Narici, M. V. (2010). Effects of Testosterone on Skeletal Muscle Architecture In Intermediate-Frail and Frail Elderly Men. Journals of Gerontology Series A-Biological Sciences and Medical Sciences, 65, 1215-1219.

Ayala, F., De Ste Croix, M., De Baranda, P. S. & Santonja, F. (2012). Absolute Reliability of Hamstring To Quadriceps Strength Imbalance Ratios Calculated Using Peak Torque, Joint Angle-Specific Torque and Joint Rom-Specific Torque Values. *International Journal of Sports Medicine*, 33, 909-916.

Baar, K. (2006). Training for Endurance and Strength: Lessons From Cell Signaling. *Medicine and Science in Sports and Exercise*, 38, 1939-1944.

Baker, D. (2001). The Effects of An In-Season of Concurrent-Training on The Maintenance of Maximal Strength and Power In Professional and College-Aged Rugby League Football Players. *Journal of Strength and Conditioning Research*, 15, 172-177.

Balabinis, C. P., Psarakis, C. H., Moukas, M., Vassiliou, M. P. & Behrakis, P. K. (2003). Early Phase Changes By Concurrent Endurance and Strength-Training. *Journal of Strength and Conditioning Research*, 17, 393-401.

Bamman, M. M., Petrella, J. K., Kim, J. S., Mayhew, D. L. & Cross, J. M. (2007). Cluster Analysis Tests The Importance of Myogenic Gene Expression During Myofiber Hypertrophy In Humans. *Journal of Applied Physiology*, 102, 2232-2239.

Bangsbo, J., Iaia, F. M. & Krustrup, P. (2007). Metabolic Response and Fatigue In Soccer. *International Journal of Sports Physiology and Performance*, 2, 111-127.

Bangsbo, J., Iaia, F. M. & Krustrup, P. (2008). The Yo-Yo Intermittent Recovery Test - A Useful Tool for Evaluation of Physical Performance In Intermittent Sports. *Sports Medicine*, 38, 37-51.

Bangsbo, J., Mohr, M. & Krustrup, P. (2006). Physical and Metabolic Demands of Training and Match-Play In The Elite Football Player. *Journal of Sports Sciences*, 24, 665-674.

Bangsbo, J., Norregaard, L. & Thorso, F. (1991). Activity Profile of Competition Soccer. *Canadian Journal of Sport Sciences*-Revue Canadienne Des Sciences Du Sport, 16, 110-116.

Bell, G. J., Syrotuik, D., Martin, T. P., Burnham, R. & Quinney, H. A. (2000). Effect of Concurrent Strength and Endurance-Training on Skeletal Muscle Properties and Hormone Concentrations In Humans. *European Journal of Applied Physiology*, 81, 418-427.

Bird, S. P., Tarpenning, K. M. & Marino, F. E. (2005). Designing Resistance-Training Programmes To Enhance Muscular Fitness - A Review of The Acute Programme Variables. *Sports Medicine*, 35, 841-851.

Bishop, D., Girard, O. & Mendez-Villanueva, A. (2011). Repeated-Sprint Ability - Part Ii Recommendations for Training. *Sports Medicine*, 41, 741-756.

Bishop, D., Jenkins, D. G., Mackinnon, L. T., Mceniery, M. & Carey, M. F. (1999). The Effects of Strength-Training on Endurance Performance and Muscle Characteristics. *Medicine and Science in Sports and Exercise*, 31, 886-891.

Blazevich, A. J. (2006a). Effects of Physical Training and Detraining, Immobilisation, Growth and Aging on Human Fascicle Geometry. *Sports Medicine*, 36, 1003-1017.

Blazevich, A. J. (2006b). Effects of Physical Training and Detraining, Immobilisation, Growth and Aging on Human Fascicle Geometry. *Sports Medicine*, 36, 1003-17.

Blazevich, A. J., Cannavan, D., Coleman, D. R. & Horne, S. (2007). Influence of Concentric and Eccentric Resistance-Training on Architectural Adaptation In Human Quadriceps Muscles. *Journal of Applied Physiology*, 103, 1565-75.

Blazevich, A. J., Gill, N. D., Bronks, R. & Newton, R. U. (2003). Training-Specific Muscle Architecture Adaptation After 5-Wk Training In Athletes. *Medicine Science in Sports and Exercise*, 35, (2013)-22.

Blazevich, A. J. & Giorgi, A. (2001). Effect of Testosterone Administration and Weight Training on Muscle Architecture. *Medicine Science in Sports and Exercise*, 33, 1688-93.

Blazevich, A. J. & Jenkins, D. (1998). Physical Performance Differences Between Weight-Trained Sprinters and Weight Trainers. *Journal of Science Medicine in Sport*, 1, 12-21.

Blazevich, A. J. & Jenkins, D. G. (2002). Effect of The Movement Speed of Resistance-Training Exercises on Sprint and Strength Performance In Concurrently Training Elite Junior Sprinters. *Journal of Sports Science* 20, 981-90.

Bogdanis, G. C., Papaspyrou, A., Souglis, A. G., Theos, A., Sotiropoulos, A. & Maridaki, M. (2011). Effects of Two Different Half-Squat Training Programs on Fatigue During Repeated Cycling Sprints In Soccer Players. *Journal of Strength and Conditioning Research*, 25, 1849-1856.

Bradley, P. S., Sheldon, W., Wooster, B., Olsen, P., Boanas, P. & Krustrup, P. (2009). High-Intensity Running In English Fa Premier League Soccer Matches. *Journal of Sports Sciences*, 27, 159-168.

Buchheit, M. & Laursen, P. B. (2013). High-Intensity Interval Training, Solutions To The Programming Puzzle Part I: Cardiopulmonary Emphasis. *Sports Medicine*, 43, 313-338.

