

**THE PHYSIOLOGICAL AND GENETIC FACTORS  
UNDERPINNING POWERFUL ACTIONS IN ELITE  
YOUTH SOCCER**

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## **ABSTRACT**

There is no information available in the scientific literature that documents a specific assessment protocol for analysing a soccer player's maximal power capabilities. As soccer-associated muscular power has not previously been investigated, it is not known how important power is in elite soccer and, if it is, the physiological and genetic determinants of soccer-associated power remain unknown. Such information could be used to optimise soccer-specific talent identification and development strategies. With this in mind, the overriding aim of our thesis was to investigate the physiological and genetic factors underpinning powerful actions in elite youth soccer.

When devising an assessment of soccer-associated muscular power, there needs to be a detailed analysis of the specific actions performed during elite competitive match-play that can be described as powerful. The aims of our first experimental study (Chapter Three) were to compare the frequency and durations of powerful actions during competitive English Premier League [under 18 (U18) and under 21 (U21)] elite youth soccer matches using a novel soccer specific powerful action (SSPA) notational analysis coding system. We found that while elite soccer match-play requires players to perform powerful actions in multiple directions [68 horizontal accelerations (in the horizontal-forward or mediolateral directions), eight sprints, and six vertical jumps (three bilateral and three unilateral)], horizontal accelerations of short duration ( $< 1.5$  s) from different starting speeds were the most dominant type of explosive action. This activity profile provides a strong rationale for devising a muscular power assessment protocol that evaluates the ability to produce maximal power in multiple directions, from a unilateral stance. Our data also suggests that such a protocol could provide a specific lower body power profile in elite soccer players (ESP).

The aim of our second study (Chapter Four) was therefore, to determine whether countermovement jumps (CMJs) in different directions [CMJs: bilateral

vertical (BV), unilateral vertical (UV), unilateral horizontal-forward (UH) and unilateral medial (UM)] assessed independent lower-limb power qualities, and if CMJ performance differed between ESP (representing an English Premier League Academy regularly at U18 and under U21 levels) and non-elite soccer players (NSP). We found that unilateral CMJs in different directions assessed independent peak vertical power (V-power) and resultant take-off velocity capabilities, and the UH CMJ required significantly greater bicep femoris electromyographic (EMG) activation in comparison all other CMJs. Moreover, in comparison to NSP, ESP achieved greater V-power during all CMJs ( $p \leq 0.032$ ) except for BV ( $p = 0.197$ ), and also achieved greater UH CMJ projectile range ( $51.6 \pm 15.4$  vs.  $40.4 \pm 10.4$  cm,  $p = 0.009$ ). Our results suggest that unilateral CMJs in different directions, but not the commonly used BV CMJ, are determinants of U18 and U21 elite soccer playing status and can be used by applied practitioners as independent assessments of soccer-associated muscular power.

As the physiological determinants of performance are of use to the applied practitioner for informing talent identification criteria, and prescribing detailed training intervention strategies, the primary aims of the third and fourth studies were to investigate the neuromuscular (Chapter Five) and tendon (Chapter Six) determinants of unilateral CMJs oriented in different directions. Our data suggests that unilateral CMJ performance is associated with direction-specific neuromuscular and tendon properties in U18 and U21 ESP. While UV CMJ performance was related to the size (quadriceps femoris muscle volume and physiological cross sectional area), architecture (vastus lateralis pennation angle) and ability to activate (vastus lateralis EMG activation level) the knee extensor muscles, UH CMJ performance was related to the elongation and compliance properties of the patellar tendon, and was inversely correlated with vastus lateralis fascicle pennation angle. Our findings highlight the

importance of targeting specific neuromuscular and tendon properties when assessing and developing muscular power performance in U18 and U21 ESP.

Many physiological changes occur during puberty (Viru et al., 1999) and our findings in Chapters Four, Five and Six may only be applicable in U18 and U21 ESP. Therefore, in our fifth study (Chapter Seven) we aimed to investigate the importance of acceleration, sprint, horizontal-forward CMJ and vertical CMJ capabilities at different stages of maturation in elite youth soccer. Elite soccer players and CON were grouped using years from/to predicted peak height velocity (PHV, a measure of growth velocity and an indirect measure of pubertal phase) to determine maturation status (ESP: pre-PHV, n=100; mid-PHV, n=25; post-PHV, n=88; CON: pre-PHV, n=44; mid-PHV, n=15; post-PHV, n=54). By comparing performance of ESP and control participants (CON) matched for maturation status, we found that acceleration and sprint performance were associated with elite youth soccer at all stages of maturation, but maximal power (horizontal-forward and vertical jumping) capabilities may only be important for elite youth soccer at mid- and post-peak height velocity. Our data could imply that assessments of acceleration and sprint capabilities should be included in soccer talent identification protocols at all stages of maturation, but maximal power should only be included at mid- and post-PHV.

The purpose of our sixth experimental study (Chapter 8) was to investigate if specific gene single nucleotide polymorphisms [SNPs: *ACTN3* R577X (rs1815739), *BDNF* G>A (rs6265), *COL5A1* C>T (rs12722), and *COL2A1* C>T (rs2070739)] played a role in determining elite youth soccer player status, and speed and power capabilities, in ESP and CON at different stages of maturation. We found that *ACTN3* R- and *BDNF* G-allele frequencies were more frequent in post-PHV compared to pre-PHV ESP. Moreover, while the *COL2A1* CC genotype was associated with greater horizontal power and faster 20 m sprint performance, *BDNF* GG genotype appears to positively influence 20 m sprint performance during the pre-PHV period only. Overall,



our findings illustrate that elite soccer may require different genetic profiles before and after maturation, and genetic screening could be included in talent identification criteria to help predict maximal power and sprint potential in ESP.

In summary, we devised a muscular power assessment battery that measured independent power qualities and could discriminate between U18 and U21 ESP and NSP. Our subsequent analysis showed that the physiological factors underpinning unilateral CMJ performance were direction-specific, and UV and UH CMJ capabilities were underpinned by separate neuromuscular and tendon properties, and should be assessed and developed, independently in U18 and U21 ESP. We then recruited a larger cohort of ESP and CON, at different stages of maturation, and demonstrated that muscular power was important for elite soccer performance at mid and post-PHV, but not pre-PHV. Finally, we showed that genetic profiles of ESP differed between pre- and post-PHV, and that certain gene variants [*COL2A1* C>T (rs2070739), *BDNF* G>A (rs6265)] were associated with specific power and speed capabilities in ESP. Overall, our studies provide novel information that could have significant implications on soccer-associated power related talent identification and training intervention strategies in elite youth soccer academies.

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## LIST OF ABBREVIATIONS

ACSA, Anatomical cross sectional area

BF, Biceps femoris

BH, Bilateral horizontal

$BM^{0.67}$ , Body mass allometrically scaled to the power of 0.67

BV, Bilateral vertical

CMJ, Countermovement jump

CON, Control

CV, Coefficient of variation

EMG, Electromyographic

EPL, English Premier League

ESP, Elite soccer player

GPS, Global positioning system

H-power, Peak horizontal-forward power

HGRF, Anterior-posterior ground reaction force

HWE, Hardy-Weinberg equilibrium

ICC, Intraclass correlation coefficient

iMVC, Isometric maximal voluntary contraction

KE, Knee extension

KF, Knee flexion

$L_f$ , Fascicle length

LG, Lateral gastrocnemius

MGRF, Mediolateral ground reaction force

M-power, Peak medial power

NSP, Non-elite soccer player

PCSA, Physiological cross sectional area

PHV, Peak height velocity

PR, Projectile range

pRFD, Peak rate of force development

QF, Quadriceps femoris

RFD, Rate of force development

RMS, Root mean square algorithm

RMVC, Ramp maximum voluntary contraction

RTD, Rate of torque development

SNP, Single nucleotide polymorphism

SSC, Stretch shortening cycle

SSPA, Soccer specific powerful action

UH, Unilateral horizontal-forward

UM, Unilateral medial

UV, Unilateral vertical

V-power, Peak vertical power

VGRF, Vertical ground reaction force

VL, Vastus lateralis

$V_m$ , Muscle volume

$\theta_p$ , Pennation angle

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## **CHAPTER ONE**

### **GENERAL INTRODUCTION**



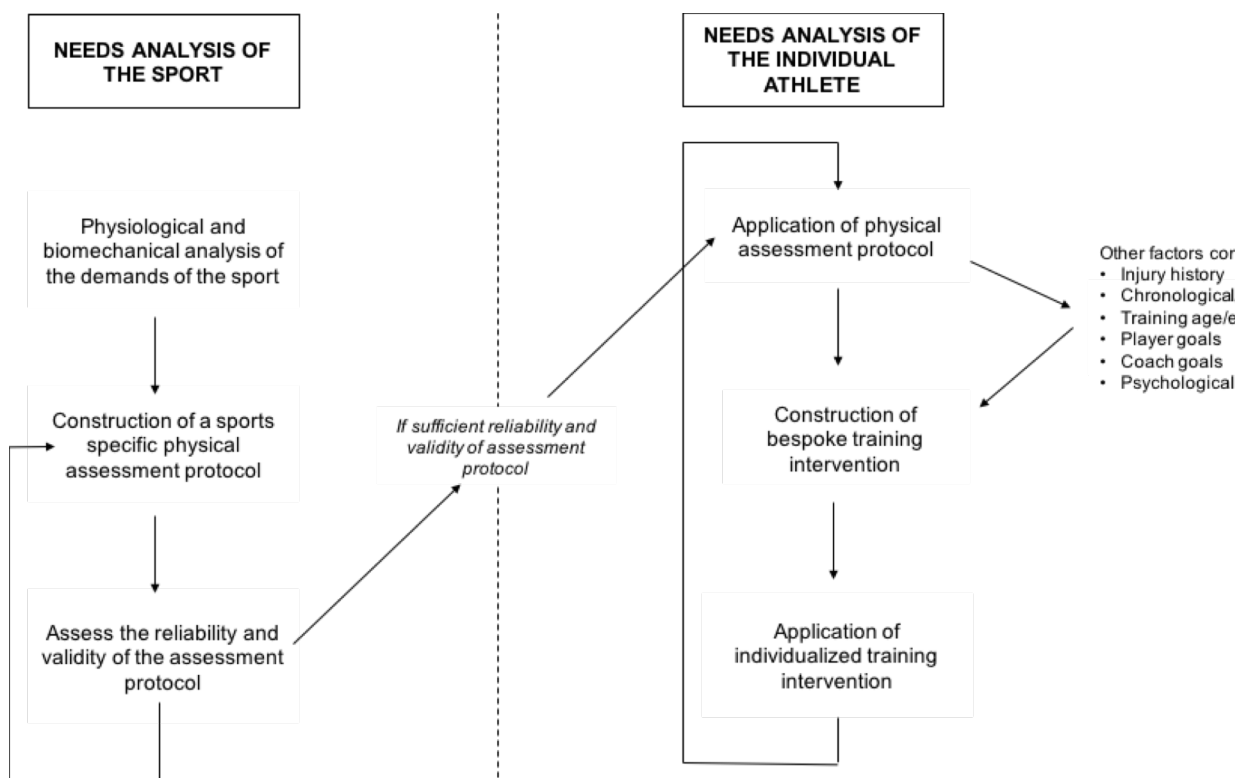
## 1.0 BACKGROUND

Professional soccer is a multi-directional sport, characterised by frequent changes in exercise type and intensity, e.g. walking, sprinting and jumping (Stolen et al., 2005). Whilst the majority of match-play is spent performing low intensity activities, it is often bursts of explosive activity that determine the outcome of competitive matches (Faude, Koch and Meyer, 2012, Mohr, Krustup and Bangsbo, 2003). Within a soccer context, maximal power is generated during single movements that are performed with the intention of producing the greatest possible velocity at take-off, release or impact (Cormie, McGuigan and Newton, 2011). Indeed, previous research reported that an elite soccer player may perform up to ~119 maximal accelerations, ~35 sprints (Bradley et al., 2010), ~50 forceful changes of direction (Withers et al., 1982), and ~16 vertical jumps (Reilly and Thomas, 1976) during the course of a competitive game. The ability to generate maximal power during complex motor skills may therefore be considered paramount to successful soccer performance. It is often a key aim of the soccer strength and conditioning practitioner to enhance the ability of the player to produce maximal power during soccer-specific actions (Chelly et al., 2009, Chelly et al., 2010b, Loturco et al., 2015).

When developing the physical capabilities of elite athletes, it is imperative to perform a comprehensive needs analysis of the sport and the individual athlete (Fig. 1.1 represents our need analysis model). This process allows the practitioner to gain an in-depth understanding of the specific demands of the sport, and the relative physical capabilities of the athlete. Individuals selected to represent the highest ranked (Category One) soccer academies in England, according to the Elite Player Performance Plan (Premier-League, 2011) audit criteria (only 24 out of 86 English soccer academies were awarded Category One status), can be classified as 'elite' youth soccer players (ESP). As ability to produce maximal power is specific to the biomechanical detail of the movement, (Coburn, 2012, Harman, 1993, Maulder and Cronin, 2005), strength and conditioning practitioners aiming to enhance muscular power performance capabilities in ESP need a

knowledge of the specific actions performed during elite soccer match-play that require the production of maximal power. Such information could inform the specific detail of assessment protocols, thus allowing the practitioner to evaluate the player's maximal power performance capabilities, and prescribe bespoke training interventions accordingly. However, due to limitations in the current literature, a detailed account of the powerful actions performed during elite soccer match-play is not available. Consequently, no assessments exist in the current literature that examine soccer-associated maximal power capabilities directly. Current soccer talent identification and training interventions focused on soccer-associated muscular power may therefore be suboptimal.

As different training modalities have previously been shown to enhance neuromuscular adaptations specific to the training stimulus (Cormie, McGuigan and



**Figure 1.1.** A flow chart illustrating our views on the needs analysis process. This process allows the prescription and periodic evaluation of individualised elite athlete training intervention programmes.

Newton, 2010a, Tillin and Folland, 2014), it is believed soccer strength and conditioning practitioners should aim to target the development of physiological adaptations, rather than just performance capabilities. However, as no specific performance assessment for soccer-associated power exists in the current literature, the physiological factors underpinning soccer-associated power remain unknown. Having access to an assessment that measures soccer-associated maximal power performance, and knowledge of the underlying physiological mechanistic determinants, could inform the specific detail of elite player talent identification and development programmes.

Many physiological changes occur during the adolescent growth spurt, which varies in timing and rate between individuals (Virus et al., 1999). Maturation is therefore a major confounding factor when identifying soccer talent (Vandendriessche et al., 2012). Soccer-associated power assessment criteria may need to be specific to maturation status. However, this concept has not yet been investigated and it is unknown if maximal power is a key determinant of elite soccer playing status at different stages of maturation. Such information could inform specific talent identification criteria at different stages of maturation thus increasing the chances of selecting players with the potential maximal power capabilities to perform at the highest level of elite soccer.

As previous research including 4428 female twins showed that genetic variation accounted for 66% of the variability in athlete status (twins who had competed at national or county level were considered elite athletes) (De Moor et al., 2007), it is thought that genetic screening may also have a role in the talent identification process. However, the only cross-sectional research associating specific genetic polymorphisms with power-associated performance measures in elite soccer players, is inconclusive (Coelho et al., 2015, Pimenta et al., 2013). Future research investigating the influence of specific genotypes on the maximal power capabilities in ESP could help predict future maximal power potential, thus informing talent identification and development strategies from a young age.

In order to identify soccer-associated maximal power potential, and prescribe subsequent detailed sport-specific maximal power development programmes for ESP, it is imperative that the powerful activity requirements of soccer match-play are understood, and talent identification performance testing and physiological assessment criteria is detailed, specific to the demands of soccer match-play, and tailored to the maturation status of the player. A knowledge of the genetic factors underpinning soccer-associated maximal power performance could also inform novel talent identification strategies and could potentially allow the prediction of a player's future maximal power potential from an early age. However, the current literature is limited in this area and there is little evidence to inform maximal power-associated soccer talent identification or genetic screening models at elite soccer clubs. In summary, we believe a greater understanding of the physiological and genetic determinants of soccer-associated maximal power should improve future talent identification and development strategies in the elite soccer population.

### **1.1 AIM AND OBJECTIVES OF THESIS**

The main aim of this thesis was to investigate the physiological and genetic factors underpinning maximal power associated with soccer performance in ESP. By providing a greater understanding of muscular power in elite youth soccer, the main objective was to identify the physiological determinants of power associated with ESP, and to develop innovative methods to measure soccer-associated maximal power for use in talent identification and development.

The specific objectives of this thesis were:

1. To characterise the powerful actions that are performed during elite youth soccer match-play. This is addressed in the work described in Chapter Three.

2. To ascertain whether unilateral countermovement jumps (CMJs) in different directions could be used as specific assessments of soccer-associated power. This is investigated in the work described in Chapter Four.
3. To determine which neuromuscular factors contribute to soccer-associated power performance, and if these factors differ between ESP and CON. This is addressed in Chapter Five.
4. To establish the relationships between patellar tendon properties and soccer-associated power, and if these properties differ between ESP and CON. This is investigated in Chapter Six.
5. To determine how the importance of different powerful actions changes with maturation in ESP. This topic is explored in the work described in Chapter Seven.
6. To determine associations between specific gene polymorphisms and power and speed in ESP at different stages of maturation. This is addressed in Chapter Eight.

## **CHAPTER TWO**

### **REVIEW OF THE LITERATURE**

## **2.0 INTRODUCTION**

In the current review, we aim to provide a rationale to investigate the physiological and genetic factors associated with powerful actions in elite youth soccer. We will identify gaps in the present body of research, which could be developed to improve the current understanding of soccer-associated maximal power. The content is presented in six sections. First, the current literature that has attempted to describe and quantify the powerful actions performed during elite youth soccer match-play will be discussed. The second section aims to analyse previous research documenting the importance of maximal power in elite youth soccer. Thirdly, the current assessments used to measure muscular power in elite youth soccer will be summarised. The fourth section aims to discuss the physiological factors that underpin muscular power and that may be related to elite soccer performance. The fifth section aims to summarise the effects of maturation on muscular power performance. The sixth section will present the most recent genetics research in soccer, and also discuss the relationship, or potential relationship, between specific gene variants and maximal muscular power performance capabilities. The final section will summarise the main findings of this literature review and articulate some recommendations for future research within a soccer talent identification context.

### **2.1 POWERFUL ACTIVITY DURING ELITE SOCCER MATCH-PLAY**

It is imperative that soccer talent identification and specific training criteria correspond to the detailed physical demands of the sport. Within a soccer context, a “powerful action” can be defined as a movement whereby the athlete propels their body to leave the ground whilst attempting to achieve the greatest possible velocity at take-off (Cormie, McGuigan and Newton, 2011). Previous literature has shown that such actions represent particularly critical moments in soccer matches (Faude,

Koch and Meyer, 2012, Haugen, Tønnessen and Seiler, 2013). If certain powerful actions are conducted frequently during competitive elite soccer match play, it can be assumed that the ability to perform these actions is important for high-level soccer performance. An account of the detail and frequency of powerful actions performed during elite soccer match play would therefore provide valuable information to inform the specificity of maximal power assessment and development protocols.

Many attempts have been made to quantify high intensity activities performed during soccer match play (Bradley et al., 2009, Buchheit et al., 2010, Di Salvo et al., 2010, Di Salvo et al., 2007, Di Salvo et al., 2009, Gregson et al., 2010, Harley et al., 2010). Recent advances in technology with multi-camera and global positioning systems (GPS) have allowed the objective quantification of the movement demands of multiple players during the same match by measuring the distance travelled and duration spent in pre-determined generic speed and acceleration categories (Carling et al., 2008). European Champions League and UEFA Cup (Di Salvo et al., 2010), and English Premier League (Bradley et al., 2009) players, have been shown to perform ~27 and ~35 sprints per game, respectively. Although sprinting may only constitute 1-12% of total distance covered in a game (Di Salvo et al., 2010), sprint capability is considered an important determinant of elite soccer performance. However, more recently it was reported that elite Norwegian (Ingebrigtsen et al., 2015) and Australian (Varley and Aughey, 2013b) players performed 5.5- and 8- fold greater maximal accelerations than sprints per game, respectively ( $91 \pm 21$  vs.  $17 \pm 8$  and  $65 \pm 21$  vs.  $8 \pm 5$ , respectively). Considering ~98% of maximal accelerations were initiated from low velocities  $<4.00 \text{ m}\cdot\text{s}^{-1}$ , and ~85% did not reach speeds higher than  $4.17 \text{ m}\cdot\text{s}^{-1}$  (Varley and Aughey, 2013b), it appears the ability to accelerate over shorter distances at lower velocities may also be an important characteristic of elite soccer performance (Varley and Aughey, 2013b). However, previous research has demonstrated that ESP within the same squad achieved different acceleration and



maximal running speeds when measured during linear speed testing protocols (Mendez-Villanueva et al., 2011, Stolen et al., 2005), and competitive games (Bradley et al., 2009, Mendez-Villanueva et al., 2011). The classification of maximal acceleration and sprint actions as being above pre-determined thresholds (i.e. maximal acceleration threshold:  $>2.78 \text{ m}\cdot\text{s}^{-1}$  (Varley and Aughey, 2013b);  $>2 \text{ m}\cdot\text{s}^{-1}$  (Ingebrigtsen et al., 2015); Sprint threshold:  $>25.2 \text{ km}\cdot\text{hr}^{-1}$  (Di Salvo et al., 2010, Di Salvo et al., 2009)) may be misleading for many players as their absolute maximal sprint and acceleration capabilities may be either higher, or lower, than these generic thresholds (Mendez-Villanueva et al., 2011, Stolen et al., 2005). It has been shown that faster players reach higher peak speeds in games (Mendez-Villanueva et al., 2011) and therefore the use of arbitrary speed thresholds when categorizing data may omit or wrongly include movements that are not indicative of a maximal action for the individual player (Dogramac, Watsford and Murphy, 2011). Consequently, current time motion analysis data reporting the frequency of maximal accelerations and sprints during a game should be analysed with caution.