Cannon, R. J. & Cafarelli, E. (1987). Neuromuscular Adaptations To Training. *Journal of Applied Physiology* , 63, 2396-402.

Carroll, T. J., Abernethy, P. J., Logan, P. A., Barber, M. & Mceniery, M. T. (1998).Resistance-Training Frequency: Strength and Myosin Heavy Chain Responses To Two and Three Bouts Per Week. *European Journal of Applied Physiology*, 78, 270-275.

Chelly, M. S., Fathloun, M., Cherif, N., Ben Amar, M., Tabka, Z. & Van Praagh, E. (2009). Effects of A Back Squat Training Program on Leg Power, Jump, and Sprint Performances In Junior Soccer Players. *Journal of Strength and Conditioning Research*, 23, 2241-2249.

Christou, M., Smilios, I., Sotiropoulos, K., Volaklis, K., Pilianidis, T. & Tokmakidis, S. P. (2006). Effects of Resistance-Training on The Physical Capacities of Adolescent Soccer Players. *Journal of Strength and Conditioning Research*, 20, 783-791.

Chtaha, M., Chaouacrn, A., Levin, G. T., Chaouachi, M., Chamari, K., Amri, M. & Laursen, P. B. (2008). Effect of Concurrent Endurance and Circuit Resistance-Training Sequence on Muscular Strength and Power Development. Journal of Strength & Conditioning Research (Lippincott Williams & Wilkins), 22, 1037-1045.

Chtara, M., Chamari, K., Chaouachi, M., Chaouachi, A., Koubaa, D., Feki, Y., Millet, G. P. & Amri, M. (2005). Effects of Intra-Session Concurrent Endurance and Strength-Training Sequence on Aerobic Performance and Capacity. *British Journal of Sports Medicine*, 39, 555-560.

Chtara, M., Chaouachi, A., Levin, G. T., Chaouachi, M., Chamari, K., Amri, M. & Laursen, P. B. (2008). Effect of Concurrent Endurance and Circuit Resistance-Training Sequence on Muscular Strength and Power Development. *Journal of Strength and Conditioning Research*, 22, 1037-1045.

Chtourou, H., Driss, T., Souissi, S., Gam, A., Chaouachi, A. & Souissi, N. (2012). The Effect of Strength-Training At The Same Time of The Day on The Diurnal Fluctuations of Muscular Anaerobic Performances. *Journal of Strength and Conditioning Research* / National Strength & Conditioning Association, 26, 217-25.

Churchley, E. G., Coffey, V. G., Pedersen, D. J., Shield, A., Carey, K. A., Cameron-Smith, D. & Hawley, J. A. (2007). Influence of Preexercise Muscle Glycogen Content on Transcriptional Activity of Metabolic and Myogenic Genes In Well-Trained Humans. *Journal of Applied Physiology* , 102, 1604-11

Cohen, J. (1988). Statistical Power Analysis for The Behavioural Sciences (2nd Ed.). Hillsdale, Nj: Lawrence Erlbaum Associates.

Coffey, V. G. & Hawley, J. A. (2006). Training for Performance: Insights From Molecular Biology. *International journal of sports physiology and performance*, 1, 284-92.

Coffey, V. G., Jemiolo, B., Edge, J., Garnham, A. P., Trappe, S. W. & Hawley, J. A. (2009a). Effect of Consecutive Repeated Sprint and Resistance Exercise Bouts on Acute Adaptive Responses In Human Skeletal Muscle. Am J Physiol Regul Integr Comp Physiol, 297, R1441-51.

Coffey, V. G., Pilegaard, H., Garnham, A. P., O'brien, B. J. & Hawley, J. A. (2009b). Consecutive Bouts of Diverse Contractile Activity Alter Acute Responses In Human Skeletal Muscle. *Journal of Applied Physiology*, 106, 1187-1197.

Coffey, V. G., Shield, A., Canny, B. J., Carey, K. A., Cameron-Smith, D. & Hawley, J. A. (2006). Interaction of Contractile Activity and Training History on Mrna Abundance In Skeletal Muscle From Trained Athletes. *The American Journal of Physiology Endocrinology and Metabolism*, 290, E849-55.

Collins, M. A. & Snow, T. K. (1993). Are Adaptations To Combined Endurance and Strength-Training Affected By The Sequence of Training? *Journal of Sports Sciences*, 11, 485-491.

Cormie, P., Mcguigan, M. R. & Newton, R. U. (2011a). Developing Maximal Neuromuscular Power Part 1-Biological Basis of Maximal Power Production. *Sports Medicine*, 41, 17-38.

Cormie, P., Mcguigan, M. R. & Newton, R. U. (2011b). Developing Maximal Neuromuscular Power Part 2-Training Considerations for Improving Maximal Power Production. *Sports Medicine*, 41, 125-146.

Craig, B. W., Lucas, J., Pohlman, R. & Stelling, H. (1991). The Effects of Running, Weightlifting and A Combination of Both on Growth Hormone Release. *Journal of Strength & Conditioning Research,* 5, 198-203.

Creer, A., Gallagher, P., Slivka, D., Jemiolo, B., Fink, W. & Trappe, S. (2005). Influence of
Muscle Glycogen Availability on Erk1/2 and Akt Signaling After Resistance Exercise In Human Skeletal Muscle. *Journal of Applied Physiology* , 99, 950-6.

Cunningham, J. T., Rodgers, J. T., Arlow, D. H., Vazquez, F., Mootha, V. K. & Puigserver, P. (2007). MTOR Controls Mitochondrial Oxidative Function Through A Yy1-Pgc-1 Alpha Transcriptional Complex. *Nature,* 450, 736-U12.

Davidsen, P. K., Gallagher, I. J., Hartman, J. W., Tarnopolsky, M. A., Dela, F., Helge, J. W., Timmons, J. A. & Phillips, S. M. (2011). High Responders To Resistance Exercise Training Demonstrate Differential Regulation of Skeletal Muscle Microrna Expression. *Journal of Applied Physiology,* 110, 309-317.

Davis, W. J., Wood, D. T., andrews, R. G., Elkind, L. M. & Davis, W. B. (2008a). Concurrent-Training Enhances Athletes' Cardiovascular and Cardiorespiratory Measures. *Journal of Strength and Conditioning Research*, 22, 1503-1514.

Davis, W. J., Wood, D. T., andrews, R. G., Elkind, L. M. & Davis, W. B. (2008b). Concurrent-Training Enhances Athletes' Strength, Muscle Endurance, and Other Measures. *Journal of Strength and Conditioning Research,* 22, 1487-1502.

Docherty, D. & Sporer, B. (2000). A Proposed Model for Examining The Interference Phenomenon Between Concurrent Aerobic and Strength-Training. *Sports Medicine*, 30, 385-394.
Dolezal, B. A. & Potteiger, J. A. (1998). Concurrent Resistance and Endurance-Training Influence Basal Metabolic Rate In Nondieting Individuals. *Journal of Applied Physiology*, 85, 695-700.

Drummond, M. J., Dreyer, H. C., Fry, C. S., Glynn, E. L. & Rasmussen, B. B. (2009). Nutritional and Contractile Regulation of Human Skeletal Muscle Protein Synthesis and MTORc1 Signaling. *Journal of Applied Physiology* , 106, 1374-84.

Drust, B., Atkinson, G. & Reilly, T. (2007). Future Perspectives In The Evaluation of The Physiological Demands of Soccer. *Sports Medicine*, 37, 783-805.

Drust, B., Waterhouse, J., Atkinson, G., Edwards, B. & Reilly, T. (2005). Circadian Rhythms In Sports Performance--An Update. Chronobiol Int, 22, 21-44.

Dudley, G. A. & Djamil, R. (1985). Incompatibility of Endurance- and Strength-Training Modes of Exercise. *Journal of Applied Physiology*, 59, 1446-1451.

Dudley, G. A. & Fleck, S. J. (1987). Strength and Endurance-Training. Are They Mutually Exclusive? *Sports Medicine*, 4, 79-85.

Duthie, G. M., Pyne, D. B., Ross, A. A., Livingstone, S. G. & Hooper, S. L. (2006). The Reliability of Ten-Meter Sprint Time Using Different Starting Techniques. *Journal of Strength and Conditioning Research*, 20, 246-251.

Earle, R. & Baechle, T. R. (2004). The Nsca's Essentials of Personal Training Text. *Strength and Conditioning Journal*, 26, 76-77.

Ekblom, B. 1969. Effect of Physical Training on Oxygen Transport System In Man. Acta Physiologica Scandinavica, S, 9-&.

Farnfield, M. M., Breen, L., Carey, K. A., Garnham, A. & Cameron-Smith, D. (2012). Activation of MTOR Signalling In Young and Old Human Skeletal Muscle In Response To Combined Resistance Exercise and Whey Protein Ingestion. *Applied Physiology* Nutr Metab, 37, 21-30.

Fitts, R. H. (1994). Cellular Mechanisms of Muscle Fatigue. *Physiological Reviews*, 74, 49-94.

Fleck, S. J. (1999). Periodized Strength-Training: A Critical Review. *Journal of Strength and Conditioning Research*, 13, 82-89.

Folland, J. P. & Williams, A. G. (2007)a. The Adaptations To Strength-Training - Morphological and Neurological Contributions To Increased Strength. *Sports Medicine*, 37, 145-168.

Folland, J. P. & Williams, A. G. (2007)b. The Adaptations To Strength-Training : Morphological and Neurological Contributions To Increased Strength. *Sports Medicine*, 37, 145-68.
ford-Smith, C. D., Wyman, J. F., Elswick, R. K. & Fernandez, T. (2001). Reliability of Stationary Dynamometer Muscle Strength Testing In Community-Dwelling Older Adults. Archives of Physical Medicine and Rehabilitation, 82, 1128-1132.

Gamble, P. (2006). Periodization of Training for Team Sports Athletes. *Strength and Conditioning Journal*, 28, 56-66.

Gibala, M. J., Little, J. P., Van Essen, M., Wilkin, G. P., Burgomaster, K. A., Safdar, A., Raha, S. & Tarnopolsky, M. A. (2006). Short-Term Sprint Interval Versus Traditional Endurance-Training: Similar Initial Adaptations In Human Skeletal Muscle and Exercise Performance. *Journal of Physiology*-London, 575, 901-911.

Girard, O. & Bishop, D. (2012). Fatigue During Repeated Sprints Precision Needed Response Part I. *Sports Medicine*, 42, 167-168.

Girard, O., Mendez-Villanueva, A. & Bishop, D. (2011). Repeated-Sprint Ability - Part I Factors Contributing To Fatigue. *Sports Medicine*, 41, 673-694.

Gleeson, N. P. & Mercer, T. H. (1992). Reproducibility of Isokinetic Leg Strength and Endurance Characteristics of Adult Men and Women. *European Journal of Applied Physiology and Occupational Physiology*, 65, 221-228.

Goldberg, A. L., Etlinger, J. D., Goldspink, D. F. & Jablecki, C. 1975. Mechanism of Work-Induced Hypertrophy of Skeletal Muscle. *Medicine & Science in Sports & Exercise*, 7, 185-98.

Goto, K., Ishii, N., Kizuka, T. & Takamatsu, K. (2005). The Impact of Metabolic Stress on Hormonal Responses and Muscular Adaptations. *Medicine and Science in Sports and Exercise*, 37, 955-963.