To further illustrate limitations associated with using automated time analysis systems to analyse the powerful activity performed during elite soccer match-play, the accuracy and reliability of most automated time motion analyses systems has been shown to be compromised at the higher speeds and greater rates of acceleration indicative of powerful efforts performed during soccer match play (Akenhead et al., 2014, Di Salvo et al., 2009, Johnston et al., 2014, Ogris et al., 2012, Valter et al., 2006, Varley, Fairweather and Aughey, 2012). In agreement with previous findings (Varley, Fairweather and Aughey, 2012), Akenhead and colleagues (2014) reported that during maximal accelerations, the accuracy of a GPS sampling at 10 Hz for measuring instantaneous velocity decreases as the acceleration increases and validity is compromised above  $>4 \text{ m}\cdot\text{s}^{-1}$ . Johnston and colleagues (2014) also reported that GPS sampling at 5 Hz provided a valid method for

analysing work rate patterns at low and moderate, but not high speeds over 20 km·h<sup>-1</sup>. Considering ESP have been shown to achieve speeds of up to 22.6 km·h<sup>-1</sup> over 10 m, and peak game speeds of up to 31.0 ± 0.4 km·h<sup>-1</sup> (average for “faster” wide midfielders; (Mendez-Villanueva et al., 2011)), the interpretation of maximal speeds must be treated with caution. The reliability of GPS for acceleration and sprint activities also seems poor with coefficient of variation reported to be 39% and 19.7-30% for 10 m and 20 m sprints, respectively (Jennings et al., 2010). Whilst utilising hardware such as microwave radio channel to 10 RadioEye™ sensors (Ingebrigtsen et al., 2015), which samples at higher frequencies (40 Hz), may improve the accuracy of measurement, this type of system has yet to be validated during soccer specific powerful actions. The inability to accurately measure actions performed in small spaces and at high speeds may suggest that automated time motion analyses reports do not give an accurate account of the powerful actions performed during elite soccer match-play. Such data should therefore be analysed and compared with caution.

Many automated time motion analyses systems do not offer a facility to measure vertical actions during a game and research documenting the frequency of vertical jumps during elite match-play is scarce (Bradley et al., 2010, Bradley et al., 2009, Di Salvo et al., 2010, Ingebrigtsen et al., 2015, Varley and Aughey, 2013b). One previous study reported soccer players to perform 15 ± 2 headers during a game but gave no information as to whether a jump was performed (Mohr, Krusturp and Bangsbo, 2003). However, vertical jumps were reported to precede 57 out of 360 goals scored in the Bundesliga during the 2007-2008 season (Faude, Koch and Meyer, 2012) and therefore, the ability to perform vertical propulsions may be important in determining the outcome of competitive games. However, the frequency and detail of powerful vertical jumps (bilateral or unilateral) during elite competitive match-play has not been reported to date.

Subjective video-based tracking notational analysis has been proven a reliable and valid method of tracking soccer-associated player movements where short distances, frequent changes in direction (Bloomfield, Polman and O'Donoghue, 2004, Dogramac, Watsford and Murphy, 2011) and vertical jumps (Faude, Koch and Meyer, 2012, Mohr, Krstrup and Bangsbo, 2003) are observed. Moreover, subjective video-based tracking notational analysis can quantify movement regardless of the velocity attained and is therefore not limited by the application of pre-determined generic acceleration or velocity thresholds to individual players with a range of maximal acceleration and sprint capacities. Indeed, it has been documented that video-based player tracking notational analysis may provide a more accurate description of the frequency and duration of the complex powerful actions elicited during elite soccer match play in comparison to global position system automated time motion methods (Dogramac, Watsford and Murphy, 2011). However, previous soccer notational systems were limited for this purpose (Table 2.1) and coded sprints but not maximal acceleration actions (Bloomfield, Polman and O'Donoghue, 2007, Faude, Koch and Meyer, 2012), failed to report action duration (Faude, Koch and Meyer, 2012), and only reported the frequency of powerful actions preceding goals (Faude, Koch and Meyer, 2012) and during isolated random fifteen-minute periods of games (Bloomfield, Polman and O'Donoghue, 2007). Therefore, whilst video-based tracking notational analysis may offer an accurate and reliable technique for evaluating the powerful activity profile of elite soccer match-play, no study to date has provided a comprehensive description of the detail of powerful actions performed over the duration of a competitive soccer match.

**Table 2.1.** A critical analysis of previous subjective notational analysis literature describing powerful actions during elite soccer match-play.

Critical Questions	Bloomfield et al. (2007)	Faude et al. (2012)
How were powerful actions defined?	An intensity modifier included a “high intensity” and “very high intensity” category. No other information explaining how powerful actions were identified.	Definitions of powerful action categories were provided, which did not include details of how to identify if the action was considered powerful.
Was the frequency of sprints and maximal accelerations reported?	No. Only maximal sprints.	No. Only maximal sprints.
Was the frequency of vertical jumps reported?	Yes.	Yes.
Was the detail of vertical jump type (unilateral or bilateral) reported?	No.	No.
Was action duration reported?	Yes, but no clear definition of action start and end time points were reported.	No.
Does the study report the powerful action profile for the whole game?	No. 15 minute periods of games were recorded and analysed.	No. Powerful actions preceding goals were reported.

In summary, to achieve specificity in soccer training and testing protocols, it is important that applied practitioners understand the specific detail of the powerful actions that are performed during elite soccer match play. However, due to limitations with current techniques and study design, the powerful action profile of elite soccer match play has not been well documented. Consequently, there is

currently limited information available to inform the specific detail of soccer maximal power assessment and training intervention protocols. While it seems that automated time motion analyses systems do not offer the best method of describing the powerful action profile of elite soccer match-play, video-based tracking notational analysis methods, although more labour intensive, may offer more flexibility around categorising the complex movements performed during soccer performance. These methods should therefore be used in future studies to provide a valid and reliable account of the powerful action profile of elite soccer match-play. Such information could help soccer practitioners apply more specific powerful action training interventions and assessment protocols.

## **2.2 THE IMPORTANCE OF MAXIMAL MUSCULAR POWER IN ELITE SOCCER**

Another method of determining the importance of a specific physical characteristic for elite soccer performance is to assess whether this quality discriminates between different practice levels (Reilly et al., 2000). A specific performance capability is indirectly considered a determinant of high-level soccer performance if ESP present greater capacities than individuals who have never been selected to perform for soccer clubs competing at the highest level (Cometti et al., 2001).

Bilateral vertical countermovement jump (BV CMJ) performance is frequently used as a performance test for maximal power in ESP (Alves et al., 2010, Arnason et al., 2004, Chelly et al., 2010b, Comfort et al., 2014, Rønnestad, Nymark and Raastad, 2011). Indeed, Arnason and colleagues (2004) found a significant relationship between average BV CMJ height and success among seventeen teams in the 2 highest divisions in Iceland. Similarly, Rosch and colleagues (2000) reported lower BV CMJ performance in amateur players compared with top level and third division players. Nevertheless, Rosch and colleagues (2000) also found similar BV CMJ performance between top level and third division players compared with local

team players. Moreover, BV CMJ did not discriminate between French (Cometti et al., 2001) or Norwegian (Haugen, Tønnessen and Seiler, 2013, Wisloff, Helgerud and Hoff, 1998) soccer players at different playing levels and was not significantly related to any match physical performance variables (Rampinini et al., 2007). Hence, the importance of vertical jumping ability in elite soccer remains unclear and no study has compared BV CMJ performance in senior English players of different competitive levels. Future studies are required to establish the relevance of vertical jump assessment as a measurement of muscular power in soccer players.

Muscular power is an important component of acceleration and sprint performance (Rumpf et al., 2013). Haugen and colleagues (2013) documented faster 20 m sprint performance in Norwegian national team and first division players in comparison to second, third, fourth and fifth- division players. In contrast, Cometti and colleagues (2001) reported no speed differences over 30 m between French elite players and amateurs, but elite players were quicker over 10 m. However, as ESP are frequently required to play games with less than three days recovery (Nédélec et al., 2013), physiological data on ESP is scarce. Subsequently, the importance of muscular power in elite soccer remains unknown and future studies should focus on comparing professional ESP at different practice levels.

As the main goal with elite youth soccer players is development, rather than performance, there are more opportunities to perform physiological testing with this population. A retrospective analysis in French U14-U16 soccer players reported no difference in sprint performances or vertical jump performances amongst players reaching future professional or amateur status (le Gall et al., 2010). In contrast, youth ESP have been shown to outperform non-elite players (NSP) in acceleration, speed and vertical jump assessments at various youth age groups including 14-17 yrs (Gil et al., 2007), 16 yrs (Reilly et al., 2000) and 14 yrs (Waldron and Murphy, 2013). However, these studies did not account for maturation that may confound differences

between levels. Based on the interaction between age, height and leg length, the maturity status of athletes can be estimated non-invasively by categorising players according to the years from peak height velocity (PHV; pre-PHV (< -1.0 years), mid-PHV (-0.99 to 0.5 years) and post-PHV (> 0.51 years)) (Meylan et al., 2014, Mirwald et al., 2002, Rumpf et al., 2012). Cross sectional data consistently shows that from the age of ~13 years, boys that are advanced in maturity status (sexual and skeletal maturation) are better represented in elite youth soccer teams (Figueiredo et al., 2009, Malina et al., 2007, Pena Reyes, Cardenas-Barahona and Malina, 1994, Wrigley et al., 2014). As the adolescent growth spurt varies in timing and rate, and is closely associated with improvements in speed and power performance in youth soccer players (Malina et al., 2004, Philippaerts et al., 2006), the difference in performance between ESP and NSP may be somewhat confounded by failure to account for differences in biological maturity status (Vandendriessche et al., 2012). Nonetheless, when maturation was accounted for and included as a covariate, Vaeyens and colleagues (2006) reported that youth ESP demonstrated greater BV CMJ, horizontal-forward jump and 30 m performance in comparison to age matched NSP players at U13-U15, but not U16 age groups. Moreover, Deprez and colleagues (2015) showed that although there was no difference in maturation between Belgian youth players retained or those who dropped out of an elite soccer development programme, players who were retained demonstrated greater 5 m acceleration and 30 m sprint from U10-U15 age groups, but only displayed greater BV CMJ and horizontal-forward jump performance at U14 and U15 age groups. Subsequently, the importance of vertical jump, horizontal-forward jump, acceleration and sprint performance in ESP still remains unknown. Moreover, it appears that different physical capabilities could discriminate between ESP and NSP at different stages of maturation and therefore the physical determinants of elite soccer may be specific to maturational status (pre-PHV, mid-PHV and post-PHV). However, no study to date

has investigated this concept and future studies should compare the maximal power capacities presented by ESP and NSP at the same stage of maturation to identify the physical determinants that are important at different stages of maturation.

In summary, elite soccer talent identification protocols should only assess muscular power associated capabilities that are important for high-level soccer performance. Due to biological changes that occur in the human body during maturation (Virus et al., 1999), the importance of muscular power capabilities for elite soccer performance may be specific to maturation status. However, the current body of literature does not document the muscular power-associated determinants of elite soccer performance at different stages of maturation, or in senior professional players. It is therefore currently unknown which specific muscular power capabilities are determinants of elite soccer performance. Such information could inform the detail of maturation specific soccer talent identification assessment and development programmes.

### **2.3 THE ASSESSMENT OF MAXIMAL MUSCULAR POWER**

Sport-specific maximal power assessments provide objective measurements, which represent the ability of the athlete to achieve the greatest instantaneous power during a single sport-related movement. This movement is performed with the aim of achieving the greatest velocity at release, impact or when leaving the ground at take-off (Cormie, McGuigan and Newton, 2011). To serve the purpose of informing ESP talent identification and development procedures, it is important that muscular power assessments provide the greatest diagnostic information in the shortest amount of time. The application of muscular power is delimited by posture, contraction type and movement pattern. Within this context, assessments of muscular power should be specific and measured using tests that are biomechanically similar to the specific



movement patterns common in the sport of interest (Coburn, 2012, Harman, 1993, Maulder and Cronin, 2005).

During the course of a match, a soccer player jumps in the vertical direction an average of 15.5 times (Reilly and Thomas, 1976), performs up to 36 sprints (Di Salvo et al., 2010), 50 forceful changes of direction (Withers et al., 1982), and many unorthodox powerful movements such as tackling, twisting and attempting to maintain or gain possession of the ball while exerting physical force against an opponent (Bloomfield, Polman and O'Donoghue, 2007, Mohr, Krustup and Bangsbo, 2003). This activity profile suggests that soccer match-play involves the application of power in vertical, horizontal-forward and mediolateral directions. Nonetheless, maximal power is often assessed in ESP by measuring bilateral vertical jump performance variables (Alves et al., 2010, Chelly et al., 2010a, Rønnestad, Nymark and Raastad, 2011). Considering the complex multi-directional movement patterns in soccer match play, and that most propulsion in sport is performed from a unilateral stance with one leg on the ground (Hewit, Cronin and Hume, 2012), the bilateral vertical jump assessment may not be the best representation of functional lower limb power performance in elite soccer players.

Unilateral jump assessments in different directions have been recently shown to provide a highly reliable (Table 2.2 shows the current literature documenting the reliability of unilateral jump assessments in different directions) and more specific lower body power profile in a range of athletes and multi-directional team sports (Chamari et al., 2008, Meylan et al., 2009a, Meylan et al., 2010, Newton et al., 2006, Paterno and Greenberger, 1996). Muscle activation (Fukashiro et al., 2005) and co-ordination (Fukashiro et al., 2005, Nagano, Komura and Fukashiro, 2007) strategies are thought to differ depending on the jump directional movement pattern, with horizontal-forward jumps requiring more hamstring activation than vertical jumps, which require greater rectus femoris muscle activation. Furthermore, a low to moderate shared variance has

**Table 2.2.** Reliability studies in the current literature investigating unilateral countermovement jump assessments in different directions.

Study	Participants	Jump Assessments	Protocol	Jump variables	Reliability Findings
Meylan et al. (2010)	Thirty non-elite team sport athletes (age, $21.9 \pm 3.8$ years).	Horizontal countermovement jump	Using the designated jumping leg, the participants were instructed to sink down and jump horizontally as far possible landing on two legs, keeping their hands on their hips. Repeat testing session seven days later.	Distance (cm)	ICC = 0.89
				HGRF (N)	ICC = 0.70
				VGRF (N)	ICC = 0.83
				Peak power (W)	ICC = 0.77
		Mediolateral countermovement jump	Using the designated jumping leg, the participants were instructed to sink down and jump laterally as far possible landing on two legs keeping their hands on their hips. Repeat testing session seven days later.	Distance (cm)	ICC = 0.92
				HGRF (N)	ICC = 0.89
				VGRF (N)	ICC = 0.90
				Peak power (W)	ICC = 0.89
		Vertical countermovement jump	Using the designated jumping leg, the participants were instructed to sink down and jump as high possible landing on two legs keeping their hands on their hips. Repeat testing session seven days later.	Height (cm)	ICC = 0.89
VGRF (N)	ICC = 0.95				
Peak power (W)	ICC = 0.94				
Maulder and Cronin (2005)	18 male subjects recreationally active in a number of sports (age, $25.1 \pm 4.3$ years).	Vertical countermovement jump	Using the designated jumping leg, the participants were instructed to sink down (to approximately $120^\circ$ knee angle) and jumped as high possible. Between two and seven days between assessments.	Height (cm)	CV = 3.3% ICC = 0.86
		Horizontal countermovement jump	Using the designated jumping leg, the participants were instructed to sink down as quickly as possible (to approximately $120^\circ$ knee angle) and jump as far as possible landing on two legs. Between two and seven days between assessments.	Distance (cm)	CV = 1.1% ICC = 0.90
Hooper et al. (2002)	13 males and six females (age, $26.8 \pm 8.4$ years) who had undergone unilateral ACL reconstruction and presented at an average of 12 months post reconstruction.	Vertical countermovement jump	Using the designated jumping leg, the participants were instructed to perform a deep squat and jump maximally landing on one foot keeping elbows clasped behind their neck. Repeat assessments were performed seven days after the initial test.	Height (cm)	Reconstructed leg: ICC = 0.94. Uninjured leg: ICC = 0.92
Bolga and Keskula (1997)	Five males and 15 females (age, $24.5 \pm 4.2$ years). No information on activity levels.	Horizontal countermovement jump	Using the designated jumping leg, the participants were instructed to hop as far as possible keeping their hands on hips. 48 hours of inactivity between testing sessions.	Distance (cm)	ICC = 0.96
(Brosky Jr et al., 1999)	15 healthy recreational male athletes following ACL reconstruction.	Horizontal countermovement jump	Using the designated jumping leg, the participants were instructed to hop as far as possible allowing the use of arms. A successful jump was performed when the landing was maintained for a minimum of two seconds.	Distance (cm)	ICC = $\sim 0.92$ (read of graph)
		Vertical countermovement jump	The subjects jumped as high as possible from a single-leg position and reached with the contralateral upper-extremity displacing plastic vanes.	Height (cm)	ICC = $\sim 0.87$ (read of graph)

Key: IICC = intraclass correlation coefficient. CV = coefficient of variation. VGRF = vertical ground reaction force. HGRF = horizontal ground reaction force. MGRF = medio-lateral ground reaction force.

been reported between kinetic and temporal variables measured during vertical, horizontal-forward and medial unilateral jumps in non-elite team sport and elite netball players (Hewitt, Cronin and Hume, 2012, Meylan et al., 2010). It is thought that the

ability to produce muscular power is specific to the direction of movement and therefore horizontal-forward, medial and vertical power capabilities are independent qualities that should be assessed and developed independently (Hewit, Cronin and Hume, 2012, Meylan et al., 2010). However, this has not yet been documented in ESP and, therefore, it is unknown whether directional-specific power profiling is necessary when assessing maximal power capability in this population.

In summary, a maximal power assessment series representative of the complex multi-directional demands of elite soccer has not yet been identified. The frequently used bilateral vertical countermovement jump appears to lack the specificity to represent a functional measure of soccer-associated maximal power. Future research should aim to identify a specific lower body power profile, which could be applied in elite soccer to improve both talent identification, player profiling and subsequent maximal power development protocols.

## **2.4 THE PHYSIOLOGICAL DETERMINANTS OF MUSCULAR POWER**

Applied practitioners can analyse the objective kinetic and kinematic performance variables achieved during a sport-specific maximal power performance assessment to compare the individual maximal power capabilities within a group of athletes. The objective measurement variables from such assessments can also be used to prescribe and monitor the effectiveness of training interventions thought to improve these specific performance capabilities. However, objective kinetic and kinematic performance variables do not reveal any information regarding the interrelated physiological factors, which underpin such specific power capabilities, such as muscle fibre type composition (Bottinelli et al., 1996, Gilliver et al., 2009), muscle volume (Pearson et al., 2006), muscle architecture (Thom et al., 2007), muscle activation (De Ruyter et al., 2004, De Ruyter et al., 2006) and tendon properties (Bojsen-Møller et al.,

2005, Kubo et al., 2007). These physiological factors are of interest to the applied practitioner as this information can be used to inform the composition of talent identification protocols. Moreover, such information will allow the prescription of more detailed maximal power training interventions, which could be developed to target the enhancement of specific physiological factors to ultimately improve performance (Cormie, McGuigan and Newton, 2010a, Tillin and Folland, 2014, Tillin, Pain and Folland, 2012). However, the physiological determinants of soccer-associated power are unknown and future studies should use non-invasive methods to investigate the contribution of factors, such as muscle volume, muscle architecture, muscle activation, and tendon properties to soccer-associated power in ESP.