Goto, K., Ishii, N., Kurokawa, K. & Takamatsu, K. (2007)a. Attenuated Growth Hormone Response To Resistance Exercise With Prior Sprint Exercise. *Medicine and Science in Sports and Exercise*, 39, 108-115.

Goto, K., Ishii, N., Sugihara, S., Yoshioka, T. & Takamatsu, K. (2007)b. Effects of Resistance Exercise on Lipolysis During Subsequent Submaximal Exercise. *Medicine and Science in Sports and Exercise*, 39, 308-315.

Haff, G. G., Jackson, J. R., Kawamori, N., Carlock, J. M., Hartman, M. J., Kilgore, J. L., Morris, R. T., Ramsey, M. W., Sands, W. A. & Stone, M. H. (2008). force-Time Curve Characteristics and Hormonal Alterations During An Eleven-Week Training Period In Elite Women Weightlifters. *Journal of Strength and Conditioning Research,*, 22, 433-46.

Haff, G. G., Lehmkuhl, M. J., Mccoy, L. B. & Stone, M. H. (2003). Carbohydrate Supplementation and Resistance-Training. *Journal of Strength and Conditioning Research,*, 17, 187-96.

Hakkinen, K., Alen, M., Kraemer, W. J., Gorostiaga, E., Izquierdo, M., Rusko, H., Mikkola, J., Hakkinen, A., Valkeinen, H., Kaarakainen, E., Romu, S., Erola, V., Ahtiainen, J. & Paavolainen, L. (2003). Neuromuscular Adaptations During Concurrent Strength and Endurance-Training Versus Strength-Training. *European Journal of Applied Physiology*, 89, 42-52.

Hansen, S., Kvorning, T., Kjaer, M. & Sjogaard, G. (2001). The Effect of Short-Term Strength-Training on Human Skeletal Muscle: The Importance of Physiologically Elevated Hormone Levels. *Scandinavian Journal of Medicine & Science in Sports*, 11, 347-354.

Hanssen, K. E., Kvamme, N. H., Nilsen, T. S., Ronnestad, B., Ambjornsen, I. K., Norheim, F., Kadi, F., Hallen, J., Drevon, C. A. & Raastad, T. (2012). The Effect of Strength-Training Volume on Satellite Cells, Myogenic Regulatory Factors, and Growth Factors. *Scandinavian Journal of Medicine & Science in Sports*.

Hawley, J. A. (2009). Molecular Responses To Strength and Endurance-Training: Are They Incompatible? Applied Physiology Nutrition and Metabolism-Physiologie Appliquee Nutrition Et Metabolisme, 34, 355-361.

Hawley, J. A., Tipton, K. D. & Millard-Stafford, M. L. (2006). Promoting Training Adaptations Through Nutritional Interventions. *Journal of Sports Science* 24, 709-21.

Hayes, L. D., Bickerstaff, G. F. & Baker, J. S. (2010). Interactions of Cortisol, Testosterone, and Resistance-Training: Influence of Circadian Rhythms. *Chronobiology International*, 27, 675-705.

Helgerud, J., Rodas, G., Kemi, O. J. & Hoff, J. (2011). Strength and Endurance In Elite Football Players. *International Journal of Sports Medicine*, 32, 677-682.

Hickson, R. C. 1980. Interference of Strength Development By Simultaneously Training for Strength and Endurance. *European Journal of Applied Physiology Occupational Physiology*, 45, 255-63.

Hickson, R. C., Rosenkoetter, M. A. & Brown, M. M. (1980). Strength-Training Effects on Aerobic Power and Short-Term Endurance. *Medicine Science in Sports and Exercise*, 12, 336-9.

Hill-Haas, S., Coutts, A., Rowsell, G. & Dawson, B. (2008a). Variability of Acute Physiological Responses and Performance Profiles of Youth Soccer Players In Small-Sided Games. *Journal of Science Medicine in Sport*, 11, 487-90.

Hill-Haas, S., Rowsell, G., Coutts, A. & Dawson, B. (2008b). The Reproducibility of Physiological Responses and Performance Profiles of Youth Soccer Players In Small-Sided Games. *International journal of sports physiology and performance*, 3, 393-6.

Hill-Haas, S. V., Coutts, A. J., Rowsell, G. J. & Dawson, B. T. (2009). Generic Versus Small-Sided Game Training In Soccer. *International Journal of Sports Medicine*, 30, 636-42.

Hill-Haas, S. V., Dawson, B., Impellizzeri, F. M. & Coutts, A. J. (2011). Physiology of Small-Sided Games Training In Football a Systematic Review. *Sports Medicine*, 41, 199-220.

Hoff, J. & Helgerud, J. (2004a). Endurance and Strength-Training for Soccer Players - Physiological Considerations. *Sports Medicine*, 34, 165-180.

Hoff, J. & Helgerud, J. (2004b). Endurance and Strength-Training for Soccer Players: Physiological Considerations. *Sports Medicine*, 34, 165-80.

Hopkins, W. G. (2000). Measures of Reliability In *Sports Medicine* and Science. *Sports Medicine*, 30, 1-15.

Hunter, G., Demment, R. & Miller, D. (1987). Development of Strength and Maximum Oxygen Uptake During Simultaneous Training for Strength and Endurance. *The Journal of Sports Medicine and Physical Fitness*, 27, 269-75.

Iga, J., George, K., Lees, A. & Reilly, T. (2006). Reliability of Assessing Indices of Isokinetic Leg Strength In Pubertal Soccer Players. *Paediatric Exercise Science*, 18, 436-445.