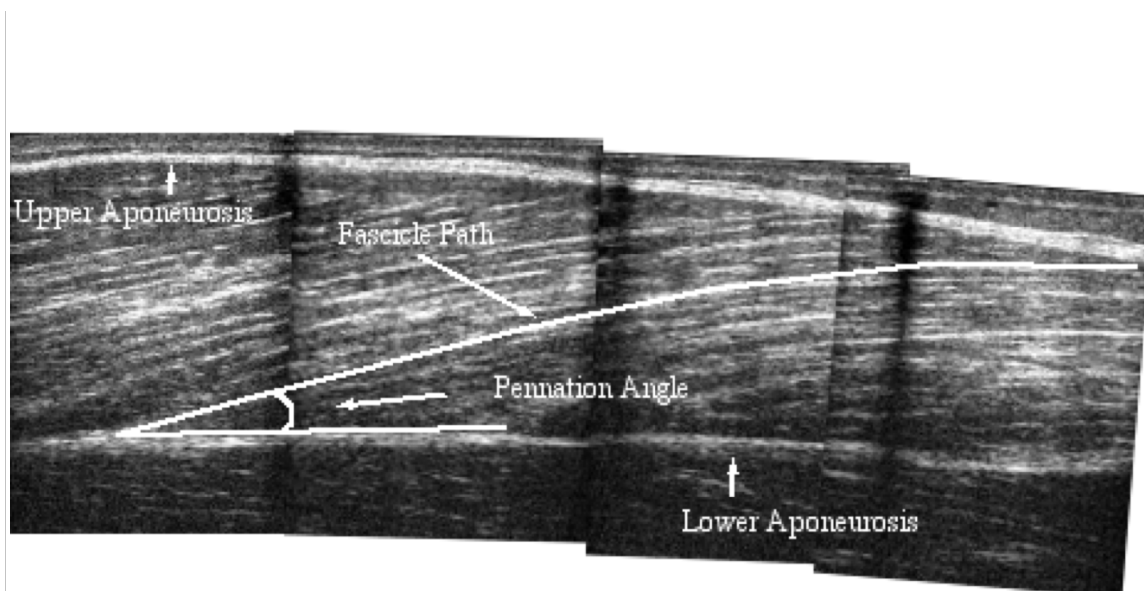
#### **2.4.1 Muscle architecture**

The architecture of the muscle becomes increasingly important as the speed of the movement changes (Bamman et al., 2000, Blazevich, 2006). Understanding the relationship between muscle structure and sport-specific muscular power can increase the efficacy of talent identification and provide practitioners with the ability to prescribe specific strength and conditioning intervention programmes that focus on specific structural adaptations rather than simply mimicking movement patterns and velocities. Figure 2.1 illustrates the resting muscle architecture of the vastus lateralis muscle in an ESP measured in our laboratory.

##### *1.4.1.1 Muscle fascicle length*

Assuming a constant magnitude of neural activation, the maximal contractile velocity of a muscle fibre is proportional to its length (MacIntosh and Holash, 2000, Sacks and Roy, 1982, Spector et al., 1980, Wickiewicz et al., 1983), which is determined by the number of sarcomeres arranged in series. Due to a longer muscle fibre being able to contract faster than a shorter fibre (i.e. greater number of sarcomeres

shortened per second) (Wickiewicz et al., 1983), and maximum shortening velocity being one component of maximal power (Edgerton et al., 1986, Jones, Rutherford and Parker, 1989), a longer muscle fibre will generate a higher maximal power output, all other things being equal (MacIntosh and Holash, 2000, Wickiewicz et al., 1983). In support of this, relative (to maximum isometric contraction) isokinetic knee extension torque at velocities greater than  $180^\circ/\text{s}$  were significantly related to muscle fascicle length ( $L_f$ ) (Kumagai, Abe and Ryushi, 2000). Moreover, longer muscle  $L_f$  have been associated with an elite sprinter population (Abe et al., 2001, Abe, Kumagai and Brechue, 2000) and were also shown to be directly related to 100 m sprint performance (Abe et al., 2001, Kumagai et al., 2000). Whilst sprint capability is considered an important determinant of elite soccer performance (Di Salvo et al., 2010), Kearns and colleagues (2001) reported no difference in gastrocnemius medialis  $L_f$  between junior soccer players and control participants (college students). However, these junior soccer players were not classed as elite and, therefore, the importance of  $L_f$  for elite soccer performance, and its role in determining soccer



**Figure 2.1.** Ultrasound image from our laboratory illustrating resting architecture of the vastus lateralis muscle of an elite youth professional soccer player. This scan was taken from one of the participants recruited for the studies described in the current thesis.

specific power, has not yet been fully investigated.

In summary, longer muscle fibres can contract faster (Wickiewicz et al., 1983), and have previously been related to 100 m sprint performance (Abe, Kumagai and Brechue, 2000, Kumagai et al., 2000). However, it is unknown if  $L_f$  is a physiological determinant of elite soccer performance. As resistance (Alegre et al., 2006, Blazevich et al., 2003, Seynnes, de Boer and Narici, 2007), and sprint/jump training (Blazevich et al., 2003) have previously been shown to increase  $L_f$ , such information could inform the specificity of soccer talent identification and development protocols.

#### *2.4.1.2 Muscle fascicle pennation angle*

The force produced by a maximally activated muscle (fibre) is determined by the number of sarcomeres arranged in parallel, i.e. the cross-sectional area (CSA) of the muscle (fibre) (Jones, Rutherford and Parker, 1989). As muscular power is the product of force and contraction velocity, muscle CSA is an important determinant of power. The muscle fibre pennation angle ( $\theta_p$ ), defined as the angle between the muscle fibres and their insertion into the aponeurosis (Huijing, 1985, Powell et al., 1984, Spector et al., 1980), may also play a role in muscular power output. An increase in  $\theta_p$  is thought to occur in response to an increase in muscle fibre CSA, due to limited attachment space on the aponeurosis (Aagaard et al., 2001, Degens, Erskine and Morse, 2009). Therefore, a larger fibre  $\theta_p$  allows more contractile material to attach to the aponeurosis, thus increasing the whole muscle physiological CSA (PCSA) and allowing the muscle to produce more force (Aagaard et al., 2001). There is, however, a trade-off between force increase as a consequence of increase in fibre CSA, and force loss as a result of fibre force generation at an angle to the direction of pull of the tendon (Alexander and Vernon, 1975, Degens, Erskine and Morse, 2009). This net increase in force, however, remains positive up to a  $\theta_p$  of 40°

(Alexander and Vernon, 1975, Degens, Erskine and Morse, 2009). With all other factors remaining constant, a greater  $\theta_p$  also results in a decrease in the shortening velocity of the whole muscle, as the amount of whole muscle shortening is the product of muscle fascicle shortening and the cosine of pennation angle (Narici, 1999). Increasing  $\theta_p$  may therefore lead to a reduced maximal muscle shortening velocity, reduced force resolved at the tendon, and therefore, a lower power output per muscle volume (Degens, Erskine and Morse, 2009, Spector et al., 1980). However, due to the trade-off between the associated increase in  $\theta_p$ , and concomitant increase fibre CSA and muscle PCSA, whole muscle power output may remain the same (Degens, Erskine and Morse, 2009). Indeed, VL fascicle  $\theta_p$  was not associated with any vertical jump power output measurement, and lateral gastrocnemius (LG)  $\theta_p$  was a weak, but significant, predictor of jump height for bilateral vertical squat ( $r^2 = 0.212$ ,  $p = 0.021$ ), countermovement ( $r^2 = 0.186$ ,  $p = 0.018$ ), and drop ( $r^2 = 0.263$ ,  $p = 0.005$ ) jump height (Earp et al., 2010). Moreover, Dobbs and colleagues (2015) reported no significant correlations between VL and LG fascicle  $\theta_p$ , and force variables during bilateral and unilateral, vertical and horizontal, squat, countermovement and drop jumps in elite rugby players. However, VL and LG fascicle  $\theta_p$  showed inverse correlations with bilateral squat jump peak velocity ( $r^2 = 0.292$ ) and time to peak velocity ( $r^2 = 0.279$ ), respectively. Vastus lateralis  $\theta_p$  also showed moderate inverse correlations with unilateral vertical countermovement jump mean velocity ( $r^2 = 0.296$ ), and peak force divided by jump duration (i.e. impulse) ( $r^2 = 0.360$ ) (Dobbs et al., 2015). In agreement with these findings, increments in  $\theta_p$  after a period of resistance training were associated with reductions in elbow flexor RFD in the first 150ms of an isometric contraction (Erskine, Fletcher and Folland, 2014). It therefore appears that greater fascicle  $\theta_p$  may not affect whole muscle power output capacity, but could negatively impact upon

contraction velocity and rate of force development capabilities. Nevertheless, the research investigating the effect of  $\theta_p$  on power output during sports specific ballistic actions is scarce and additional research in other team sport athletes such as ESP, that also analyses horizontal power performance measures, is required to confirm these findings.

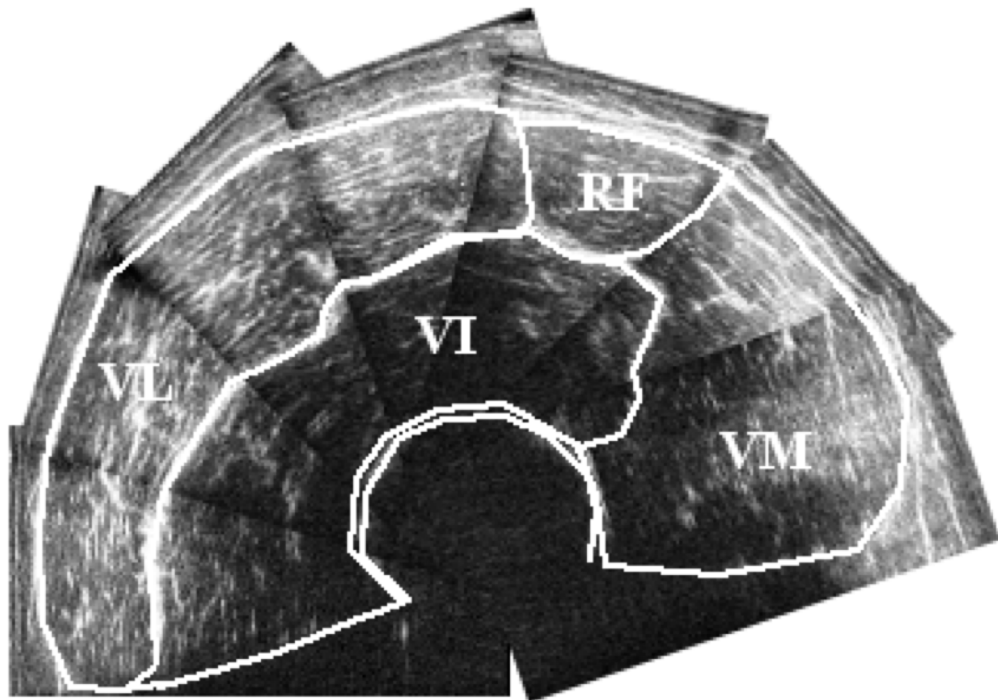
In summary, although previous research has also shown that highly trained sprinters had smaller VL fascicle  $\theta_p$  than both lesser sprinters (Kumagai et al., 2000), untrained controls (Abe et al., 2001) and distance runners (Abe et al., 2001), no research has documented the role of  $\theta_p$  in determining soccer playing status. Such information could help inform the detail of soccer specific physiological talent identification criteria and resistance training programme guidelines.

## **2.4.2 Muscle size**

### *2.4.2.1 Physiological cross sectional area*

Whole muscle anatomical CSA (ACSA) has been shown to be proportional to maximal voluntary isometric force (Ikai and Fukunaga, 1968, Maughan, Watson and Weir, 1983, Maughan, Watson and Weir, 1984) and strong correlations have been observed between knee extension maximal force and quadriceps ACSA (Jones, Rutherford and Parker, 1989, Rutherford and Jones, 1986). In parallel-fibred muscles, the ACSA may provide an accurate estimation of the muscle PCSA (Davies et al., 1988, Kawakami et al., 1994). However, in pennate-fibred muscles, such as the quadriceps femoris (Figure 2.2 depicts an ACSA ultrasound image of the quadriceps femoris muscle from our lab), where the muscle fibres are arranged at an angle to the line of pull of the tendon, the ACSA has been shown to underestimate the PCSA (Alexander and Vernon, 1975, Wickiewicz et al., 1983). The PCSA represents the total area of all fibres within that muscle at right-angles to their long axes, and therefore the maximum force-generating capacity of that muscle (Close, 1972, Degens, Hoofd and Binkhorst, 1995). Hence,





**Figure 2.2.** Ultrasound image from our laboratory illustrating the QF ACSA at 40% femur length, highlighting four component muscles: vastus lateralis (VL), vastus medialis (VM), vastus intermedius (VI), Rectus Femoris (RF). This scan was taken from one of the participants recruited for the studies described in the current thesis.

normalising maximum force to PCSA will provide a more accurate calculation of muscle specific force (maximum force per unit PCSA) and provide an *in vivo* estimation of the single fibre specific tension (maximum force per fibre CSA). Such information provides an insight into the intrinsic contractile properties of the muscle fibres (Erskine et al., 2009). It is possible to estimate the PCSA in the QF muscles *in vivo* by measuring QF volume and fascicle length using ultrasound (Erskine et al., 2009). Elite soccer performance requires the application of explosive force in multiple directions. However, the role of PCSA and muscle specific force in elite soccer performance is yet to be

elucidated. These non-invasive techniques could therefore be used to investigate the role of muscle PCSA and specific force in elite soccer, and more specifically, the contribution of these physiological factors to soccer-associated power performance.

#### *2.4.2.2 Muscle volume*

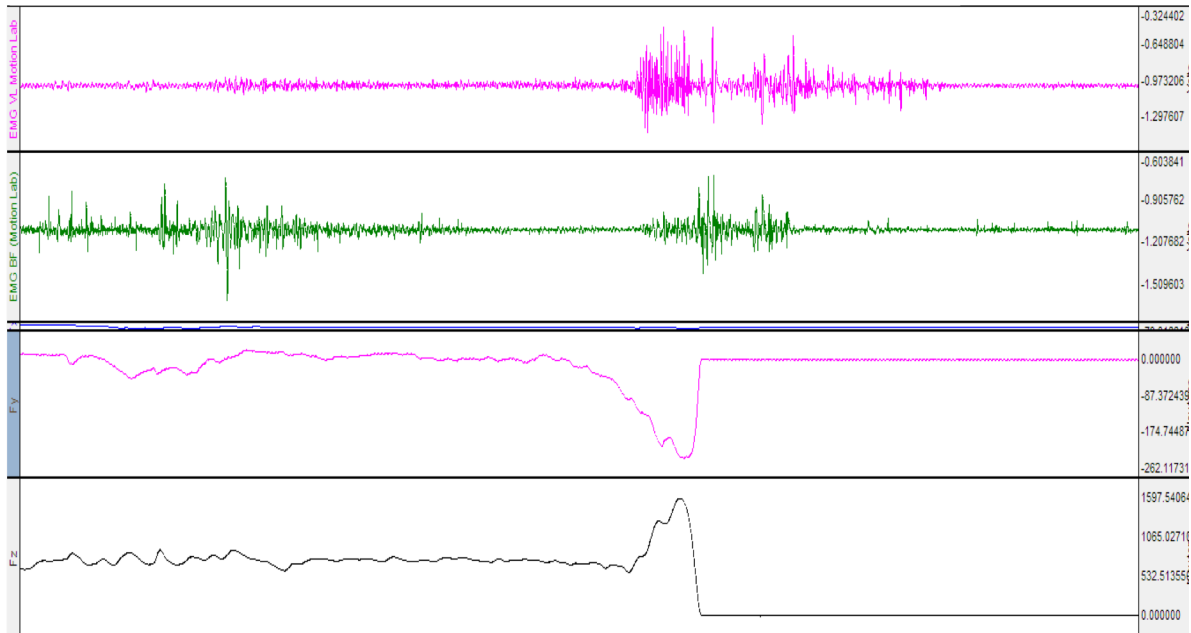
Muscle volume ( $V_m$ ) is the product of fascicle length x muscle PCSA (Erskine et al., 2009), and as power is the product of force (major determinant: muscle PCSA) x velocity (major determinant: fascicle length), it follows that  $V_m$  should be a major determinant in maximum muscle power. Indeed, quadriceps femoris (QF)  $V_m$  has been shown to be strongly related to mean power produced during bilateral vertical countermovement jumps (BV CMJs) in adults and children (O'Brien et al., 2009a), and moderately related in male children alone ( $r^2 = 0.3$ ) (Temfemo et al., 2009). However, the current literature has not investigated the association between  $V_m$  and power output during ballistic tasks which are more specific to the movement patterns associated with multi-directional team sports.

In summary,  $V_m$  is a major determinant in maximum muscle power (Jones, Rutherford and Parker, 1989). However, the importance of  $V_m$  has never been investigated in ESP. Moreover, the contribution of  $V_m$  to more specific assessments of soccer-associated power has never been investigated. Research documenting the importance of  $V_m$  for elite soccer playing status, and its contribution to soccer-associated power performance, could inform the specificity of soccer talent identification protocols and resistance training interventions.

#### **2.4.3 Voluntary muscle activation**

Maximal power is not only underpinned by the size and architectural properties of the muscle, but the ability of the nervous system to optimise activation of the specific

muscles involved in the action. It is believed that greater neural drive will induce a higher rate of cross bridge binding due to a faster increase of the free intra-cellular  $[Ca^{2+}]$  which allows force to develop at a faster rate (De Ruyter et al., 2006). Indeed, differences in neuromuscular activation (significantly greater mean agonist electromyographic (EMG) amplitude and synchrony in activation onset of agonist muscles), and not the similar intrinsic contractile properties of the muscle-tendon unit, were thought to explain the greater voluntary rate of force development during the first 50 ms of an explosive isometric contraction in explosive power athletes compared to untrained individuals (Tillin et al., 2010). Other cross-sectional studies showed similar findings documenting that the ability to produce high EMG peaks at the beginning of an explosive contraction accounted for 75-83% of the variance in the isometric torque development in the first 40ms of an explosive isometric contraction (De Ruyter et al., 2004, De Ruyter et al., 2006, De Ruyter et al., 2007) However, whilst the association between neural activation and single joint isometric explosive contractions has been well documented, there remains a paucity of research investigating contribution of muscle activation to more dynamic sport-specific actions, such as jumping. The surface EMG activity can be recorded from specific muscles simultaneously with ground reaction force during dynamic sports specific movements (Fig. 2.3). One study in the literature reported high correlations ( $r = 0.80-0.86$ ) between the rise in force, and the knee extensor and knee flexor muscle EMG activation during the first 100 ms of bilateral vertical squat jumps thus suggesting that jump ability was determined to a large degree by the ability of the individual to produce high initial efferent neural drive immediately before the onset of the movement (De Ruyter et al., 2006). Nevertheless, this study was conducted in a group of untrained individuals (De Ruyter et al., 2006) and subsequent research



**Figure 2.3.** Electromyography (EMG) signals sampled simultaneous with ground reaction force data at a frequency of 1000 Hz during a unilateral horizontal-forward countermovement jump. From top to bottom: The highest pink trace represents the EMG activity of the vastus lateralis muscle. The green trace below represents the EMG activity of the bicep femoris muscle. The pink trace below represents the horizontal ground reaction force and the black trace at the bottom represents the vertical ground reaction force. These data were taken from one of the participants recruited for the studies described in the current thesis.

including elite volleyball players reported that neural activation during the first 40 ms of an isometric explosive contraction was not associated with bilateral vertical jump performance (De Ruiter et al., 2007). As maximal knee extensor rate of torque development during electrical stimulation was significantly related to bilateral vertical jump height, these authors concluded that the intrinsic contractile speed of the muscle pre-determines jump performance in these athletes (De Ruiter et al., 2007). Other research documented that greater vastus lateralis and vastus medialis neural

drive during the eccentric phase of the bilateral vertical CMJ and drop jump was associated with increased force output during the concentric phase (McBride, McCaulley and Cormie, 2008). However, concentric phase neural activation was similar between squat jumps, vertical CMJs and vertical drop jumps, and therefore did not contribute to greater jump heights achieved during vertical CMJs and drop jumps, in comparison to vertical squat jumps (McBride, McCaulley and Cormie, 2008). While concurrent increases in bilateral vertical jump, speed performance and neural activation have been reported after strength (Cormie, McGuigan and Newton, 2010a) and ballistic power (Cormie, McGuigan and Newton, 2010a, Cormie, McGuigan and Newton, 2010b) training interventions, these studies did not determine the relationships between relative changes in neural and morphological adaptations, and dynamic performance variables. Therefore, the specific contribution of the neural and morphological mechanisms to improvements in performance were not documented (Cormie, McGuigan and Newton, 2010a, Cormie, McGuigan and Newton, 2010b). Subsequently, the contribution of muscle neural activation to ballistic jump performance remains unknown.

In summary, whilst increased neural activation has previously been shown to enhance single joint isometric explosive force production (De Ruyter et al., 2004, De Ruyter et al., 2006, De Ruyter et al., 2007), the contribution of muscle neural activation to sports specific dynamic performance remains unknown. More research is therefore required to establish the relationship between voluntary muscle activation and sport-specific dynamic power performance capabilities. Future research that aims to investigate the importance of muscle activation for elite soccer playing status, and its contribution to soccer associated power performance, could inform the detail of talent identification protocols and soccer specific muscular power training interventions.

#### **2.4.4 Tendon properties**

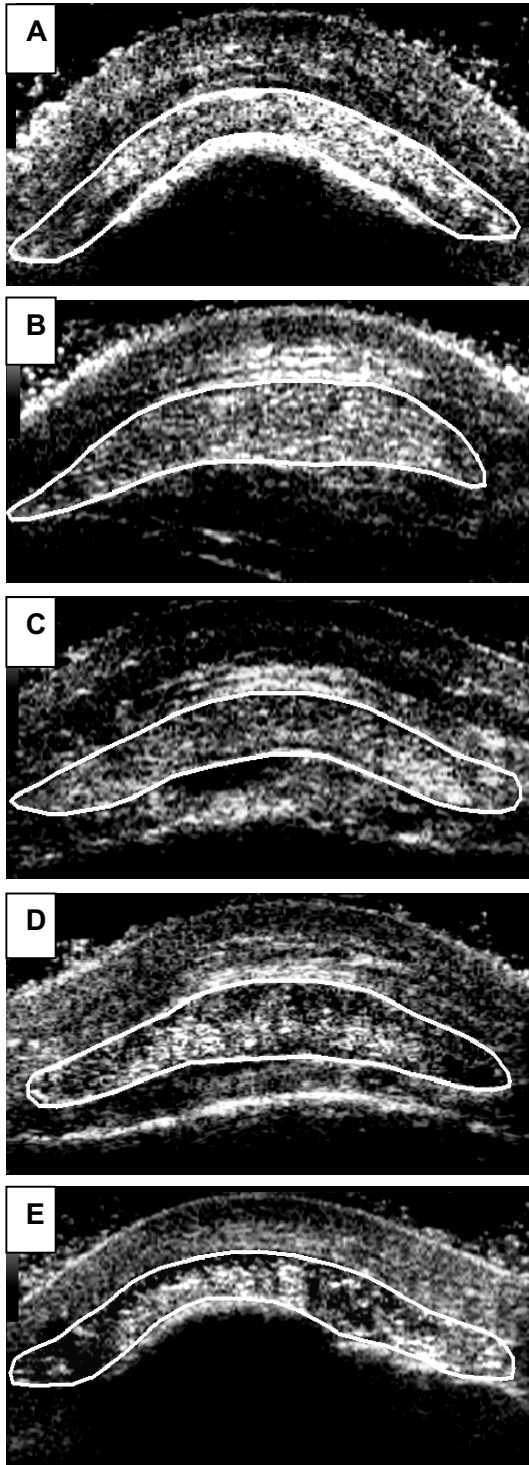
When muscles are activated, contractile force is transmitted to the skeleton through viscoelastic tendons. Indeed, fascicle behaviour is affected by the synergy between the contractile and elastic elements of the muscle-tendon unit (Kawakami et al., 2002, Kubo et al., 2000c, Kurokawa et al., 2003). Tendons are primarily composed of collagen fibres, which exhibit elastic properties and have the potential to store energy when stretched (Alexander and Bennet-Clark, 1977, Proske and Morgan, 1987). The interaction between muscle and tendon during movement is complex, but is thought to be co-ordinated to maximise movement performance, minimise energy expenditure and reduce injury risk (Finni, 2006, Fukunaga et al., 2002, Magnusson et al., 2008).

The most common type of muscle contraction in multidirectional sports specific movement involves the successive combination of eccentric and concentric actions, which is termed the stretch shortening cycle (SSC) (Cavanagh and Komi, 1979). The force and power generated when a muscle is activated, the muscle tendon unit is stretched, and then immediately shortened, is greater than during a concentric only contraction (Cavagna, Saibene and Margaria, 1965, Edman, Elzinga and Noble, 1978). Subsequently, maximal muscular power is greater during movements that involve a SSC (Anderson and Pandy, 1993, Gollhofer and Kyrolainen, 1991, Takarada et al., 1997). Although the mechanisms responsible for greater power output during actions that involve a SSC are an issue of debate in the literature, it has been proposed that the complex muscle-tendon interaction allows for substantial storage and utilisation of elastic energy during recoil of the series elastic component (Abellaneda, Guissard and Duchateau, 2009, Baratta and Solomonow, 1991). It has also been suggested that the muscle works at a more optimal length and velocity (Baratta and Solomonow, 1991), and that there is an increased time

availability for muscle activation and subsequent force generation (Bobbert, Ettema and Huijing, 1990, van Ingen Schenau, Bobbert and de Haan, 2010).

As tendon exhibits viscoelastic properties, its mechanical properties (e.g. stiffness, strain) are strongly influenced by both the magnitude and rate of force acting on it (Baratta and Solomonow, 1991, Ettema and Huijing, 1994, Kubo, Kanehisa and Fukunaga, 2005, Kubo et al., 2007, Netti et al., 1996). Real-time ultrasonography has also allowed the *in vivo* observation of the complex behaviour of the tendon during different SSC movements, including running (Ishikawa, Pakaslahti and Komi, 2007), jumping and drop jumping (Finni et al., 2001, Finni et al., 2003, Ishikawa et al., 2006, Ishikawa, Pakaslahti and Komi, 2007, Reeves and Narici, 2003, Sousa et al., 2007). This research has found that, during the initial preload eccentric SSC phase of explosive jump or running exercises, the muscles lengthen less, and tendon elongates more, as the intensity of the action increases. Moreover, during high intensity movements where the range of joint motion is small (i.e. drop jumps, sprint actions), the muscle lengthens only marginally, if at all during the eccentric phase (Finni et al., 2001, Finni et al., 2003) and is thought to function quasi-isometrically. Hence, the quasi-isometric action of the muscle allows for greater tendon lengthening (Reeves and Narici, 2003), and the tendon therefore stores more potential energy and recoils at greater speed, thus acting as a power amplifier (Ettema, 1996, Nagano, Komura and Fukashiro, 2004).

Real time ultrasonography has also been used to investigate and compare the cross sectional area (Fig. 2.4 depicts an ultrasound scan showing the cross sectional area of the patellar tendon) and mechanical properties (Fig. 2.5 depicts an ultrasound scan of the patellar tendon during a ramped isometric contraction used to measure tendon elongation/stiffness) of the tendon during

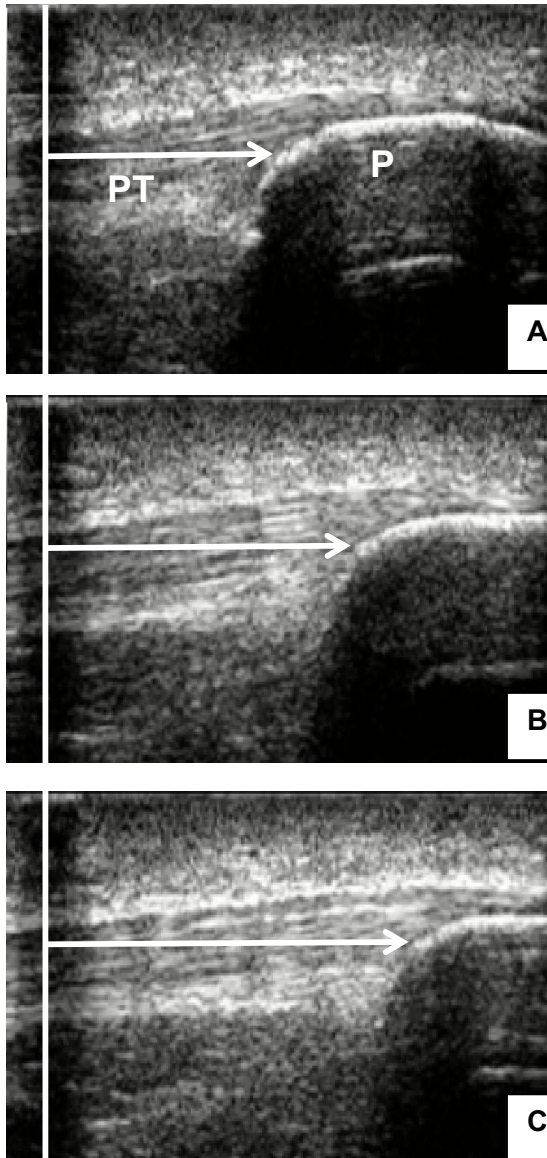


**Figure 2.4.** Example of a typical transverse plane ultrasound scan of the patellar tendon CSA outlined at 0% (A) 25% (B) 50% (C) 75% (D) and 100% (E) of the tendon length from proximal to distal end. This scan was taken from one of the participants recruited for the studies described in the current thesis.

isometric contractions (Bojsen-Møller et al., 2005, Kubo et al., 2011). Such research has reported that the aponeurosis-tendon complex in the knee extensors of sprinters was more compliant than untrained controls (Kubo et al., 2000b). Moreover, although there was no difference in the properties of the gastrocnemius medialis tendon and aponeurosis, the maximal and relative aponeurosis-tendon elongation in the vastus lateralis (VL) of faster sprinters (best record of a 100 m race;  $11.04 \pm 0.17$  s) was greater than that in inferior sprinters (best record of a 100 m race;  $11.64 \pm 0.23$  s) (Stafilidis and Arampatzis, 2007). In two separate cohorts of male sprinters, maximal VL aponeurosis-tendon elongation ( $r = -0.567$ ,  $P = 0.003$ ) (Stafilidis and Arampatzis, 2007), and VL aponeurosis-tendon compliance ( $r = -0.757$ ,  $P < 0.05$ ) (Kubo et al., 2000b), were negatively correlated with 100 m sprint completion time and therefore, associated with greater sprint performance. However, the sprinters included in these studies (Kubo et al.,



2000b, Stafilidis and Arampatzis, 2007) had best official race times of around 11.0 s and therefore could not be classed as elite. Subsequent research investigating elite sprinters with average personal best times of ( $10.79 \pm 0.17$  s) showed that, although there was no difference in tendon thickness between elite sprinters and untrained controls, elite sprinters had greater vastus lateralis aponeurosis-tendon maximal elongation and elongation at force production magnitudes over 400 N. This study also showed that sprinters possessed lower vastus lateralis aponeurosis-tendon stiffness but there was no difference in plantar flexor tendon elongation or stiffness between elite sprinters and untrained subjects (Kubo et al., 2011). In contrast to findings from Stafilidis and Arampatzis (2007), no tendon properties correlated with best official 100 m time in this cohort of elite sprinters (Kubo et al., 2011). Subsequently, it seems that more compliant aponeurosis-tendon structures in the knee extensors are advantageous for sprinters, and may determine 100 m sprint performance between moderate (Stafilidis and Arampatzis, 2007), but not high level (Kubo et al., 2011) performers. It is thought that the more compliant knee extensor tendons of elite sprinters play a role in lowering the velocity of the muscle fibres to near isometric conditions in the early phase of the concentric phase of the SSC, thus allowing for higher force magnitudes to be produced upon ground contact in the stance phase of sprinting (Kubo et al., 2011).



**Figure 2.5.** Example of typical sagittal plane ultrasound images used to measure tendon elongation/stiffness during a ramped maximum voluntary contraction (RMVC) showing the distance from the echo-absorbent marker (drawn over with white line), patella (P) and patellar tendon (PT), at rest (A), at 50% RMVC (B) and at 100% RMVC (C). The white arrow shows the measurement taken in each position. This scan was taken from one of the participants recruited for the studies described in the current thesis.

In agreement with findings in sprint athletes, the stiffness of the aponeurosis-tendon structures in the knee extensors were shown to be inversely correlated with differences in bilateral vertical jump height, when jumps were performed with and without countermovement (Kubo et al., 2000a, Kubo, Kawakami and Fukunaga, 1999). Similar results were displayed for the medial gastrocnemius tendon structure during isokinetic SSC actions, suggesting that the pre-stretch effect was more pronounced in participants with more compliant tendon structures (Kubo, Kanehisa and Fukunaga, 2005). However, the jump tests employed in these studies (Kubo, Kanehisa and Fukunaga, 2005, Kubo et al., 2000a, Kubo, Kawakami and Fukunaga, 1999) consisted of multi-joint movements and it was therefore difficult to specify the main muscles performing the task. Subsequently, further research from Kubo and colleagues (2007) demonstrated that Achilles tendon stiffness was inversely correlated with

relative differences in unilateral jump height between squat and countermovement jumps ( $r = -0.471$ ), and squat and drop jumps ( $r = -0.572$ ), using sledge apparatus, which allowed the isolation of the ankle joint, thus minimising any contribution of the hip and knee joints (Kubo et al., 2007). These results suggest that compliant tendon structures are more efficient in utilizing elastic strain during SSC exercises. However, previous literature disagrees with these findings by demonstrating the vastus lateralis tendon-aponeurosis stiffness correlated with knee extensor rate of torque development (RTD), accounting for 30% of variance in RTD. Moreover, a correlation was also observed between vastus lateralis stiffness, and vertical bilateral squat ( $r = 0.64$ ,  $P < 0.05$ ) and countermovement ( $r = 0.55$ ,  $P < 0.05$ ) jump height, suggesting that a stiffer tendon contributes to enhanced muscle output during high force isometric and dynamic vertical jumping tasks (Bojsen-Møller et al., 2005). Discrepancies between previous results and these findings may be due to different methods for measuring vertical jump height performance, and variation in training status of the subjects (Bojsen-Møller et al., 2005). Nevertheless, the role of tendon-aponeurosis stiffness in the performance of dynamic sport-specific activity remains to be elucidated.

In summary, while the properties of the knee extensor tendon-aponeurosis structures have previously been associated with sprinter athlete status (Kubo et al., 2011, Stafilidis and Arampatzis, 2007) and 100 m sprint performance (Stafilidis and Arampatzis, 2007), their association with elite soccer playing status, and contribution to ballistic jump performance, still remains unknown (Bojsen-Møller et al., 2005, Kubo, Kawakami and Fukunaga, 1999). Future research should therefore investigate if the morphological and mechanical tendon properties of the knee extensors influence elite soccer playing status and ballistic power performance, in assessments such as unilateral CMJs in different directions, that may be more specific to the movement demands associated with soccer performance (Meylan et al., 2010). The

results of such investigations could inform elite soccer physiological testing criteria which could be included in novel elite soccer talent identification protocols.

## **2.5 THE EFFECT OF MATURATION ON MUSCULAR POWER**

Maturation is a major a confounding factor when identifying future soccer talent during adolescence (Vandendriessche et al., 2012). Significant morphological and neurological changes occur during growth and maturation (Malina, Bouchard and Bar-Or, 2004), leading to accelerated improvement of certain physical capabilities (e.g. speed and power) at specific stages of chronological and biological development (Balyi and Hamilton, 2004). Indeed, maximal power has been reported to increase by as much as 375% between the ages of 7 and 17 years in young males (Martin et al., 2004). An adolescent performance increment in strength and power development has been reported to occur around 1.5 years prior to PHV, and to peak approximately 0.5-1.0 years after PHV (Fig. 2.6) (Beunen, 1988, Philippaerts et al., 2006). As power is the product of force x velocity, maximal power output may improve following an increased ability to develop force at a given velocity, and/or velocity at a given force (Cormie, McGuigan and Newton, 2011). Quantitative (e.g. lean muscle mass, muscle volume, muscle fascicle length) and qualitative (e.g. muscle fibre type, motor unit recruitment, inter-muscular co-ordination, and tendon material properties) changes in the neuromuscular-tendon system during growth and maturation may explain the increment in muscular power output. Subsequently, the physiological factors underpinning muscular power may be specific to maturation status (Martin et al., 2003, Martin et al., 2004, Meylan et al., 2014).

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**Figure 2.6.** Mean constant growth velocity for (B) bilateral horizontal countermovement jump (SLJ) and bilateral vertical countermovement jump (VTJ,  $\text{cm}\cdot\text{yr}^{-1}$ ); (C) shuttle sprint (SSPRINT), shuttle run (SHR) and 30 m dash (DASH,  $\text{s}\cdot\text{yr}^{-1}$ ). Adapted from Philippaerts and colleagues (2006).

In pre-PHV children, the natural increase in muscular power associated with chronological age has been related to an increase in optimal contraction velocity (Martin et al., 2003, Meylan et al., 2014). Although Hautier and colleagues (1996) reported a strong correlation between optimal velocity *in vivo* and muscle fibre type in the knee extensors, the lack of circulating androgen in pre-PHV children suggests that the natural development of contraction velocity capabilities is not caused by factors related to the selective hypertrophy of type II fibres (Croix, 2007, Glenmark et al., 1994, Krotkiewski, Kral and Karlsson, 1980). This natural development of optimal velocity and peak power may therefore be caused by neurological rather than muscular factors (Malina et al., 2006; Mextaxas et al., 2014; Viru et al., 1999). Indeed, the neuromuscular system undergoes a rapid natural acceleration (Borms, 1986) during the pre-PHV years with peak rates of brain maturation being reported to occur between 6 and 8, and 10 and 12 years (Rabinowickz, 1986). Subsequently, it appears that the age-related development in muscular power in pre-PHV children may be underpinned by neural factors, specifically characterised by gains in inter-muscular coordination and intra-muscular synchronisation (Lloyd and Oliver, 2012, Viru et al., 1999).

In contrast to the pre-PHV period, adolescent growth during the mid-PHV period is characterised by a surge in growth hormone and testosterone (Malina, Bouchard and Bar-Or, 2004, Viru et al., 1999). Testosterone interacts with the intracellular androgen receptor to stimulate protein synthesis [anabolic effect (Mauras et al., 1998)] and inhibit protein degradation [anti-catabolic effect (Demling and Orgill, 2000)], thus resulting in a net anabolic effect. Increases in serum concentrations of testosterone during puberty are therefore important for the development of whole body muscle mass (Mauras et al., 1994) and strength (Round et al., 1999). Growth hormone has a synergistic effect on testosterone's promotion of muscle protein synthesis (Mauras et al., 2003) and plays an essential role in promoting growth and

stature during maturation (Rogol, Blimkie and Bar-Or, 1996, Viru et al., 1998). In accordance with research that suggested the surge in testosterone and growth hormones occurs approximately one year before PHV (Croix, 2007), the percentage of muscle mass, calculated via creatine excretion, was shown to increase by 0.6% and 29% per year from the age of 7 to 13.5, and 13.5 to 15 yrs, respectively (Malina, 1969). Hence, the large increase in muscular power during the mid-PHV period (Meylan et al., 2014) could be largely attributed to the increase in muscle cross-sectional area during growth and its direct relationship with peak force (Jones and Round, 2008, Martin et al., 2003). In support of this theory, Meylan and colleagues (2014) evaluated ballistic concentric squat performance on a supine squat machine at different relative loads and reported that, whilst the difference in maximal velocity capabilities between pre- and mid-PHV athletes was unclear, the difference in 1 repetition maximum (1RM) strength and peak force variables were large. These findings suggested that the large increment in peak power during the mid-PHV period is primarily due to an increase in lean muscle mass. However, during the mid-PHV period, as the athlete approaches his fastest rate of growth (PHV), the differential timing of growth in both leg and trunk length has a negative effect on motor co-ordination skills (Beunen, 1988, Philippaerts et al., 2006). Hence, the absence of a difference between pre- and mid-PHV athletes in maximal velocity capabilities (Meylan et al., 2014) may be due to reduced intra-muscular synchronisation and inter-muscular co-ordination abilities during fast ballistic movements (Cormie, McGuigan and Newton, 2011). Moreover, when peak power was allometrically scaled to body mass, the difference between pre- and mid-PHV athletes was only a small practical magnitude (Meylan et al., 2014) thus providing further evidence for an increase in lean muscle mass and muscle cross sectional area as the primary factor underpinning muscular power increments during the mid-PHV period.

Muscular power increases from mid-PHV to post-PHV (Martin et al., 2003, Meylan et al., 2014), reaching a peak commensurate with the peak rate of increase in body weight (PWV) and lean muscle mass (0.5-1.0 yrs after PHV) (Malina, Bouchard and Bar-Or, 2004). This may suggest that the increase in lean muscle mass is the primary physiological factor underpinning the increment in peak power during the post-PHV period. However, the difference between mid-PHV and post-PHV athletes during ballistic concentric supine squat assessments was large for velocity dependent variables (maximal velocity), but only of moderate magnitude for force dependent variables (1 RM and peak force). When normalised to body mass, the difference between mid-PHV and post-PHV athletes remained large for velocity dependent variables, but was small to non-existent in force dependent variables (Meylan et al., 2014). Subsequently, it appears that whilst the increase in lean muscle mass contributes to the development of power output during the post-PHV years, it may not be the primary underpinning physiological factor. Rather, an increased ability to produce high velocity contractions and optimally transfer force into powerful actions seems to be the primary reason for post-PHV athletes achieving higher peak power outputs than mid-PHV athletes (Meylan et al., 2014). The increase in power from mid-PHV to post-PHV may therefore be underpinned by both quantitative (muscle volume, fascicle length) and qualitative (neurological, muscle fibre type and tendon modulus changes) physiological adaptations (Martin et al., 2003, O'Brien et al., 2010b).

Children have previously been shown to have shorter fascicle lengths than adults in the vastus lateralis, vastus medialis and vastus intermedius muscles (O'Brien et al., 2010a). It therefore appears that, as the athlete continues to grow during adolescence, muscle fibres increase in length as sarcomeres appear to be added onto the end of the myofibrils (Van Praagh and Dore, 2002). The increase in fibre length during maturation may therefore contribute to the ability of post-PHV



athletes to produce greater velocity during ballistic contractions (Lodder, De Haan and Sargeant, 1991). In addition to the length of the fascicle/fibre, myosin ATPase activity is important in determining the maximal shortening velocity of a muscle (Bárány, 1967, Schluter and Fitts, 1994). Indeed, in comparison to isolated human type I fibres, isolated type II fibres are larger, contract faster and produce greater absolute magnitudes of force and power output (Bottinelli et al., 1996, Gilliver et al., 2009). It has been proposed that the increase in testosterone associated with maturation may induce a selective hypertrophy of type II fibres (Glenmark et al., 1994, Krotkiewski, Kral and Karlsson, 1980), thus increasing contraction velocity and peak muscular power (Pearson et al., 2006). Adults are thought to have a greater ability to activate high threshold fast twitch type II motor units during ballistic contractions than children (Dotan et al., 2012) and therefore increases in motor unit recruitment during maturation may also underpin the increment in power performance during the post-PHV period. In support of this, it has been shown that pre-PHV boys may not be able to maximally activate their muscles, as their voluntary neural drive is lower than post-PHV males (Paasuke, Ereline and Gapeyeva, 2000). In agreement with this study and others (O'Brien et al., 2009a, O'Brien et al., 2010a), a substantial difference occurred in the degree of voluntary activation of motor units in the knee extensors: 77% at the age of 10 versus 95.3% at the age of sixteen (Blimkie, 1989). This provides evidence to suggest that the myelination of many nerves is incomplete until after sexual maturity. Improvements in motor unit recruitment, inter-muscular coordination and intramuscular synchronization after the mid-PHV period may allow athletes to co-ordinate ballistic actions at greater velocities, thus increasing the rate of force development and impulse (peak force divided by time) during sport-specific actions (Philippaerts et al., 2006, Viru et al., 1999). Increased tendon stiffness has also been associated with greater rate of force development (Bojsen-Møller et al., 2005) and a reduced electromechanical delay

(EMD; the time delay between the onset of electrical activity at the muscle and the onset of force (Winter and Brookes, 1991b)) during isometric contractions. The material properties of the tendon, irrespective of its dimensions (i.e. Young's modulus, which is defined as the relationship between tendon stress and strain), have been reported to change during maturation, with adult males ( $28.2 \pm 3.2$  yrs) presenting with 94% stiffer patellar tendons than young males ( $8.9 \pm 0.7$  yrs) (O'Brien et al., 2010b). Subsequently, the more efficient transfer of force through the muscle-tendon complex may contribute to the increased velocity capabilities in post-PHV compared to mid-PHV athletes (Meylan et al., 2014). However, lower tendon stiffness has also been associated with greater elastic energy storage for a given force applied during stretch-shortening cycles (Kubo, Kawakami and Fukunaga, 1999, Morgan, Proske and Warren, 1978), and the optimal tendon properties for the enhancement of sport-specific ballistic actions remains to be elucidated.