Impellizzeri, F. M., Bizzini, M., Rampinini, E., Cereda, F. & Maffiuletti, N. A. (2008). Reliability of Isokinetic Strength Imbalance Ratios Measured Using The Cybex Norm Dynamometer. *Clinical Physiology and Functional Imaging,* 28, 113-119.

Impellizzeri, F. M., Marcora, S. M., Castagna, C., Reilly, T., Sassi, A., Iaia, F. M. & Rampinini, E. (2006). Physiological and Performance Effects of Generic Versus Specific Aerobic-Training In Soccer Players. *International Journal of Sports Medicine*, 27, 483-492.

Impellizzeri, F. M., Rampinini, E., Coutts, A. J., Sassi, A. & Marcora, S. M. (2004). Use of Rpe-Based Training Load In Soccer. *Medicine and Science in Sports and Exercise*, 36, 1042-1047.

Izquierdo-Gabarren, M., Exposito, R. G. D., Garcia-Pallares, J., Sanchez-Medina, L., De Villarreal, E. S. S. & Izquierdo, M. (2010). Concurrent Endurance and Strength-Training Not To Failure Optimizes Performance Gains. *Medicine and Science in Sports and Exercise*, 42, 1191-1199.

Jackson, N. P., Hickey, M. S. & Reiser, R. F. (2007). High Resistance/Low Repetition Vs. Low Resistance/High Repetition Training: Effects on Performance of Trained Cyclists. *Journal of Strength and Conditioning Research,* 21, 289-295.

Jeukendrup, A. E. (2004). Carbohydrate Intake During Exercise and Performance. *Nutrition,* 20, 669-77.

Jeukendrup, A. E. & Jentjens, R. (2000). Oxidation of Carbohydrate Feedings During Prolonged Exercise: Current Thoughts, Guidelines and Directions for Future Research. *Sports Medicine,* 29, 407-24.

Jones, S. & Drust, B. (2007). Physiological and Technical Demands of 4 V 4 and 8 V 8 Games In Elite Youth Soccer Players. / Fizioloå Ki I Tehniäœki Zahtjevi Igranja Malog Nogometa 4 Protiv 4 I 8 Protiv 8 Kvalitetnih Mladih Nogometaå A. Kinesiology, 39, 150-156.

Karvonen, J. & Vuorimaa, T. (1988). Heart-Rate and Exercise Intensity During Sports Activities - Practical Application. *Sports Medicine*, 5, 303-311.

Kellis, E., Kellis, S., Gerodimos, V. & Manou, V. (1999). Reliability of Isokinetic Concentric and Eccentric Strength In Circumpubertal Soccer Players. *Paediatric Exercise Science*, 11, 218-228.

Kentta, G. & Hassmen, P. (1998). Overtraining and Recovery. A Conceptual Model. *Sports Medicine*, 26, 1-16.

Kraemer, W. J., Adams, K., Cafarelli, E., Dudley, G. A., Dooly, C., Feigenbaum, M. S., Fleck, S. J., Franklin, B., Fry, A. C., Hoffman, J. R., Newton, R. U., Potteiger, J., Stone, M. H., Ratamess, N. A. & Triplett-McBride, T. (2002a). American College of Sports Medicine Position Stand. Progression Models In Resistance-Training for Healthy Adults. *Medicine and Science in Sports and Exercise*, 34, 364-80.

Kraemer, W. J., Adams, K., Cafarelli, E., Dudley, G. A., Dooly, C., Feigenbaum, M. S., Fleck, S. J., Franklin, B., Fry, A. C., Hoffman, J. R., Newton, R. U., Potteiger, J., Stone, M. H., Ratamess, N. A. & Triplett-Mcbride, T. (2002)b. Joint Position Statement: Progression Models In Resistance-Training for Healthy Adults. *Medicine and Science in Sports and Exercise*, 34, 364-380.

Kraemer, W. J., Duncan, N. D. & Volek, J. S. (1998). Resistance-Training and Elite Athletes: Adaptations and Program Considerations. *Journal of Orthopaedic & Sports Physical Therapy*, 28, 110-9.

Kraemer, W. J., Patton, J. F., Gordon, S. E., Harman, E. A., Deschenes, M. R., Reynolds, K., Newton, R. U., Triplett, N. T. & Dziados, J. E. (1995). Compatibility of High-Intensity Strength and Endurance-Training on Hormonal and Skeletal Muscle Adaptations. *Journal of Applied Physiology* , 78, 976-89.

Kraemer, W. J. & Ratamess, N. A. (2005). Hormonal Responses and Adaptations To Resistance Exercise and Training. *Sports Medicine*, 35, 339-61.

Kraemer, W. J., Vescovi, J. D., Volek, J. S., Nindl, B. C., Newton, R. U., Patton, J. F., Dziados, J. E., French, D. N. & Hakkinen, K. (2004). Effects of Concurrent Resistance and Aerobic-Training on Load-Bearing Performance and The Army Physical Fitness Test. *Military Medicine*, 169, 994-9.

Krustrup, P., Mohr, M., Amstrup, T., Rysgaard, T., Johansen, J., Steensberg, A., Pedersen, P. K. & Bangsbo, J. (2003). The Yo-Yo Intermittent Recovery Test Is Highly Reproducible, Sensitive, and Valid. *Medicine and Science in Sports and Exercise*, 35, 2120-2120.

Krustrup, P., Mohr, M., Nybo, L., Jensen, J. M., Nielsen, J. J. & Bangsbo, J. (2006). The Yo-Yo Ir2 Test: Physiological Response, Reliability, and Application To Elite Soccer. *Medicine and Science in Sports and Exercise*, 38, 1666-1673.

Kumagai, K., Abe, T., Brechue, W. F., Ryushi, T., Takano, S. & Mizuno, M. (2000). Sprint Performance Is Related To Muscle Fascicle Length In Male 100-M Sprinters. *Journal of Applied Physiology*, 88, 811-816.