In summary, the increase in peak muscular power during the pre-PHV period is related to increased velocity capabilities due to chronological age-related enhancements in neurological efficiency. In contrast, inter-muscular co-ordination and intra-muscular synchronisation are reduced during the mid-PHV phase and velocity capabilities therefore do not appear to improve. Rather, the maturity-related increment in peak power during the mid-PHV period is related to increased androgen production and the subsequent increments in lean muscle mass enhance the ability to produce force. During the post-PHV period further increases in lean muscle mass, neurological improvements in motor unit recruitment, inter-muscular co-ordination and intra-muscular synchronisation, selective hypertrophy of type II muscle fibres, and increased tendon stiffness are all thought to underpin the increase in peak muscular power which is driven primarily through gains in maximal velocity capabilities (Meylan et al., 2014). Hence, the combination of physiological factors underpinning muscular power appear to be different at pre-, mid- and post-PHV. This

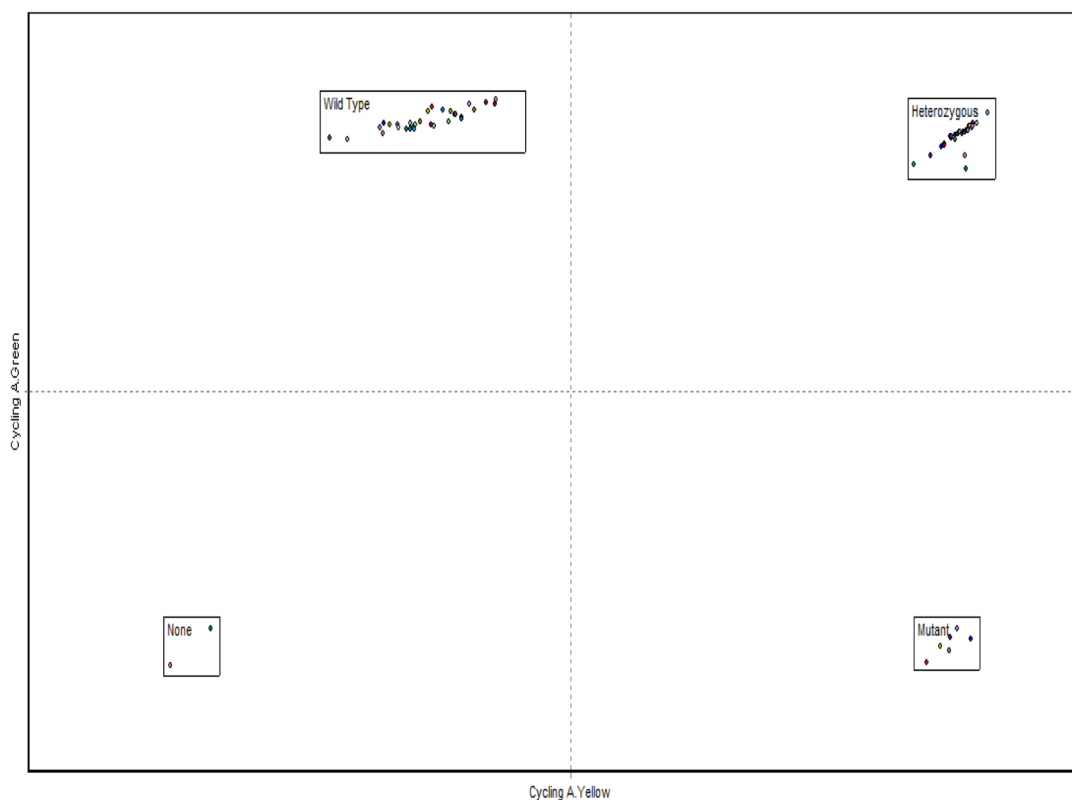
suggests that the detail of physiological assessment and talent identification protocols should be specific to maturation status. However, this has not been investigated ESP and such information could inform the detail of maturation specific assessment criteria thus improving the efficacy of muscular power soccer talent identification procedures.

## **2.6 THE IMPORTANCE OF GENETIC VARIATION IN ELITE SOCCER AND ITS CONTRIBUTION TO MUSCULAR POWER**

### **2.6.1 The importance of genetic variation in elite soccer**

Recent research in sports genomics suggests that genetic variation accounts for 66% of the variability in athlete status (De Moor et al., 2007), and 74% of maximal muscular power output (assessed using the Wingate anaerobic 5-s interval test) (Calvo et al., 2002). This has led to suggestions that genetic profiling should be included in talent identification protocols, e.g. in elite youth soccer. The most common type of DNA sequence variant is a single-nucleotide polymorphism (SNPs), where one nucleotide substitutes another. Another type of common sequence variation is the insertion/deletion (I/D) polymorphism, in which a specific nucleotide sequence is present (insertion) or absent (deletion) from the allele. Figure 2.7 illustrates a scatterplot of the results from a real-time polymerase chain reaction (RT-PCR), used to establish the genotype frequency distribution of specific SNPs in a cohort of 35 ESP. Gene polymorphisms can affect the amount and structure of mRNA/protein produced and may therefore account for the differences in human phenotypic traits. It follows, therefore, that polymorphisms of genes encoding key proteins in the muscle-tendon unit may have implications for muscular power performance, thus potentially determining soccer playing status (Ahmetov and Fedotovskaya, 2012).

Numerous case control studies have associated specific gene polymorphisms with soccer playing status (Egorova et al., 2014, Ginevičienė et al., 2010, Juffer et al., 2009, Micheli et al., 2011, Santiago et al., 2008), thus implying that if a genotype or allele is more prevalent in ESP than the general public, it may enhance soccer performance. One of the first studies investigating the genetic variation in elite soccer showed that ESP representing clubs in Spain were associated with a higher



**Figure 2.7.** A screenshot showing how genotype groups (wild type, heterozygous, mutant terms were used) of single nucleotide polymorphisms were determined following real time polymerase chain reaction (PCR), according to the quantity of fluorescent dye measured using Rotor-Gene Q Pure Detection 2.1.0 software (Qiagen Ltd.). All samples were analysed in duplicate with one negative control (bottom left of screen) only containing 1 $\mu$ L nuclease-free H<sub>2</sub>O. This screenshot was taken from one of the PCR runs from the participants recruited for the studies described in the current thesis.

frequency of the *ACTN3* (rs1815739) R-allele in comparison to non-elite control participants (Santiago et al., 2008). The common *ACTN3* R577X (rs1815739) SNP results in either an arginine (R) or a stop codon (X) at amino acid 577 of exon 16 on chromosome 11 (North and Beggs, 1996), leading to the existence of three genotypes: RR, RX, and XX. XX homozygotes are unable to produce alpha-actinin-3, thus leading to the compensatory upregulation of the closely related isoform alpha-actinin-2 (Beggs et al., 1992, North and Beggs, 1996). Whilst alpha-actinin-3 deficiency is not associated with any disease phenotype; the absence of this protein may impair the performance of type II fibres (MacArthur and North, 2007). Alpha-actinin-2 regulates calcineurin signalling in skeletal muscle and induces activation of the slow myogenic program causing a shift in fast twitch muscle fibre characteristics towards a more slow twitch, oxidative phenotype (Delling et al., 2000, Seto et al., 2013), thus enhancing fatigue resistance and endurance performance (Jiang et al., 2010, Pimenta et al., 2013). The *ACTN3* R577X SNP was also previously associated with muscle fibre type and muscle volume, with XX homozygotes presenting with a greater proportion of slow twitch muscle fibres (Ahmetov et al., 2011, Vincent et al., 2007) and lower quadriceps femoris muscle volume (Erskine et al., 2014), in comparison to RR homozygotes. As muscle power output is a function of muscle volume and muscle myosin heavy chain composition (Pearson et al., 2006), and XX homozygotes have been reported to be underrepresented in elite sprint/power athletes (Eynon et al., 2009, Niemi and Majamaa, 2005, Yang et al., 2003), findings from Santiago and colleagues (2008) suggest that elite soccer players are associated with a genetic profile precluding them to superior muscular power performance, rather than endurance capabilities.

More recent research is in agreement with these findings and it has been reported that the frequencies of angiotensin-I converting enzyme (*ACE* I/D rs4646944) D (65.0 vs. 48.9%), alpha-actinin-3 (*ACTN3* rs1815739) R (67.5 vs.

60.4%), peroxisome proliferator-activated receptor  $\alpha$  (*PPARA*, rs4253778) C (24.3 vs. 17.3%) and uncoupling protein 2 (*UCP2*, rs660339) 55Val T (44.4 vs. 35.8%,  $P = 0.0022$ ) alleles were significantly higher in soccer players representing clubs in the Russian Premier, National and Second Division leagues, in comparison to non-athletic Russian control participants (Egorova et al., 2014). This research suggested that elite soccer performance is a polygenic trait and having 4 or more of these alleles may be advantageous for soccer performance, thus increasing the likelihood of becoming an ESP (Egorova et al., 2014). Moreover, as the *ACTN3* R-, *ACE* D- and *PPARA* C-alleles have previously been associated with strength/power phenotypes in over 20 case control studies, and *UCP2* Ala55Val has been associated with endurance performance [reviewed in (Ahmetov and Fedotovskaya, 2012)], these results provide evidence to support the hypothesis that whilst muscular endurance is important to meet the aerobic demands of elite soccer, strength and power capabilities may play a more important role in determining successful soccer performance (Bangsbo, Nørregaard and Thorsoe, 1991, Faude, Koch and Meyer, 2012). These findings are supported by research reporting the -C-allele of the nitric oxide synthase 3 (*NOS3* rs2070744) SNP, which has previously been found to be more common in elite power-oriented athletes in comparison to non-athletic controls (Drozdovska et al., 2009, Gómez-Gallego et al., 2009, Sessa et al., 2011), was also overrepresented in elite soccer players playing in Spain, compared to non-elite control participants (Eynon et al., 2012). In further support of the association between strength and power genetic profiles and soccer playing status, youth ESP players representing Italian clubs were associated with a higher frequency of the FF genotype of the vitamin D *FokI* receptor (*VDR* rs28934604) SNP (Micheli et al., 2011), which has previously been associated with greater femoral neck bone mineral density adaptation after strength training (Rabon - Stith et al., 2005). However, case control studies investigating importance of the *ACE* gene I/D polymorphism in elite

soccer remain inconclusive. Angiotensin-I converting enzyme (ACE) has been shown to generate vasopressor angiotensin II and degrading vasodilator kinins (Dzau, 1988), which have both been shown to have growth regulatory effects (Geisterfer, Peach and Owens, 1988, Ishigai et al., 1997), with angiotensin II specifically mediating skeletal muscle growth in response to mechanical load (Gordon et al., 2001). Circulating ACE activity has been significantly correlated with isometric and isokinetic quadriceps strength (Williams et al., 2005), and the D-allele of the ACE gene I/D polymorphism has been associated with higher ACE activity. Accordingly, although few studies have reported conflicting results, the D-allele has also been associated with power athlete status [reviewed in: (Puthuchearry et al., 2011)], and greater strength and muscle volumes at baseline (Ahmetov et al., 2013, Charbonneau et al., 2008, Hopkinson et al., 2004, Wagner et al., 2006). In contrast, the ACE I-allele has been associated with endurance athlete status, and endurance related phenotypes such as the proportion of slow twitch type I fibres, maximal oxygen consumption, fatigue resistance and cardiac output [reviewed in: (Ahmetov and Rogozkin, 2009)]. In accordance with findings in Russian soccer players (Egorova et al., 2014), Juffer and colleagues (2009) reported that the ACE II genotype was less common in Spanish professional soccer players compared to endurance athletes, thus suggesting that ESP tend to have a strength/power oriented genotype. In contrast, professional soccer players representing Lithuanian clubs were associated with a lower frequency of ACE DD genotype compared to control participants, thus suggesting that endurance, rather than strength and power capabilities, are more important for professional soccer performance in the Lithuanian National League (Gineviciene et al., 2014). Such research implies that specific genetic profiles may be advantageous for elite soccer performance in different countries.

Considering that National Leagues in different countries may have different physical and technical requirements (Dellal et al., 2011), case control genetic association studies aiming to establish favourable genetic profiles for elite soccer performance should be specific to the National League and country. No study to date has investigated the most favourable genetic profile in English Premier League players and therefore, the importance of genetic variation for successful performance in the English Premier League remains unknown. Moreover, as the physiological factors associated with muscular power appear to be different at pre-, mid- and post-PHV (Virus et al., 1999), the gene polymorphisms characterising elite soccer performance may be specific to maturation status. This has not been investigated in any National soccer league and future case control studies should investigate the importance of genetic profile for elite soccer performance at different stages of maturation.

### **2.6.2 The contribution of genetic variation to muscular power in elite soccer players**

While it is important to establish if a specific combination of gene variants may characterise elite soccer in different countries, case control studies do not reveal the relationship between specific genetic polymorphisms and physical performance capabilities. Cross sectional studies, investigating associations between gene variants and specific soccer performance predictors, may provide more diagnostic information for applied soccer practitioners. Such information could help inform talent identification and talent development protocols. However, there is a paucity of cross-sectional association studies in elite youth soccer (Coelho et al., 2015, Pimenta et al., 2013) and therefore, the relationship between genetic variation and muscular power in ESP remains unknown.

Muscular power has previously been associated with over 20 genetic



polymorphisms to date. Extensively reviewed by both Eynon and colleagues (2013), and Ahmetov and colleagues (2012), the alpha-actinin-3 (*ACTN3* rs1815739) R577X SNP provides the most consistent results. Strongly supported by mechanistic data from the knock out mouse model, the *ACTN3* R577X SNP is the only SNP that has demonstrated a genotype-performance association across multiple cohorts of elite power athletes. The *ACE* I/D polymorphism, angiotensinogen (*AGT* Met235Thr rs699), skeletal adenosine monophosphate deaminase (*AMPD1* Gln(Q)12Ter(X) [also termed C34T, rs17602729]), interleukin-6 (*IL-6-174* G/C, rs1800795), *NOS3* - 786 T/C, (rs2070744), *PPARA* (intron 7 G/C, rs4253778), and *UCP2* Ala55Val (rs660339) polymorphisms have also been associated with elite power performance, although these polymorphisms have not been studied as extensively and findings are less consistent. It is predicted that many additional common polymorphisms will be associated with soccer performance in the future. It is therefore recommended that future research should aim to identify and investigate the relationship between novel candidate genes that are associated with the physiological factors that may underpin soccer power performance (Ahmetov and Rogozkin, 2009, Hughes et al., 2011).

Muscle power output is largely determined by the volume of the muscle, and the proportion of fast twitch type II fibres (Pearson et al., 2006). As the *ACTN3* R-allele has been associated with greater quadriceps femoris muscle volume (Erskine et al., 2014), and a greater proportion of fast twitch fibres (Ahmetov et al., 2011, Vincent et al., 2007), it follows that this genotype could influence muscular power output in youth ESP. However, the only two previous cross sectional association studies investigating the relationship between athletic performance and genetic variation in elite soccer, reported contrasting results. While Pimenta and colleagues (2013) documented that the *ACTN3* R-allele was associated with greater 10 m acceleration, 20 m sprint and vertical CMJ, but lower YoYo endurance test performance in Brazilian professional soccer players (Fig. 2.8), Coelho and

colleagues (2015) found no relationship between these performance tests and the *ACTN3* R-allele in ESP. The role of *ACTN3* R577 in elite soccer, particularly elite youth soccer, therefore remains to be elucidated. The *ACTN3* R-allele has also previously been associated with increased testosterone production that may explain, in part, the association between the *ACTN3* R-allele and greater muscle volume (Ahmetov, Donnikov and Trofimov, 2014). Consequently, as circulating testosterone is lower in pre-PHV compared to mid- and post-PHV males (Malina, Bouchard and Bar-Or, 2004), the *ACTN3* SNP may influence muscular power differentially according to maturation status. However, this theory has never been investigated, and such information could inform genetic screening protocols and the prediction of future performance in pre-PHV ESP.

Maximal power is not only governed by the morphology and size of the muscle, but also by the ability to activate the muscles involved in the action (Cormie, McGuigan and Newton, 2011). Brain derived neurotrophic factor (BDNF), is a member of a family of neurotrophins and regulates neuronal survival, growth, maintenance, neurogenesis and synaptic plasticity (McAllister, Katz and Lo, 1999). The *BDNF* gene is located on chromosome 11p14.1 and has numerous polymorphic markers. The val66met SNP results in an amino acid substitution (valine to methionine) at codon 66 [(val66met) (dbSNP number: rs6265)] of the proBDNF molecule, and is associated with reduced secretion of BDNF in response to exercise (Egan et al., 2003). Subsequently, the *BDNF* val66met SNP may be related to neuronal adaptation following exercise and could therefore influence maximal power and speed performance. However, the association between this SNP and power capabilities in soccer players has never been investigated and it remains unknown if *BDNF* val66met SNP may influence power capabilities. Moreover, as the muscular power performance in pre-PHV males is thought to be characterised by neural factors, such as inter-muscular co-ordination and intra-muscular synchronization

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**Figure 2.8.** The association between *ACTN3* (rs1815739) RR, RX, and XX genotypes and (A) vertical countermovement and squat jump assessments, and (B) YoYo endurance assessment estimation of maximal oxygen consumption, in professional Brazilian soccer players. Data are presented as mean and *SD*. In graph A, \* illustrates a difference in comparison to XX. In graph B, \* illustrates a difference in comparison to RR. Adapted from Pimenta and colleagues (2013).

(Virtu et al., 1999), the *BDNF* val66met SNP may influence muscular power differentially depending on the maturation status.

The majority of explosive actions performed during soccer match-play require the cyclical expression of force (i.e. accelerations, sprints, jumps) and therefore involve the stretch shortening cycle (SSC) (Di Salvo et al., 2010, Faude, Koch and Meyer, 2012, Ingebrigtsen et al., 2015). During SSC actions, tendinous recoil has been shown to increase the power generated during the subsequent concentric phase (Ettema, Van Soest and Huijning, 1990, Kubo et al., 2000c, Kurokawa et al., 2003). According to previous training studies, we have no means of enhancing the extensibility of tendon structures (Kongsgaard et al., 2007, Kubo et al., 2001, Reeves, Maganaris and Narici, 2003), except for bed rest (Kubo et al., 2004, Reeves et al., 2005) and detraining (Kubo et al., 2010). However, greater knee extensor tendon-aponeurosis compliance has been associated with elite sprinters (Kubo et al., 2011, Kubo et al., 2000b, Stafilidis and Arampatzis, 2007) and 100 m sprint performance (Kubo et al., 2000b, Stafilidis and Arampatzis, 2007). Subsequently, it could be assumed that the more compliant knee extensor tendon-aponeurosis structures of elite sprinters are partly determined by genetic variation. Moreover, gene polymorphisms that may affect tendon properties could potentially influence power output during soccer actions.

The majority of the tendon (approximately 85% of the dry mass) consists of collagen, and the mechanical and physiological characteristics of the collagenous tissue dictate the properties of the tendon (Kirkendall and Garrett, 1997). The *COL5A1* gene encodes the pro alpha chain of the type V collagen, a quantitatively minor fibrillar collagen that through its heterotypic interactions with type I collagen, may have regulatory roles in controlling fibril diameter in connective tissue such as tendon (Birk et al., 1990, Wenstrup et al., 2011). The CC genotype of the *COL5A1* (rs12722) gene variant was associated with more extensible knee extensor tendons

in a population of Japanese males (Kubo, Yata and Tsunoda, 2013). In agreement, the *COL5A1* (rs12722) T-allele was associated with a stiffer quadriceps femoris tendon in healthy recreational men (Kirk et al., 2016). However, not all studies have reported an association between the functional and dimensional properties of the patellar tendon and the *COL5A1* (rs12722) gene variant (Foster et al., 2014). Hence, more studies are required to establish the role of this gene variant in determining patellar tendon properties and functional performance.