Kvorning, T., andersen, M., Brixen, K. & Madsen, K. (2006). Suppression of Endogenous Testosterone Production Attenuates The Response To Strength-Training: A Randomized, Placebo-Controlled, and Blinded Intervention Study. American *Journal of Physiology-Endocrinology and Metabolism*, 291, E1325-E1332.

Kvorning, T., Andersen, M., Brixen, K., Schjerling, P., Suetta, C. & Madsen, K. (2007). Suppression of Testosterone Does Not Blunt Mrna Expression of Myod, Myogenin, Igf, Myostatin Or androgen Receptor Post Strength-Training In Humans. *Journal of Physiology*-London, 578, 579-593.

Laughlin, M. H. & Roseguini, B. (2008). Mechanisms for Exercise Training-Induced Increases In Skeletal Muscle Blood Flow Capacity: Differences With Interval Sprint Training Versus Aerobic Endurance-Training. *Journal of Physiology and Pharmacology*, 59 Suppl 7, 71-88.

Lepers, R., Pousson, M. L., Maffiuletti, N. A., Martin, A. & Van Hoecke, J. (2000). The Effects of A Prolonged Running Exercise on Strength Characteristics. *International Journal of Sports Medicine*, 21, 275-80.

Leveritt, M. & Abernethy, P. J. (1999). Acute Effects of High-Intensity Endurance Exercise on Subsequent Resistance Activity. *Journal of Strength and Conditioning Research*, 13, 47-51.

Leveritt, M., Abernethy, P. J., Barry, B. & Logan, P. A. (2003). Concurrent Strength and Endurance-Training: The Influence of Dependent Variable Selection. *Journal of Strength and Conditioning Research* / National Strength & Conditioning Association, 17, 503-508.

Little, T. & Williams, A. G. (2007). Measures of Exercise Intensity During Soccer Training Drills With Professional Soccer Players. *Journal of Strength and Conditioning Research,*, 21, 367-71.

Lundberg, T. R., Fernandez-Gonzalo, R., Gustafsson, T. & Tesch, P. A. (2012). Aerobic Exercise Alters Skeletal Muscle Molecular Responses To Resistance Exercise. *Medicine and Science in Sports and Exercise,* 44, 1680-1688.

Lundberg, T. R., Fernandez-Gonzalo, R., Gustafsson, T. & Tesch, P. A. (2013). Aerobic Exercise Does Not Compromise Muscle Hypertrophy Response To Short-Term Resistance-Training. *Journal of Applied Physiology*, 114, 81-89.

Macdougall, J. D., Elder, G. C., Sale, D. G., Moroz, J. R. & Sutton, J. R. 1980. Effects of Strength-Training and Immobilization on Human Muscle Fibres. *European Journal of Applied Physiology Occupational Physiology,* 43, 25-34.

Mcbride, J. M., Mccaulley, G. O., Cormie, P., Nuzzo, J. L., Cavill, M. J. & Triplett, N. T. (2009). Comparison of Methods To Quantify Volume During Resistance Exercise. *Journal of Strength and Conditioning Research*, 23, 106-110.

Mccarthy, J. P., Agre, J. C., Graf, B. K., Pozniak, M. A. & Vailas, A. C. (1995). Compatibility of Adaptive Responses With Combining Strength and Endurance-Training. *Medicine and Science in Sports and Exercise,* 27, 429-436.

Mccarthy, J. P., Pozniak, M. A. & Agre, J. C. (2002). Neuromuscular Adaptations To Concurrent Strength and Endurance-Training. *Medicine and Science in Sports and Exercise*, 34, 511-519.

Mcgawley, K. & andersson, P. I. (2013). The Order of Concurrent-Training Does Not Affect Soccer-Related Performance Adaptations. *International Journal of Sports Medicine*, 34, 983-990.
Mcguigan, M. R., Wright, G. A. & Fleck, S. J. (2012). Strength-Training for Athletes: Does It Really Help Sports Performance? *International Journal of Sports Physiology and Performance*, 7, 2-5.

Mckay, B. R., Paterson, D. H. & Kowalchuk, J. M. (2009). Effect of Short-Term High-Intensity Interval Training Vs. Continuous Training on O-2 Uptake Kinetics, Muscle Deoxygenation, and Exercise Performance. *Journal of Applied Physiology*, 107, 128-138.

Mendez-Villanueva, A., Buchheit, M., Kuitunen, S., Douglas, A., Peltola, E. & Bourdon, P. (2011). Age-Related Differences In Acceleration, Maximum Running Speed, and Repeated-Sprint Performance In Young Soccer Players. *Journal of Sports Sciences*, 29, 477-484.

Michels, G. & Hoppe, U. C. (2008). Rapid Actions of androgens. Frontiers In *Neuroendocrinology*, 29, 182-198.

Milner-Brown, H. S., Stein, R. B. & Lee, R. G. 1975. Synchronization of Human Motor Units: Possible Roles of Exercise and Supraspinal Reflexes. *Electroencephalography and Clinical Neurophysiology*, 38, 245-54.

Mjolsnes, R., Arnason, A., Osthagen, T., Raastad, T. & Bahr, R. (2004). A 10-Week Randomized Trial Comparing Eccentric Vs. Concentric Hamstring Strength-Training In Well-Trained Soccer Players. *Scandinavian Journal of Medicine & Science in Sports*, 14, 311-317.

Mohr, M., Krustrup, P. & Bangsbo, J. (2003). Match Performance of High-Standard Soccer Players With Special Reference To Development of Fatigue. *Journal of Sports Sciences*, 21, 519-528.

Moir, G., Button, C., Glaister, M. & Stone, M. H. (2004). Influence of Familiarization on The Reliability of Vertical Jump and Acceleration Sprinting Performance In Physically Active Men. *Journal of Strength and Conditioning Research*, 18, 276-280.

Morse, C. I., Thom, J. M., Mian, O. S., Muirhead, A., Birch, K. M. & Narici, M. V. (2005). Muscle Strength, Volume and Activation Following 12-Month Resistance-Training In 70-Year-Old Males. *European Journal of Applied Physiology*, 95, 197-204.

Morton, J. P., Atkinson, G., Maclaren, D. P., Cable, N. T., Gilbert, G., Broome, C., Mcardle, A. & Drust, B. (2005). Reliability of Maximal Muscle force and Voluntary

Activation As Markers of Exercise-Induced Muscle Damage. *European Journal of Applied Physiology*, 94, 541-8.

Nader, G. A. (2006). Concurrent Strength and Endurance-Training: From Molecules To Man. *Medicine and Science in Sports and Exercise*, 38, (1965)-1970.

Noorkoiv, M., Nosaka, K. & Blazevich, A. J. (2010). Assessment of Quadriceps Muscle Cross-Sectional Area By Ultrasound Extended-Field-of-View Imaging. *European Journal of Applied Physiology*, 109, 631-9.

Rampinini, E., Coutts, A. J., Castagna, C., Sassi, R. & Impellizzeri, F. M. (2007)a. Variation In Top Level Soccer Match Performance. *International Journal of Sports Medicine*, 28, 1018-1024.

Rampinini, E., Coutts, A. J., Castagna, C., Sassi, R. & Impellizzeri, F. M. (2007)b. Variation In Top Level Soccer Match Performance. *International Journal of Sports Medicine*, 28, 1018-24.

Rampinini, E., Impellizzeri, F. M., Castagna, C., Abt, G., Chamari, K., Sassi, A. & Marcora, S. M. (2007)c. Factors Influencing Physiological Responses To Small-Sided Soccer Games. *Journal of Sports Science* 25, 659-66.

Reilly, T. (2005). An Ergonomics Model of The Soccer Training Process. *Journal of Sports Sciences*, 23, 561-572.
Rhea, M. R., Oliverson, J. R., Marshall, G., Peterson, M. D., Kenn, J. G. & Ayllón, F. N. (2008). Noncompatibility of Power and Endurance-Training Among College Baseball Players. *Journal of Strength & Conditioning Research*, 22, 230-234

Ritti-Dias, R. M., Avelar, A., Salvador, E. P. & Cyrino, E. S. (2011). Influence of Previous Experience on Resistance-Training on Reliability of one-Repetition Maximum Test. *Journal of Strength and Conditioning Research*, 25, 1418-1422.

Ronnestad, B. R., Kvamme, N. H., Sunde, A. & Raastad, T. (2008). Short-Term Effects of Strength and Plyometric Training on Sprint and Jump Performance In Professional Soccer Players. *Journal of Strength and Conditioning Research*, 22, 773-780.

Ronnestad, B. R., Nygaard, H. & Raastad, T. (2011)a. Physiological Elevation of Endogenous Hormones Results In Superior Strength-Training Adaptation. *European Journal of Applied Physiology*, 111, 2249-2259.

Ronnestad, B. R., Nymark, B. S. & Raastad, T. (2011)b. Effects of In-Season Strength Maintenance Training Frequency In Professional Soccer Players. *Journal of Strength and Conditioning Research* / National Strength & Conditioning Association, 25, 2653-60.

Rutherford, O. M. & Jones, D. A. (1992). Measurement of Fibre Pennation Using Ultrasound In The Human Quadriceps In Vivo. *European Journal of Applied Physiology Occupational Physiology*, 65, 433-7.

Sale, D. G., Jacobs, I., Macdougall, J. D. & Garner, S. (1990). Comparison of 2 Regimens of Concurrent Strength and Endurance-Training. *Medicine and Science in Sports and Exercise*, 22, 348-356.

Sale, D. G., Mccomas, A. J., Macdougall, J. D. & Upton, A. R. 1982. Neuromuscular Adaptation In Human Thenar Muscles Following Strength-Training and Immobilization. *Journal of Applied Physiology* , 53, 419-24.

Santtila, M., Kyrolainen, H. & Hakkinen, K. (2009). Changes In Maximal and Explosive Strength, Electromyography, and Muscle Thickness of Lower and Upper Extremities Induced By Combined Strength and Endurance-Training In Soldiers. *Journal of Strength and Conditioning Research,*, 23, 1300-8.

Saunders, P. U., Pyne, D. B., Telford, R. D. & Hawley, J. A. (2004). Factors Affecting Running Economy In Trained Distance Runners. *Sports Medicine*, 34, 465-485.

Sedliak, M., Finni, T., Cheng, S., Lind, M. & Hakkinen, K. (2009). Effect of Time-of-Day-Specific Strength-Training on Muscular Hypertrophy In Men. *Journal of Strength and Conditioning Research,*, 23, 2451-7.

Siegl, P. & Schultz, K. (1984). The Borg Scale As An Instrument for The Detection of Subjectively Experienced Stress In Industrial Medicine Laboratory and Field Studies. Z Gesamte Hyg, 30, 383-6.

Smith, D. J. (2003). A Framework for Understanding The Training Process Leading To Elite Performance. *Sports Medicine*, 33, 1103-1126.

Smith, J. & Mcnaughton, L. (1993). The Effects of Intensity of Exercise on Excess Postexercise Oxygen-Consumption and Energy-Expenditure In Moderately Trained Men and Women. *European Journal of Applied Physiology and Occupational Physiology*, 67, 420-425.

Souissi, N., Gauthier, A., Sesboue, B., Larue, J. & Davenne, D. (2002). Effects of Regular Training At The Same Time of Day on Diurnal Fluctuations In Muscular Performance. *Journal of Sports Science* 20, 929-37.