The *COL2A1* gene is located on 12q13.11, contains 54 exons, and encodes the alpha 1 chain of procollagen type II. A SNP has been identified in the *COL2A1* gene (rs2070739), which involves a C>T missense substitution on human chromosome 12 (Nishimura et al., 2005). The *COL2A1* rs2070739 SNP may regulate the concentration of procollagen type II produced (Donoso et al., 2003, Tarpey et al., 2013). Type II collagen is a large homotrimeric protein that forms strong fibrils and has a function to maintain the structure of connective tissues, such as the hyaline cartilage, intervertebral discs, adult vitreous, and the inner ear (Barat-Houari et al., 2016, Wardale and Duance, 1994, Watanabe, Yamada and Kimata, 1998). Type II collagen is also present in the tendon near the bone insertion (Adamczyk et al., 2008, Buckley et al., 2013) and may therefore play a role in the series elastic stored energy during stretch shortening cycle actions such as accelerating, sprinting and jumping in different directions. However, SNPs of the *COL2A1* gene have never been investigated in athletes, nor associated with elite soccer playing status or physical performance characteristics.

In summary, there is a scarcity of research investigating the role of genetic profiles in determining elite soccer playing status. Such studies need to be specific to account for differences in playing styles and physical requirements of National leagues in different countries (Dellal et al., 2011). Whilst results from case control studies may offer useful information for soccer talent identification procedures, more

cross-sectional genetic association studies are needed to establish the influence of specific genetic polymorphisms on physical predictors of soccer performance, such as muscular power. As maturation is a confounder when analysing power associated performance assessments, such studies could also help practitioners identify genetic deficiencies and predict future muscular power performance potential in pre-PHV soccer players. This information would allow soccer practitioners to apply specific training interventions that aim to eradicate genetic deficiencies in maximal power performance. In addition to improving the detail and effectiveness of adult soccer player maximal power development strategies, such research would allow the application of specific training interventions to target predicted physical deficiencies in developing young soccer players from an early age. The application of bespoke training interventions would ultimately improve the maximal power capabilities of youth ESP, thus allowing elite soccer academies to develop more players with the physical capacity to succeed in elite soccer at the highest level.

## **2.7 SUMMARY**

As a greater ability to produce muscular power results in superior athletic performance (Kraemer and Newton, 2000, Sleivert and Taingahue, 2004, Young et al., 2005), it is believed that enhancing a player's maximal power capabilities could increase their chances of succeeding at the highest level of soccer performance. Our review of the current literature highlights that there is a limited base of research available that allows soccer strength and conditioning practitioners to perform a detailed soccer-associated maximal power needs analysis. To construct and evaluate individualised specific maximal power development programmes, the practitioner needs to employ and analyse measurements from a maximal power assessment protocol that is specific to demands of elite soccer match-play. However, no study to date has provided a detailed account of the powerful actions that occur

during elite soccer match-play. Subsequently, no information exists that is in sufficient detail to inform the construction of a soccer-associated maximal power assessment protocol. There is currently limited information revealing the specific maximal-power associated physiological adaptations that are advantageous for elite soccer performance, and that underpin soccer-associated maximal power. Soccer strength and conditioning coaches therefore do not currently have access to information that would allow them to target, or assess, specific physiological mechanisms in the maximal power development, or talent identification processes. Many physiological changes occur in the human body during maturation (Virtanen et al., 1999), but it remains unknown if specific maximal power capabilities are important for elite soccer performance at different stages of maturation. The talent identification process is extremely important for elite soccer clubs at all ages, and a successful process could result in major financial rewards. However, the current soccer literature offers no guidance as to which maximal power-associated assessments should be employed to identify talented soccer players at different stages of maturation. As elite soccer players have been previously associated with a more favourable genetic profile than players selected at a lower level (Egorova et al., 2014, Ginevičienė et al., 2010, Juffer et al., 2009, Micheli et al., 2011, Santiago et al., 2008), the inheritance of specific characteristics is also thought to enhance a soccer player's chance of performing at the elite level. However, the only cross sectional studies performed in ESP that associated specific genetic polymorphisms, with power-associated performance measures, revealed conflicting results (Coelho et al., 2015, Pimenta et al., 2013). More research is therefore required to establish if certain genetic variants play a role determining soccer playing status and soccer-associated maximal power potential.

In summary, the current literature does not provide enough detailed information to allow soccer strength and conditioning practitioners to understand the

specificity, physiological underpinnings, and genetic determinants influencing maximal power within a soccer context. Research addressing the issues discussed should provide valuable information to inform the talent identification, needs analysis and training prescription processes in ESP at all stages of maturation.



## **CHAPTER THREE**

HORIZONTAL POWERFUL ACTIONS PLAY AN  
IMPORTANT ROLE IN ELITE YOUTH SOCCER MATCH-  
PLAY: AN OBSERVATIONAL STUDY USING VIDEO  
BASED PLAYER TRACKING

## STUDY 1: ABSTRACT

### HORIZONTAL POWERFUL ACTIONS PLAY AN IMPORTANT ROLE IN ELITE YOUTH SOCCER MATCH-PLAY: AN OBSERVATIONAL STUDY USING VIDEO BASED PLAYER TRACKING

#### Abstract

Approaches to determining the powerful activity profile of elite soccer match-play has not been documented appropriately to inform specific maximal power assessment and development criteria. The aims of the current study were to compare the frequency and durations of powerful actions during elite youth soccer match-play using a novel soccer specific powerful action (SSPA) notational analysis coding system. Sixteen elite male English Premier League (EPL) Academy players ( $19 \pm 1$  yrs) were recorded by an individual camera during sixteen competitive EPL U18 and U21 games. Video footage was analysed using performance analysis software and SSPAs were coded according to the following categories: initial acceleration, leading acceleration, sprint, unilateral jump and bilateral jump. Elite youth EPL soccer players undertook significantly more initial ( $31 \pm 9$ ) and leading ( $37 \pm 12$ ) accelerations than sprints ( $8 \pm 3$ ;  $P=0.014$  and  $P<0.001$ , respectively) and vertical jumps ( $6 \pm 5$ ;  $P=0.002$  and  $P<0.001$ , respectively). Players performed a significantly greater number of initial and leading accelerations with action durations below 1.5 s compared to above 1.5 s ( $P=0.001$  and  $P=0.002$ ), respectively. Horizontal accelerations of short duration ( $< 1.5$  s) from different starting speeds appear the most dominant powerful action in elite youth soccer match-play. Soccer conditioning coaches should therefore prioritise the assessment and development of both initial, and leading, horizontal acceleration performance.

**Keywords:** vertical, sprint, jump, English Premier League.

### 3.0 INTRODUCTION

An analysis of movement is important for understanding the physiological demands of a sport (Carling et al., 2008) as evaluating the movements provides the basis for categorising the types of actions that may be important for performance. Sport specific actions can be described as powerful when the athlete attempts to generate the greatest possible velocity at take-off, release or impact (Cormie, McGuigan and Newton, 2011). Submaximal running is the predominant activity during soccer match-play but powerful efforts often determine the outcome of competitive games (Faude, Koch and Meyer, 2012). Understanding the specific nature of the powerful actions performed during elite soccer match-play can help inform assessments of muscular power and training strategies in this domain (Issurin, 2013, Maulder and Cronin, 2005).

Much of the available data on the performance of powerful actions within soccer come from studies that have used automated time motion analysis systems to quantify the “high intensity” aspects of the game. Such studies have classified maximal accelerations (Bradley et al., 2010, Ingebrigtsen et al., 2015, Varley and Aughey, 2013a) and sprint (Di Salvo et al., 2010, Gregson et al., 2010) efforts as actions which require the player to complete both accelerations and running velocities over pre-determined thresholds [i.e. maximal acceleration threshold:  $>2.78 \text{ m}\cdot\text{s}^{-2}$  (Varley and Aughey, 2013a);  $>2 \text{ m}\cdot\text{s}^{-2}$  (Ingebrigtsen et al., 2015);  $>2.5 \text{ m}\cdot\text{s}^{-2}$  (Bradley et al., 2010); Sprint threshold:  $>25.2 \text{ km}\cdot\text{hr}^{-1}$  (Di Salvo et al., 2010, Di Salvo et al., 2009)]. However, during linear speed testing protocols (Mendez-Villanueva et al., 2011, Stolen et al., 2005) and competitive games (Bradley et al., 2009, Mendez-Villanueva et al., 2011), elite soccer players present a range of individual capabilities in terms of accelerations and maximal running speeds. As a consequence, the classification of accelerations and sprints as maximal could be misleading as these arbitrary speed thresholds may incorrectly classify movements that are not truly

indicative of a maximal action for a specific individual player (Dogramac, Watsford and Murphy, 2011). The accuracy and reliability of time motion analyses systems are frequently compromised at such higher speed ranges, and in actions that require both greater rates of acceleration and during efforts involving a change of direction (Akenhead et al., 2014, Di Salvo et al., 2009, Jennings et al., 2010, Johnston et al., 2014, Ogris et al., 2012, Valter et al., 2006, Varley, Fairweather and Aughey, 2012). Such issues could further compromise the appropriate identification of powerful actions during elite soccer match-play using such methods. Automated time motion analyses systems also often fail to report the vertical jump demands of soccer. It is therefore unknown how frequently a player is required to produce vertical power to propel their bodies in the vertical direction during a competitive game. Subsequently, studies using automated time motion analysis systems may not characterise the powerful activity in elite soccer match-play in sufficient detail to inform the specificity of soccer-associated muscular power assessment and development protocols.

Notational analysis systems have suggested to provide a reliable and valid method of tracking player movements where short distances, frequent changes in direction (Dogramac, Watsford and Murphy, 2011) and vertical jumps (Faude, Koch and Meyer, 2012, Mohr, Krustup and Bangsbo, 2003) are observed. Unlike automated time motion analyses systems, this method offers more flexibility for the identification of powerful actions based on the circumstances during which the action is performed (i.e. During a situation when two players from opposite teams are accelerating in a race to get to an area of the pitch, or to a free soccer ball, this would suggest that the acceleration is performed as (or nearly as) explosively as possible, and can therefore be described as a powerful action). Notational analysis may therefore provide a more accurate description of the frequency and duration of the complex powerful actions performed by individual players during soccer match-play (Dogramac, Watsford and Murphy, 2011).

To date, previous soccer notational systems coded sprints but not accelerations (Bloomfield, Polman and O'Donoghue, 2007, Faude, Koch and Meyer, 2012), failed to report action duration (Faude, Koch and Meyer, 2012), and only reported the frequency of powerful actions preceding goals (Faude, Koch and Meyer, 2012) and during isolated random fifteen-minute periods of games (Bloomfield, Polman and O'Donoghue, 2007). No study has therefore provided a comprehensive description of the detail of powerful actions performed over the duration of a competitive soccer match. Moreover, it remains unknown if the frequency of powerful actions change as a function of time throughout the duration of a competitive soccer match. Consequently, there is currently limited information available to inform the specific detail of soccer-associated power assessment and training intervention protocols.

In light of the limited research in this area, the primary aim of our study was to assess and compare the frequency and durations of various powerful actions during elite youth soccer match-play by using a novel soccer specific powerful action (SSPA) notational analysis coding system. A second aim was to examine the temporal patterns of powerful actions (i.e. frequency differences between the two halves of a football match) during competitive elite youth English Premier League (EPL) soccer match-play.

### **3.1 METHODS**

#### **3.1.1 Participants**

Sixteen elite male soccer players registered to an EPL football academy provided consent to participate in the study. The study was approved by the Liverpool John Moores University ethics committee and complied with the Declaration of Helsinki. Twelve of the players were members of their respective youth national teams with three players having also previously represented their senior national team. Player's

age, height, body mass, sum of seven skinfold sites (taken at the biceps, triceps, subscapular, supraspinale, abdominal, mid-thigh, and calf) and estimated % body fat were  $18.5 \pm 1.0$  years,  $180.5 \pm 7.2$  cm,  $74.9 \pm 8.6$  kg,  $44.3 \pm 7.1$  mm and  $7.9 \pm 1.2$  %. The sample of players included three central defenders, three full backs, three central midfielders, three wide midfielders and four centre forwards. Three of the players were substituted at various time-points during the second half. Therefore, their first-half performance data were reported but removed from the statistical analyses.

### **3.1.2 The development of the SSPA Coding System**

The procedure for developing the SSPA coding system involved five sequential stages. This process was similar to that detailed in previous research (Brewer and Jones, 2002). The first stage involved the researcher becoming familiarised with the concepts and procedures that are employed during systematic observation notational analysis. During the second stage, previous soccer coding systems were critically analysed to evaluate their potential use for the project. The third stage of the process involved constructing a broad categorisation of SSPAs that occur in games. During the fourth stage, this broad categorisation of SSPAs was refined into the SSPA coding system. This stage also included the researcher attempting to establish the face validity of this novel SSPA coding system. The fifth stage established the intra and inter-reliability of the novel coding system.

#### *3.1.2.1 Stage 1: Researcher Familiarisation*

It is recommended that the researcher becomes familiarised with the techniques required for practical data collection prior to the development of any novel coding system (Brewer and Jones, 2002). This process may help reduce the risk of error and hence support the future determination of the reliability of the system prior to the

commencement of the study. The researcher completed some initial training in systematic observation. This involved familiarisation of the methods adopted when tracking individual players during games. This familiarisation was completed during 45 min of an U16 EPL Academy League game with an experienced video analyst employed at an English Premier League Academy. Techniques required for zooming in and out to provide clear images of player movement patterns during games were demonstrated. An explanation of how to transfer the video footage to a desktop computer (Apple iMac, California, USA) and analyse general player activities using performance analysis software (Studiocode, Sportscode, NSW, Australia) was also completed.

As part of the familiarisation procedure, the author then also filmed 45 min of footage of four players during an U18 EPL Youth Academy League games. Four different positions were included in this filming task (central defender, wide defender, central midfielder and forward) to ensure that a wide range of position specific movement patterns could be observed and analysed. The video footage was then downloaded and analysed using performance analysis software. Previous soccer movement classification systems were then implemented to code various soccer specific actions (Bloomfield, Polman and O'Donoghue, 2007, Faude, Koch and Meyer, 2012). This procedure allowed the author to practice the identification and recording of soccer specific playing actions using a template of the definitions delineated by previous coding systems (Bloomfield, Polman and O'Donoghue, 2007, Faude, Koch and Meyer, 2012).

### *3.1.2.2 Stage 2: The critical analysis of previously used soccer coding systems*

It was deemed important to conduct a critical analysis of other previously used soccer notational analysis coding systems that have attempted to categorize explosive efforts. This process allowed an evaluation of previously used systems to

take place. From this evaluation the requirements for the system to be used in the current chapter could be determined. This enabled an informed decision to be made about whether relevant data could be collected by the implementation of an existing system or through the development of a novel protocol. Upon close examination previous soccer coding systems in the area did not seem to provide a clear definition of what actions can be defined as powerful (Table 3.1; how were the powerful actions defined?). Moreover, the definitions of powerful actions in previous soccer coding systems (Table 3.1; was the frequency of sprints and maximal accelerations reported? Was the frequency of vertical jumps reported? Was the detail of vertical jump type reported? Was the action duration reported?) were not in sufficient detail to inform the biomechanical specificity of soccer testing and training intervention protocols (Coburn, 2012, Maulder and Cronin, 2005). Details such as the duration of the action and the type of jump actions (bilateral or unilateral) performed, were deemed important as they can inform the specificity of physical assessment protocols and training intervention criteria in soccer. Previous soccer coding systems did not also provide an account of the whole game (Table 3.1; does the study report the powerful action profile for the whole game?). Such information is important to provide a representation and hence enhance our understanding of the total frequency of the range of SSPAs performed during match-play. Subsequently, in light of the limited previous literature documenting the profiles of powerful actions in elite soccer match-play, a detailed account of the SSPAs performed throughout the duration of soccer match-play remains elusive and it was deemed imperative to attempt to overcome these limitations if the current novel coding system is to be capable of informing future soccer testing and training protocols.



### *3.1.2.3 Stage 3: A broad categorization of SSPAs*

The aim of the third stage of the process was to develop a broad categorisation of SSPAs. Considering the limitations of previous soccer coding systems (Table 3.1), it seemed appropriate initially to clearly define what actions can be considered powerful and hence could be incorporated into a notation system. A powerful action was defined as an effort that was performed as (or nearly as) explosively as possible. The identification of powerful actions was therefore based on the researcher recognizing circumstances in which the player performed an explosive effort.

The authors observed four forty-five min of pilot video footage (detailed above) and identified discrete movements that were “powerful”. From this analysis the researcher observed that accelerations requiring the player to propel his body in the horizontal-forward and mediolateral directions were performed frequently. Accelerations and sprints were considered powerful actions in situations when the player was perceived to be aiming to travel to a specific area of the pitch as quickly as possible. Such actions were generally performed under circumstances which required the player to advance towards the ball before an oncoming opponent, move away from an advancing opponent, or travel to a specific area of the pitch in an attempt to gain possession of the ball from an opponent (Table 3.2; linear and lateral accelerations). Players were also required to perform explosive vertical jumps, off one or two legs, to contest balls in the air. Vertical jumps were considered powerful actions when it was assumed that the player was attempting to meet the ball at its highest point and therefore jumping as high as possible. It was assumed that if the player was attempting to meet the ball at its highest point, these jumps can be considered to be performed as (or nearly as) explosively as possible (Table 3.2; unilateral and bilateral vertical jumps). Powerful efforts were also relevant when players collided with each other when dueling for the ball. If the player was perceived to have attempted to exert maximal (or near maximal) force to protect or win the ball,

he was considered to have performed a powerful effort (Table 3.2; collisions). It was also observed that slide tackles required the player to forcefully extend their ankle, knee and hip and perform an explosive jump in the horizontal direction to try and meet the ball before the oncoming opponent. When carrying out such actions, the player was perceived to have performed the effort as (or nearly as) explosively as possible (Table 3.2; slide tackles). The final action that was identified that could be proposed as a powerful effort was a forceful strike of the ball. As the player often

**Table 3.1.** A critical analysis of previous subjective notational analysis literature describing powerful actions during elite soccer match-play.

Critical Questions	Bloomfield et al. (2007)	Faude et al. (2012)
How were powerful actions defined?	An intensity modifier included a “high intensity” and “very high intensity” category. No other information explaining how to powerful actions were identified.	Definitions of powerful action categories were provided which did not include details of how to identify if the action was powerful.
Was the frequency of sprints and maximal accelerations reported?	No. Only maximal sprints.	No. Only maximal sprints.
Was the frequency of vertical jumps reported?	Yes.	Yes.
Was the detail of vertical jump type (unilateral or bilateral) reported?	No.	No.
Was action duration reported?	Yes, but no clear definition of action start and end time points were reported.	No.
Does the study report the powerful action profile for the whole game?	No. 15 minute periods of games were recorded and analysed.	No. Powerful actions preceding goals were reported.

attempted to optimise the velocity of the ball in situations such as shooting at the goal, this action was assumed to require a maximal (or near maximal) extension of the knee joint (Table 3.2; forceful strike of ball). When the author was satisfied that all potential SSPAs for all positional groups (central defenders, full backs, central midfielders, wide midfielders and centre forwards) had been identified and defined in Table 3.2, the broad categorisation of SSPAs was completed.

**Table 3.2.** A broad categorisation of soccer specific powerful actions (SSPAs) used in the first phase of pilot work.

<b>Powerful action</b>	<b>Definition</b>
Linear Acceleration	At least one powerful propulsion of the body in the horizontal-forward direction. At least one knee, ankle & hip extension movement.
Lateral Acceleration	At least one powerful propulsion of the body in the mediolateral direction. At least one knee, ankle & hip extension movement.
Sprint	A very high intensity run at near maximal velocity in a straight direction (no angle of more than 50 degree change of direction) after a distinct acceleration period.
Change of direction	Two distinct accelerations of the body at an angle of more than 50 degrees from the initial sprint line. Slightly curved runs with no second acceleration were defined as linear sprints.
Bilateral vertical jump	Propulsion of body off one leg in a primary vertical direction with only partial horizontal direction. This must have a clear identifiable take-off and landing phase.
Unilateral vertical jump	Propulsion of body off one leg in a primary vertical direction with only partial horizontal direction. This must have a clear identifiable take-off and landing phase.
Collision	A powerful effort to protect or try and win the ball at least one foot is in contact with the ground.
Slide tackle	Horizontal acceleration of player's body mass in an attempt to win the ball whereby both feet leave the ground.
Forceful strike of the ball	When a player strikes the ball with force in an attempt to optimise the velocity of the ball.

#### *3.1.2.4 Stage 3: Refining the broad categorisation of SSPAs and validating the SSPA coding system*

Complex notational analysis coding systems are more likely to be limited in their application by reliability issues. Subsequently, the first aim of stage 4 was to refine the broad categorisation of SSPAs (Table 3.2) into a more simplistic SSPA coding

system that not only accounted for all types of powerful action performed during soccer match-play but was practically operational. The second aim was to validate this SSPA coding system to establish whether it would be suitable for characterising SSPA in sufficient detail to inform soccer testing and training protocols.