Spiering, B. A., Kraemer, W. J., anderson, J. M., Armstrong, L. E., Nindl, B. C., Volek, J. S. & Maresh, C. M. (2008). Resistance Exercise Biology. *Sports Medicine*, 38, 527-540.

Stagno, K. M., Thatcher, R. & Van Someren, K. A. (2007). A Modified Trimp To Quantify The In-Season Training Load of Team Sport Players. *Journal of Sports Sciences*, 25, 629-634.

Staron, R. S. (1991). Correlation Between Myofibrillar Atpase Activity and Myosin Heavy Chain Composition In Single Human Muscle Fibers. Histochemistry, 96, 21-4.

Stolen, T., Chamari, K., Castagna, C. & Wisloff, U. (2005). Physiology of Soccer - An Update. *Sports Medicine*, 35, 501-536.

Stone, M. H., O'bryant, H. S., Schilling, B. K., Johnson, R. L., Pierce, K. C., Haff, G. G., Koch, A. J. & Stone, M. (1999)a. Periodization: Effects of Manipulating Volume and Intensity. Part 1. *Strength and Conditioning Journal*, 21, 56-62.

Stone, M. H., O'bryant, H. S., Schilling, B. K., Johnson, R. L., Pierce, K. C., Haff, G. G., Koch, A. J. & Stone, M. (1999)b. Periodization: Effects of Manipulating Volume and Intensity. Part 2. *Strength and Conditioning Journal*, 21, 54-60.

Tesch, P. A., Colliander, E. B. & Kaiser, P. (1986). Muscle Metabolism During Intense, Heavy-Resistance Exercise. *European Journal of Applied Physiology Occupational Physiology*, 55, 362-6.

Tipton, K. D. & Ferrando, A. A. (2008). Improving Muscle Mass: Response of Muscle Metabolism To Exercise, Nutrition and Anabolic Agents. *Essays Biochemistry*, 44, 85-98.

Tipton, K. D. & Wolfe, R. R. (2004). Protein and Amino Acids for Athletes. *Journal of Sports Science* 22, 65-79.

Todd, G., Gorman, R. B. & Gandevia, S. C. (2004). Measurement and Reproducibility of Strength and Voluntary Activation of Lower-Limb Muscles. *Muscle & Nerve,* 29, 834-842.

Vieillevoye, S., Poortmans, J. R., Duchateau, J. & Carpentier, A. (2010). Effects of A Combined Essential Amino Acids/Carbohydrate Supplementation on Muscle Mass, Architecture and Maximal Strength Following Heavy-Load Training. *European Journal of Applied Physiology*, 110, 479-88.

Wang, L., Mascher, H., Psilander, N., Blomstrand, E. & Sahlin, K. (2011). Resistance Exercise Enhances The Molecular Signaling of Mitochondrial Biogenesis Induced By Endurance Exercise In Human Skeletal Muscle. *Journal of Applied Physiology*, 111, 1335-1344.

West, D. W. D., Kujbida, G. W., Moore, D. R., Atherton, P., Burd, N. A., Padzik, J. P., De Lisio, M., Tang, J. E., Parise, G., Rennie, M. J., Baker, S. K. & Phillips, S. M. (2009). Resistance Exercise-Induced Increases In Putative Anabolic Hormones Do Not Enhance Muscle Protein Synthesis Or Intracellular Signalling In Young Men. *Journal of Physiology*-London, 587, 5239-5247.

Westing, S. H. & Seger, J. Y. (1989). Eccentric and Concentric Torque-Velocity Characteristics, Torque Output Comparisons, and Gravity Effect Torque Corrections for The Quadriceps and Hamstring Muscles In Females. *International Journal of Sports Medicine*, 10, 175-180.

Wilson, G. J. & Murphy, A. J. (1996). The Use of Isometric Tests of Muscular Function In Athletic Assessment. *Sports Medicine*, 22, 19-37.

Wilson, J. M., Marin, P. J., Rhea, M. R., Wilson, S. M. C., Loenneke, J. P. & anderson, J. C. (2012). Concurrent-Training: A Meta-Analysis Examining Interference of Aerobic and Resistance Exercises. *Journal of Strength and Conditioning Research*, 26, 2293-2307.

Wisloff, U., Castagna, C., Helgerud, J., Jones, R. & Hoff, J. (2004). Strong Correlation of Maximal Squat Strength With Sprint Performance and Vertical Jump Height In Elite Soccer Players. *British Journal of Sports Medicine*, 38, 285-288.

Wisloff, U., Helgerud, J. & Hoff, J. (1998). Strength and Endurance of Elite Soccer Players. *Medicine and Science in Sports and Exercise*, 30, 462-467.

Wong, P. L., Chaouachi, A., Castagna, C., Lau, P. W. C., Chamari, K. & Wisloff, U. (2011). Validity of The Yo-Yo Intermittent Endurance Test In Young Soccer Players. *European Journal of Sport Science*, 11, 309-315.

Wong, P. L., Chaouachi, A., Chamari, K., Dellal, A. & Wisloff, U. (2010). Effect of Preseason Concurrent Muscular Strength and High-Intensity Interval Training In Professional Soccer Players. *Journal of Strength and Conditioning Research*, 24, 653-660.

Woodard, C. M., James, M. K. & Messier, S. P. (1999). Computational Methods Used In The Determination of Loading Rate: Experimental and Clinical Implications. *Journal of Applied Biomechanics*, 15, 404-417.

Xu, J., Ji, J. & Yan, X. H. (2012). Cross-Talk Between AMPK and MTOR In Regulating Energy Balance. *Critical Reviews in Food Science and Nutrition*, 52, 373-381.