The detail of the broad categorisation of SSPAs was refined across a three-month period to devise the novel SSPA coding system (Tables 3.3 and 3.4). The broad categorisation of SSPAs (Table 3.2) identified during Stage 2 was re-evaluated using a slow motion analysis. This enabled the biomechanical detail of the actions to be analysed. This detailed analysis showed that it was practically very difficult to distinguish between linear and lateral accelerations (Table 3.2; linear acceleration; lateral acceleration). It was therefore concluded that these two powerful actions should be combined and placed in the same activity category (Table 3.3; initial or leading accelerations). The difficulty in identifying collisions (Table 3.2; collisions), as well as the problems with ascertaining if these are powerful efforts (performed as, or nearly as, explosively as possible), resulted in the decision to not include this type of action in the SSPA coding system (Table 3.3). The detailed analysis of the data also identified that powerful accelerations could be initiated from different movement speeds. This consideration may affect the muscular power qualities that a player may utilize to overcome the inertia of a movement. Subsequently, it was decided that accelerations should be divided into two categories; initial and leading (Table 3.3; initial accelerations and leading accelerations). Analyzing the biomechanical requirements of the powerful actions in slow motion also highlighted that many of the actions detailed in Table 3.1 could be classified within more than one of the categories detailed in the SSPA coding system in Table 3.3. For example, a slide tackle of powerful effort (Table 3.2; slide tackle) could be defined as a horizontal leading acceleration as this movement requires a propulsive action in the horizontal-forward or mediolateral directions (Table 3.3; leading acceleration). Similarly,

powerful change of direction (Table 3.2; change of direction) actions can be defined as two powerful horizontal accelerations (Table 3.3; a leading or initial acceleration, followed by an initial acceleration). Removing such actions that were difficult to identify and where possible combining actions with similar biomechanical requirements into the same category reduced the complexity of the SSPA coding system while still allowing an accurate account of SSPAs to be recorded.

A knowledge of the duration of SSPAs was also considered important when constructing the detail and specificity of soccer assessment and training intervention protocols. Subsequently, in contrast to previous soccer coding systems, the start and end points of each action were clearly defined in the notation system (Table 3.4). These start and end points could also be used to measure the duration of the action for each SSPA. It was decided that SSPAs of durations less than 0.5 s should not be included in the analysis due to the practical difficulties of identifying the start and end points of these short actions. Detailing specific criteria (Table 3.4) for action “start

**Table 3.3.** Soccer specific powerful action (SSPA) coding system categories and definitions.

Category	Definition
Initial acceleration	Very high-intensity horizontal acceleration where the player propels their body in the forward or sideways direction whilst initiating the first propulsion when either static, walking, or after changing direction.
Leading acceleration	Very high-intensity horizontal acceleration where the player propels their body in the forward or sideways direction whilst initiating the first propulsion when performing a movement that cannot be defined as static, walking or changing direction.
Sprint	If the player is perceived to continue to perform the very high intensity acceleration effort for over 1.72 s, the acceleration now turns into a sprint action. At this time point the acceleration terminates and a sprint action will begin.
Bilateral jump	Very high-intensity propulsion of body off two legs in a primary vertical direction with only partial horizontal direction. This must have a clear identifiable take off and flight phase.
Unilateral jump	Very high-intensity propulsion of body off one leg in a primary vertical direction with only partial horizontal direction. This must have a clear identifiable take off and flight phase. This category can include actions such as jumping to control the ball and does not necessarily have to be a jump for a header.

points” was also important for coding the frequency of acceleration and sprint actions (Table 3.3; initial acceleration; leading acceleration; sprint). As acceleration (10 m sprint time) and sprint (30 m sprint time) capabilities are independent attributes (Little and Williams, 2005), it was thought to be important to ensure that the broad categorisation of SSPAs also included specific criteria to allow the frequency of both of these types of powerful actions to be coded during games. The average 10 m sprint assessment times for the ESP recruited for the current study was  $1.72 \pm 0.7$  s. Therefore, when the player had accelerated as (or nearly as) explosively as possible for more than 1.72 s, it can be assumed that they have progressed through the acceleration phase and now transitioned into performing a sprint action. Subsequently, when coding an initial or leading acceleration (Table 3.3; initial acceleration; Leading acceleration), the action was timed from the start point (Table 3.4) using performance analysis software (Studiocode, Sportscodex, NSW, Australia). If the player continued to accelerate for 1.72 s, the acceleration ended at this specific time point and a sprint action commenced (a sprint action was coded from this time point). As 98% of maximal accelerations performed during soccer match-play are performed from low velocities ( $< 4 \text{ m}\cdot\text{s}^{-1}$ ) (Varley and Aughey, 2013b), the same threshold ( $> 1.72$  s) was used to determine the end of an acceleration and beginning of a sprint for both initial and leading accelerations (Table 3.3; initial acceleration; leading acceleration; sprint). Such detail was considered important if the SSPA coding system (Table 3.3; initial acceleration; leading acceleration; sprint) was going to be used to provide information that could inform soccer linear speed assessment and conditioning interventions.

To complete the refinement of the notation system, the researcher then revised the detail of the SSPA coding system by observing the four forty-five min of pilot video footage (detailed above) again and checking that all-important powerful efforts could be coded by the current system. Indeed, the definitions and criteria

**Table 3.4.** Original criteria for defining start and end point of all powerful actions.

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*Start point of powerful actions:*

- The beginning of all powerful actions was defined as the time frame before the moment where the first noticeable extension of ankle, knee or hip joint occurred during the initiation of the first explosive propulsion of the movement.

*End point of powerful actions:*

- All powerful actions ended one-time frame before the first ground contact of the deceleration or landing phase.
  - The deceleration phase of horizontal actions began when the player's stride pattern changed and his landing foot contacted the ground in front of his centre of mass acting to slow him down.
  - This was often marked by a heel strike when the foot initially made ground contact.
- 

outlined in Tables 3.3 and 3.4 were considered sufficient to allow the detailed coding of SSPAs for all positions during elite match-play.

In order to be able to use this SSPA coding system as a measuring tool for analyzing powerful action profiles within soccer match-play, the face validity of the SSPA coding system (Tables 3.3 and 3.4) needed to be established (Brewer and Jones, 2002). Face validity can be defined as the extent to which a test is subjectively viewed as covering the concept it purports to measure (Nevo, 1985). It was therefore necessary to demonstrate that this observation instrument (Tables 3.3 and 3.4) would record the most frequent and important powerful actions performed during soccer match-play. For this purpose, it was deemed appropriate to establish face validity via interactions with a number of “experts” in the field; these included one experienced football researcher University Professor, one video analyst and two sports scientists, all currently employed by an English Premier League Club. These specialists were invited to review and informally subjectively validate the coding system. This process consisted of the author explaining and demonstrating the coding classification system and receiving verbal feedback on it during a series of

meetings. Following these discussions all the specialists agreed with the SSPA coding system categories and rules. As a consequence, the SSPA coding system was not changed and remained in the same format (Tables 3.3 and 3.4).

#### *3.1.2.5 Stage 6: Intra- and Inter-observer Reliability Analyses*

It is imperative to investigate the intra-observer reliability of a novel coding system to establish that the test-retest reliability for the principle researcher using the system is acceptable. Likewise, it is also important to investigate the inter-observer reliability of a novel coding system to establish that the system was as not restricted to a single user and could be used in future research studies. The process for establishing the intra- and inter- observer reliability of the New SSPA coding system is illustrated in Figure 1.

##### *(i) Intra-observer Reliability Analyses*

The intra observer-reliability process was completed on three separate occasions (Fig. 3.1; Intra-observer reliability 1, 2 and 3). The methodological approach on each of these occasions followed the same process each time. The researcher initially viewed the player cam video footage of a single full competitive game and coded the powerful actions based on the criteria of the SSPA coding system being assessed. The individual player cam game codes were also extrapolated to a timeline with a recording scale of 0.5 s. As well as providing a template for matching this coded timeline to subsequent coded timelines from the same player cam footage, this process allowed the researcher to remove SSPAs of durations less than 0.5 s. Twelve days later, the same researcher then repeated this analysis process again coding the powerful actions during the same player cam footage (same game and player) and extrapolating the SSPA coding data to a timeline with a recording scale of 0.5 s. The extrapolated timelines from both datasets were matched on the exact



same time scale (recording scale of 0.5 s) to assess whether the actions coded by the researcher during the same player cam footage occurred at the same time point during the game footage. The level of agreement between timelines was analysed for intra observer-reliability using kappa statistics.

The first intra-observer reliability assessment (Fig. 3.1; Intra-observer reliability 1) was performed by comparing both timelines coded by the researcher from the same player cam footage according to the criteria detailed in the SSPA coding system (Tables 3.3 and 3.4). The Kappa coefficient for intra observer-reliability of the overall SSPA coding system (Tables 3.3 and 3.4) was  $k = 0.827$ , which represented very good reliability (Table 3.5; *intra-observer reliability 1*).

**Table 3.5.** Results of intra-observer reliability test-retest analyses of the overall respective coding system performed during the development of the final New SSPA coding system.

Intra-observer Reliability	$\kappa$
Test-Retest	
<i>Intra-observer reliability 1</i>	0.827
<i>Intra-observer reliability 2</i>	0.718
<i>Intra-observer reliability 3</i>	0.839

*Key: Intra-observer reliability 1* = Intra-observer test-retest reliability assessment analysing the SSPA coding system (Tables 3.3 and 3.4); *Intra-observer reliability 2* = Intra-observer test-retest reliability assessment analysing the New SSPA coding system (Tables 3 and 7); *Intra-observer reliability 3* = Intra-observer test-retest reliability assessment check on the New SSPA coding system (Tables 3 and 7) after seven games;  $\kappa$  = Kappa Coefficient.

The second intra-observer reliability assessment of the overall New SSPA coding system (Fig. 1; Intra-observer reliability 2) was performed by comparing both timelines coded by the researcher from the same player cam footage according to the criteria detailed in the New SSPA coding system (Tables 3.3 and 3.7). The

Kappa coefficient for the second intra observer-reliability assessment on the New SSPA coding system (Tables 3.3 and 3.7) was  $k = 0.834$ , which represented very good reliability (Table 3.5; intra-observer reliability 2).

The final reliability assessment of the overall New SSPA coding system (Fig. 3.1; Intra-observer reliability 3) was completed mid-way through the analysis of the sample of games to confirm that the observation of actions are not influenced by learning effects associated with familiarisation with the observation system. A third intra-observer reliability assessment was therefore performed using the New SSPA coding system (Tables 3.3 and 3.7) after the seventh game using the similar procedures described previously. The only difference in the analysis at this point was that only the actions in the first 45 minutes were analysed at both time points. The kappa coefficient for the intra-observer-reliability check of the overall New SSPA coding system was  $k = 0.839$  (Table 5; *Intra-observer reliability 3*), which represented very good reliability. This analysis indicated that the intra-observer reliability of the system is maintained after analysing multiple games.

**Table 3.6.** Results of inter-observer reliability test-retest analyses performed during the development of the coding system.

Inter-observer	Reliability	$\kappa$
Test-Retests		
<i>Inter-observer reliability 1</i>		0.593
<i>Inter-observer reliability 2</i>		0.834

*Key: Inter-observer reliability 1* = Inter-observer test-retest reliability assessment analysing the SSPA coding system (Tables 3 and 4); *Inter-observer reliability 2* = Inter-observer test-retest reliability assessment analysing the New SSPA coding system (Tables 3 and 7);  $\kappa$  = Kappa Coefficient.

*(ii) Inter-observer Reliability Analyses*

The inter-observer reliability analysis determined whether the author, and an inexperienced observer who had no previous experience of notational analysis methods, could record the same movements, at the same time points, during the same game. The observer was allowed a familiarization session prior to commencement of the coding. This familiarization session consisted of the author briefly explaining the rules of the coding system and the observer coding 45 min from a player cam video footage.

Two separate inter-observer reliability assessments were performed following the same procedure (Fig. 3.1; Inter-observer reliability 1 and 2). During the inter-observer reliability procedure, the observer was required to view the player cam video footage of a full competitive game and code the powerful actions based on the criteria of the SSPA coding system being assessed. The observer was allowed to rewind, fast forward and to play the footage in slow motion whenever he felt it was necessary. No time limitations were placed on the observer completing the analysis. The observer was instructed to extrapolate the individual game codes to a timeline with a recording scale of 0.5 s and remove SSPAs with durations less than 0.5 s. This extrapolated observer timeline was matched with the corresponding timeline from the same player cam footage coded by the researcher during the intra-reliability analysis. The level of agreement between timelines was analysed for inter observer-reliability using kappa statistics.

The first inter-observer reliability assessment compared the timelines coded by the observer and researcher based on the criteria of the SSPA coding system detailed in Tables 3.3 and 3.4 (Fig. 3.1; Inter-observer reliability 1). The Kappa coefficient for the first inter observer-reliability of the overall SSPA coding system was  $k = 0.593$ , which represented moderate reliability (Table 3.6; *inter-observer reliability 1*). The moderate inter-tester reliability results indicated that modifications

needed to be made to the coding system in order to improve the reliability of the system for use in future research studies. From analyzing the results and consulting the inter-observer, it appeared that the start points of powerful actions were the main source of error affecting the inter-observer reliability. Subsequently, the author decided to change the definition of the start points of actions to allow these time points to be easier to identify. The powerful coding system with modified start and end point criteria is detailed in Table 3.7. Subsequently, the New SSPA coding system is represented in Tables 3.3 (SSPA coding system categories and definitions) and 3.7 (Modified criteria for defining start and end point of all powerful actions).

Once the intra-observer reliability of the New SSPA coding system (Table 3.3 and 3.7) was established as being very good (Table 3.5; *Test-retest 2*), the second inter-observer-reliability assessment of the overall New SSPA coding system was performed (Fig. 3.1; *Inter-observer Reliability 2*). The kappa coefficient was  $k = 0.718$  (Table 3.6; *Inter-observer reliability 2*), which represented good reliability. Subsequently, the New SSPA coding system was deemed to have acceptable inter-observer reliability. Hence, in addition to being a reliable coding instrument for use within the principle researcher, the revised New SSPA coding system (Tables 3.3 and 3.7) was also believed to be reliable for other users.

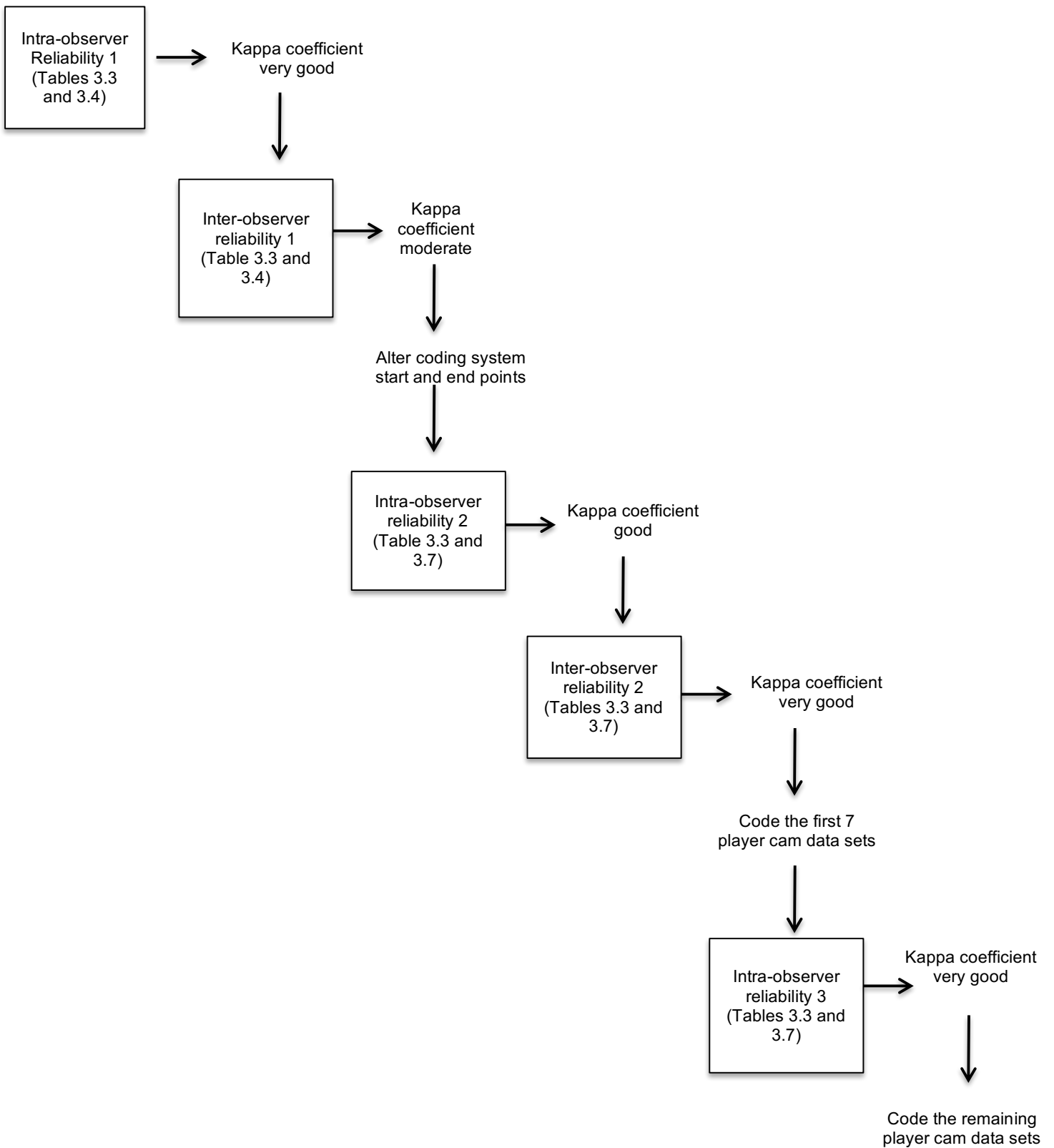
**Table 3.7.** Modified criteria for defining start and end point of all powerful actions.

*Start point of powerful actions:*

- The beginning of all powerful actions was defined as the moment that the players' foot first made contact with the ground immediately before initiation of the first explosive propulsion of the movement.
- On the rare occasion that the player initiated the powerful action from a static stance with both feet in contact with the ground, the action began at the instance (time frame before) marked by the first noticeable extension of ankle, knee or hip.

*End point of powerful actions*

- All powerful actions ended one-time frame before the first ground contact of the deceleration or landing phase.
- The deceleration phase of horizontal actions began when the player's stride pattern changed and his landing foot contacted the ground in front of his centre of mass acting to slow him down.
- This was often marked by a heel strike when the foot initially made ground contact.



**Figure 3.1.** An illustration of the intra- and inter-observer reliability process.

### **3.1.3 Procedures**

#### **Procedure**

The comprehensive development of the New SSPA coding system indicated that the tool was a reliable observer instrument to code SSPAs. Following this evaluation, the data collection procedures commenced. Filming was conducted during sixteen competitive EPL Academy Youth League soccer matches (thirteen U21 and three U18 League Games) in the 2013-2014, and 2014-2015 season. All games were played on a grass surface and filmed using a digital video camera (Canon XM2, Amstelveen, Netherlands) mounted on a stationary tripod (Libec, Arizona, USA). Individual players were recorded and tracked by an individual camera, which was zoomed to provide clear, unobstructed and close images of the specific player in question from an elevated position. A total of sixteen performances from sixteen separate players were analysed.

The video footage of each game was transferred to a desktop computer (Apple iMac, California, USA) and then analysed using performance analysis software (Sportscodel Gamebreaker Plus, Sportscodel, NSW, Australia), operating at a frequency of 25 Hz. Only actions when the circumstances would suggest that the player had to perform an effort as (or nearly as) explosively as possible were coded according to the categorisation criteria detailed in Table 3.3. The start and end points of powerful actions were coded to provide frequency counts and action duration outcomes. The video footage could be played back frame-by-frame, or in slow motion, to allow specific start and end points to be identified. Specific criteria used to identify these time points are illustrated in Table 3.7. Initial accelerations, leading accelerations and sprints of durations  $<0.5$  s were not included in the analysis as the intra-observer reliability for identifying such powerful actions during pilot testing was found to be limited.

### **3.1.4 Statistics**

Due to the relatively low number of observations for both unilateral and bilateral jumps, these actions were grouped together as one category (vertical jumps) for analysing differences within and between powerful actions. All data were checked for normality and the frequency data for vertical jumps were not normally distributed. Therefore, a Friedman's test was used to determine if there were differences between the total frequency of different powerful actions performed during the whole game (initial accelerations, leading accelerations, sprints, vertical jumps). Pairwise comparisons were performed with a Bonferroni correction to determine specific differences between the different powerful actions. Wilcoxon signed ranked tests were used to detect differences between the same powerful action performed during the first half compared to the second half. Wilcoxon signed ranked tests were also used to detect differences between the number of powerful actions performed in the two duration categories (0.5 - 1.49 s and  $\geq 1.5$  s) and the number of unilateral compared to bilateral vertical jumps performed during the whole game. All statistical analyses were completed using SPSS version 21 (SPSS Inc., Chicago, IL), and statistical significance was set at  $P \leq 0.05$ . All data are expressed as mean  $\pm$  SD.

## **3.3 RESULTS**

### **3.3.1 Comparing the frequencies of powerful actions**

A descriptive account of which powerful actions occur most frequently during games may be useful information for determining which physical qualities may be most important for soccer performance. During a competitive soccer match, ESP performed a total of  $81 \pm 18$  powerful actions. There were significant differences between the frequency of actions performed during the match ( $\chi^2(4) = 48.043$ ,  $P < 0.001$ ). Pairwise comparisons revealed that players performed a significantly greater

number of initial accelerations and leading accelerations than vertical jumps during the whole game ( $P = 0.002$  and  $P < 0.001$ , respectively; Figure 3.2A). Similarly, a significantly greater number of initial accelerations and leading accelerations were performed compared to sprints during the whole game ( $P = 0.014$  and  $P < 0.001$ , respectively; Figure 3.2A). There was no difference in the number of vertical jumps performed compared to sprints during the entire match ( $P = 1.000$ ; Figure 3.2A). Likewise, players performed a similar number of initial and leading accelerations during the whole game ( $P = 1.000$ ; Figure 3.2A).

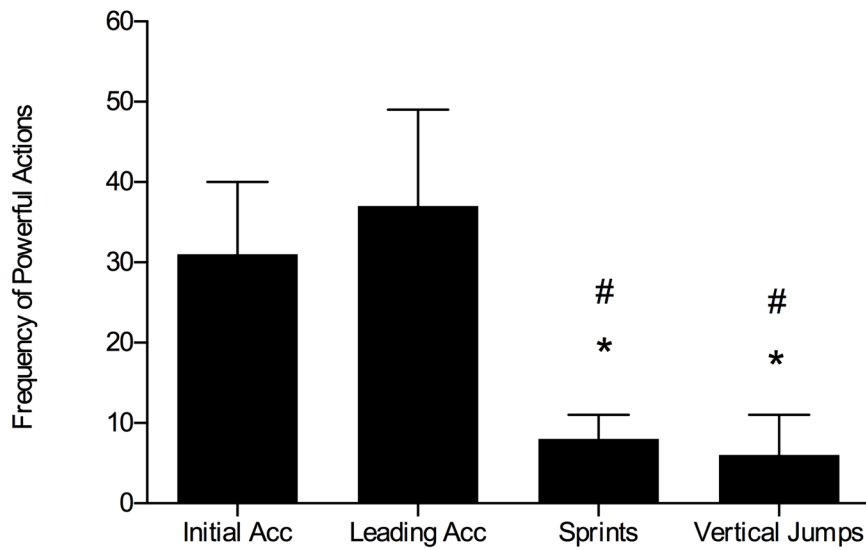
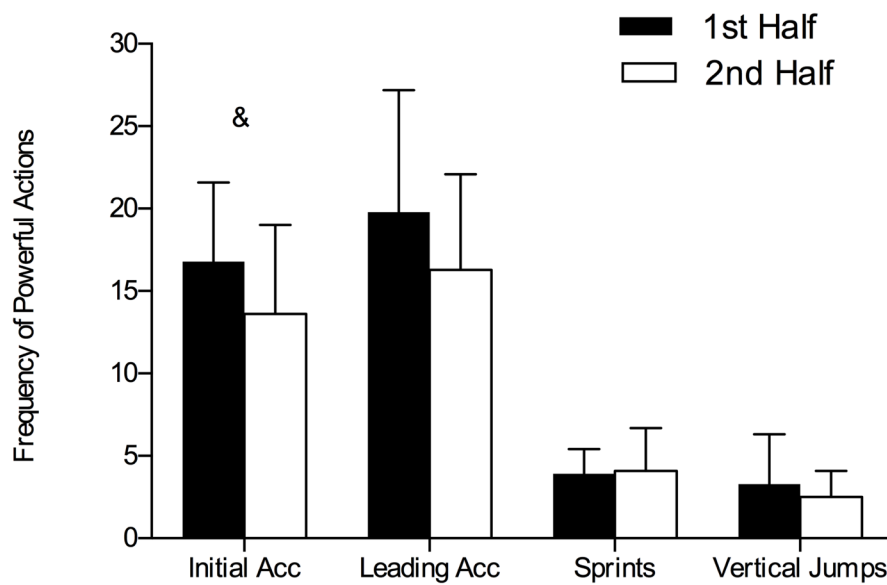
### **3.3.2 Temporal pattern of powerful actions**

The temporal pattern of powerful actions performed over the course of a game allows an insight into any changes in the frequency of these actions as a function of time. A significantly higher total number of powerful actions were performed during the first compared to the second half of matches ( $45 \pm 10$  vs.  $37 \pm 10$ ;  $Z = -2.944$ ,  $P = 0.003$ ). More specifically, ESP performed a significantly greater number of initial accelerations in the first half ( $Z = -1.959$ ;  $P = 0.050$ ; Fig. 3.2B). A higher number of leading accelerations ( $Z = -1.889$ ;  $P = 0.059$ ; Fig. 3.2B) was observed during the first, compared to the second half of the matches though this difference was not significant. There was no difference between the numbers of sprints ( $Z = -0.158$ ,  $P = 0.874$ ; Figure 2B) or vertical jumps ( $Z = -1.437$ ,  $P = 0.151$ ; Fig. 3.2B) performed during either half.

### **3.3.3 Duration of powerful actions**

There were significantly greater number of initial accelerations ( $Z = -3.189$ ,  $P = 0.001$ ; Fig. 3.3), leading accelerations ( $Z = -3.115$ ,  $P = 0.002$ ; Fig. 3.3), and sprints ( $Z = -2.325$ ,  $P = 0.020$ ; Fig. 3.3) performed that lasted for durations between 0.5-1.49 s compared to the number of these activities performed for more than 1.5 s.



**A****B**

**Figure 3.2.** Frequency count of powerful actions performed during (a) the 90 minutes of competitive match-play ( $n = 13$ ); and (b) the first half (*black bars*;  $n = 16$ ) and second half (*white bars*;  $n = 13$ ) of competitive match-play. Data are mean  $\pm$  SD.

\* Significantly lower frequency count than initial accelerations ( $P < 0.050$ ).

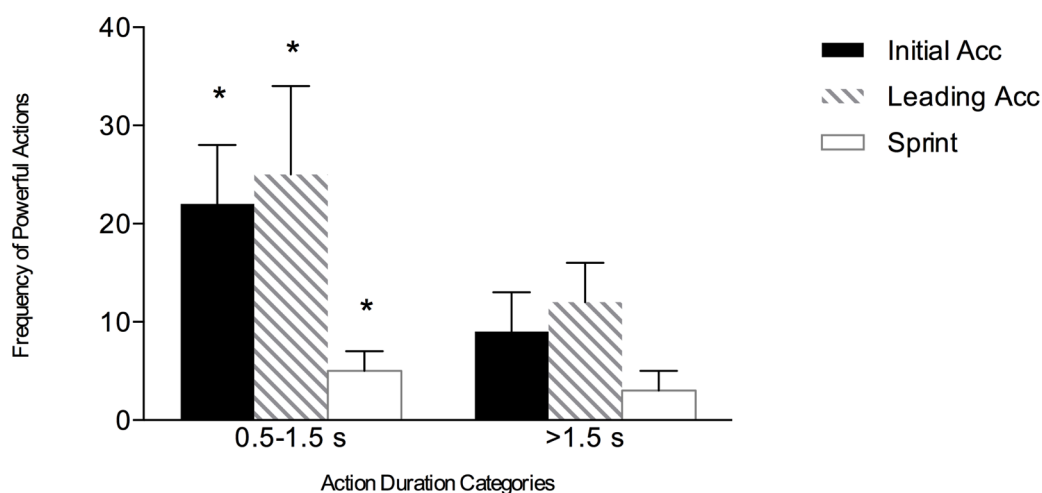
# Significantly lower frequency count than leading accelerations ( $P < 0.001$ ).

& Significantly lower frequency count during second half compared to first half ( $P \leq 0.050$ ).

Key: Acc = accelerations.

### 3.3.4 Jump type frequency

There was no difference in the total number of unilateral compared to bilateral jumps performed during the matches ( $3 \pm 3$  vs.  $3 \pm 3$ ;  $Z = -3.180$ ,  $P = 0.437$ ). The range of total vertical jumps performed, however, was large (Total vertical jumps: 2 – 18).



**Figure 3.3.** Frequency count of initial accelerations (*black bars*), leading accelerations (*striped bars*), and sprints (*white bars*) performed for durations between 0.5-1.5 s and > 1.5 s during a whole match ( $n = 13$ ), mean  $\pm$  SD.

\* Significantly greater number of powerful actions with duration between 0.5-1.49 s, than > 1.5 s ( $P < 0.05$ ).

### 3.5 DISCUSSION

We developed a new analysis approach for characterising powerful activity profiles of ESP and are the first to identify differences between the frequencies of powerful actions performed during elite soccer match-play. The video based player tracking notational analysis SSPA coding system (Tables 3.3 and 3.7) developed was shown to be reliable for identifying powerful actions during soccer match-play. The main finding from analysing the individual elite player footage using the New SSPA coding

system (Tables 3.3 and 3.7) was that over the course of a competitive game, EPL youth players performed a significantly greater number of initial and leading accelerations compared to both sprints and vertical jumps. Action duration data showed that the majority of initial accelerations, leading accelerations and sprints performed over the course of a game lasted less than 1.5 seconds. Our findings suggest that accelerations of short duration (<1.5 seconds), from different starting speeds that are oriented in the horizontal direction, are the most dominant powerful action in elite youth soccer match-play. This information suggests that soccer-associated maximal power assessment and development protocols could specifically focus on evaluating and enhancing the ability to perform horizontal, rather than vertical, powerful actions.

If a video based player tracking notational analysis coding system is to be used to provide information to inform the prescription of assessment and training strategies for ESP, it is imperative that the coding system has been validated and shown to be reliable for observers using the instrument. Due to the range of acceleration and maximal speed capabilities presented by soccer players in the same team (Mendez-Villanueva et al., 2011, Stolen et al., 2005), and the compromised reliability of automated time motion analysis systems for quantifying soccer specific high intensity actions (Akenhead et al., 2014, Varley, Fairweather and Aughey, 2012), there is currently no gold standard for quantifying the range of powerful actions performed during soccer match-play. Subsequently, the face validity of the SSPA coding system definitions and powerful action descriptions (Table 3.3) in the current study were established after interviewing a series of experts in the applied (one performance analyst and two sports scientists currently working at a Premier League Club) and research (an experienced performance analysis researcher) fields (see The development of the system: Stage 5). This informal validation process was thought to be sufficient to consider the New SSPA coding

system (Tables 3.3 and 3.7) as a valid player tracking notational analysis coding system for analysing the powerful action profile of elite soccer match-play. The New SSPA coding system (Tables 3.3 and 3.7) was also shown to have good intra- and inter-observer reliability (see The development of the system: Stages 6 and 7) and was therefore a reliable coding instrument for use within the principle researcher, and others (Tables 3.5 and 3.6). The current study is the first to demonstrate that a novel SSPA coding system (Tables 3.3 and 3.7) is a suitable video based player tracking notational analysis coding system for providing a valid and reliable account of the powerful actions performed during elite soccer match-play.

If certain powerful actions occur more frequently during elite competitive match-play, it can be assumed that the ability to perform this specific task may be important for elite soccer performance and should be prioritised in the training process. EPL youth soccer players undertook 8-fold more horizontal accelerations than sprints (~68 vs. 8, respectively), thus suggesting the ability to frequently perform horizontal accelerations is a more important characteristic of elite youth soccer performance (Figure 2). We also show that elite EPL youth soccer players performed 11-fold more horizontal accelerations (initial and leading accelerations combined) than vertical jumps (~68 vs. 6, respectively) during a competitive match. Subsequently, powerful efforts oriented in the horizontal-forward and mediolateral directions can be considered more important during elite youth soccer match-play than efforts oriented the vertical direction. Considering it has been previously documented that unilateral jump capabilities in different directions are independent qualities that should be assessed and developed separately (Hewit, Cronin and Hume, 2012, Meylan et al., 2010), it appears that future soccer specific power assessment and development protocols should prioritise horizontal-forward and mediolateral power production. However, the range in vertical jump frequency in the

current study (2-18) may also suggest that this capacity is more important for some positions than others, or perhaps dependent on the type of game and opposition.

To optimise muscular power assessment and development programmes for soccer players, knowledge of the detail of these actions is important. The majority of horizontal accelerations and sprints were performed for durations of less than 1.5 s (Figure 3). This information suggests that the ability to initiate short duration explosive horizontal efforts, is an important characteristic of elite youth soccer match play. These findings are in agreement with Cometti and Colleagues (2001) and, as acceleration performance has been associated with horizontal-forward jump performance (Dobbs et al., 2015, Maulder and Cronin, 2005, Meylan et al., 2009b), these findings may support the inclusion of this assessment in elite soccer talent identification protocols.

Our study is the first to categorise accelerations as initial or leading, based on the inertia that the player is required to overcome before initiating the acceleration. As there was no difference in the number of initial and leading accelerations completed by EPL youth soccer players (Figure 2), our results show that both of these actions are of equal importance and should be developed during soccer training interventions. Previous literature documenting the biomechanical detail of acceleration from a static start illustrated that as the acceleration progresses, ground contact times and positive horizontal impulse (impulse = force x time) decreased [For review please see: (Wild et al., 2011)]. Indeed, Salo and colleagues (2008) found propulsive impulse to decrease from 93.5 Ns, to 49.1 Ns, between steps one and four of a maximum acceleration action from a static start. The maximal power capabilities required to accelerate are therefore dependent on the initial inertia of the player. Initial accelerations performed from a walking or static start may require the production of greater positive horizontal impulse and relative ground reaction forces to overcome the inertia. In contrast, leading accelerations are initiated when the

player is already moving and therefore may require less relative ground reaction force and propulsive impulse to overcome the moving inertia. Our data therefore suggests that elite soccer match-play requires the ability to produce horizontal impulse equally from both static and moving inertias and therefore, training interventions with elite soccer players should aim to develop acceleration capabilities from both static and moving starts. Moreover, soccer specific assessments of maximal power should evaluate the ability to produce horizontal impulse from both static and moving inertias, using both acyclic (i.e. countermovement jumps) and cyclic unilateral assessments (i.e. drop jumps or multiple jumps).

Analysing the effect of time on the frequency of powerful actions may also provide useful information for the prescription of soccer conditioning programmes. Elite EPL youth soccer players performed fewer powerful actions in the second half in comparison to the first half. More specifically, significantly fewer initial accelerations, and a tendency for fewer leading accelerations, were performed in the second half, thus suggesting that powerful horizontal actions were reduced as a function of time. Due to the complexity of factors that could influence the reduction in running performance during soccer match-play (Paul, Bradley and Nassis, 2015), the significance of these findings is not yet known from a practical or theoretical perspective. Nevertheless, our data may suggest that soccer practitioners could aim to apply specific conditioning interventions to help players perform initial accelerations more frequently during the second half of competitive matches.

We must acknowledge that there were a number of limitations in our study. Due to the time consuming procedures associated with tracking and recording an individual player with a camera for 90 minutes, the sample size was relatively small, and only included players from one EPL club. The powerful activity profile reported may therefore have been biased by the tactical and/or training strategies employed by this club. The protocol for establishing the face validity of our coding system also

only included individuals connected with only one club and could also have been affected by bias towards certain club philosophies. However, as we are the first to document the powerful activity profile of an ESP population (twelve of the players were members of their respective youth national teams with three players having also previously represented their senior national team) in sufficient detail to inform detailed assessment and training intervention protocols, we have provided novel information for the applied practitioner and a platform for future research in this area.

### **Conclusion**

Our study demonstrated that a novel video based player tracking notational analysis coding system (novel SSPA coding system; Tables 3.3 and 3.7) has sufficient face validity and can be used to provide a reliable account of the powerful actions performed during elite soccer match-play. While we show that EPL U18 and U21 elite soccer match-play requires the performance of powerful actions oriented in multiple directions, vertical jump and sprint actions were performed less frequently than both initial and leading horizontal accelerations. Our results show that initial and leading horizontal accelerations of short duration ( $< 1.5$  s) are the most frequently performed powerful actions during elite youth soccer match-play. This suggests that the assessment and development of acceleration capabilities from different starting speeds should be prioritised in soccer talent identification and development programmes. More specifically, our results may imply that the ability to generate maximal power during actions oriented in the horizontal-forward and mediolateral directions could be considered paramount to successful soccer performance. Our data could be used to inform the detail and specificity of novel soccer-associated maximal power assessment protocols.

## **CHAPTER FOUR**

### **UNILATERAL JUMPS IN DIFFERENT DIRECTIONS: A NOVEL ASSESSMENT OF SOCCER-ASSOCIATED POWER?**



## STUDY 2: ABSTRACT

### UNILATERAL JUMPS IN DIFFERENT DIRECTIONS: A NOVEL ASSESSMENT OF SOCCER-ASSOCIATED POWER?

**Purpose:** We aimed to determine whether CMJs (unilateral and bilateral) performed in different directions assessed independent lower-limb power qualities, and if unilateral CMJs would better differentiate between elite and non-elite soccer players than BV CMJs. **Methods:** Elite (ESP; n=23; age, 18.1 ± 1.0yrs) and non-elite (NSP; n=20; age, 22.3 ± 2.7yrs) soccer players performed three BV, unilateral vertical (UV), unilateral horizontal-forward (UH) and unilateral medial (UM) CMJs. Jump performance (height and projectile range), kinetic and kinematic variables from ground reaction forces, and peak activation of the vastus lateralis and biceps femoris (BF) muscles from surface electromyography, were compared between jumps and groups of players. **Results:** Peak vertical power (V-power) was greater in BV (220.2 ± 30.1 W/kg) compared to UV (144.1 ± 16.2 W/kg), which was greater than UH (86.7 ± 18.3 W/kg) and UM (85.5 ± 13.5 W/kg) (all, p<0.05) but there was no difference between UH and UM (p=1.000). Peak BF EMG was greater in UH compared to all other CMJs (p≤0.001). V-power was greater in ESP than NSP for all CMJs (p≤0.032) except for BV (p=0.197). Elite achieved greater UH projectile range than NSP (51.6 ± 15.4 vs. 40.4 ± 10.4 cm, p=0.009). **Conclusions:** We have shown that UH, UV and UM CMJs assess distinct lower-limb muscular power capabilities in soccer players. Furthermore, as ESP outperformed NSP players during unilateral but not BV CMJs, unilateral CMJs in different directions should be included in soccer-specific muscular power assessment and talent identification protocols, rather than the BV CMJ.

**Keywords:** *jump, countermovement, horizontal, mediolateral, vertical, electromyography.*

## 4.1 INTRODUCTION

Maximal power is often assessed in ESP by measuring bilateral vertical countermovement jump (BV CMJ) performance (Chelly et al., 2010b, Rønnestad, Nymark and Raastad, 2011). As part of the Elite Player Performance Plan, which was developed in an attempt to address the apparent shortcomings in the youth player development process in England, all English Soccer Academies are currently required to employ the BV CMJ as a performance assessment for measuring maximal power (Premier League, 2011). However, we reported that ESP performed an average of 81 powerful actions (defined as activities when the circumstances require the player to perform an effort as, or nearly as, explosively as possible) comprising 68 accelerations (in the horizontal-forward or mediolateral directions), eight sprints, and six vertical jumps (three bilateral and three unilateral) (please see Chapter three). This activity profile implies that elite soccer match-play requires the ability to produce maximal power in the horizontal-forward, mediolateral and vertical directions. Moreover, whilst elite soccer performance requires both unilateral and bilateral vertical propulsion, the majority of powerful actions are in fact performed unilaterally in the horizontal-forward and mediolateral directions. The use of unilateral jump assessments in different directions, rather than the BV CMJ, may therefore provide a more specific lower body power profile in ESP.

As the number of competitive matches per season in elite soccer is high [(several Spanish players played 70 competitive games during the 2009-2010 season) (Nedelec et al., 2012)], the time available for administering lower body power profiling is limited. Therefore, selected tests in a specific lower body power profile should not assess the same capabilities and should provide the greatest relevant information, in the shortest amount of time. Unilateral jump assessments in different directions have previously been shown to measure independent lower-limb power qualities specific to the direction of the jump (Hewit, Cronin and Hume, 2012,

Meylan et al., 2010), although this has not yet been established in soccer players. Previous studies have documented that jump direction is controlled by different coordination strategies (Nagano, Komura and Fukashiro, 2007) and muscle activation magnitudes (Fukashiro et al., 2005, Jones and Caldwell, 2003). However, no study has compared muscle activation during bilateral and unilateral CMJs directed in the vertical, horizontal-forward and medial directions. Comparing muscle activation during unilateral CMJs in different directions would give an insight into whether such assessments evaluate specific muscle activation strategies.

The results of lower body power assessments should be used to inform detailed training intervention protocols. Identifying the most important kinetic and kinematic predictors of jump performance allows the practitioner to monitor and aim to develop jump-specific performance variables. Although previous research has documented the greatest kinetic and kinematic predictors of unilateral (Meylan et al., 2010) and bilateral (Markovic and Jaric, 2007) CMJs in non-elite participants, this has never been investigated in ESP.

Physical training interventions designed for ESP need to be specific for improving qualities related to high-level soccer performance. It is therefore imperative that physical assessments measure capabilities that are important for elite soccer performance. A specific performance capability is indirectly considered important if ESP have greater capacity than NSP (Cometti et al., 2001). It is currently unknown, however, whether bilateral and unilateral jump abilities in different directions are important determinants of elite soccer performance.

Knowledge of which maximal power assessments may predict soccer performance at the elite level could inform the specificity of future training intervention and talent identification criteria. Given the limited research in this area, the aims of this study were to: (1) establish whether CMJs performed in different directions [BV, unilateral vertical (UV), unilateral horizontal-forward (UH) and

unilateral medial (UM) CMJs] assessed independent lower-limb power qualities by assessing whether differences existed in the kinetic and kinematic performance variables, and vastus lateralis (VL) and biceps femoris (BF) muscle activation, in ESP and NSP; (2) establish the best kinetic predictors of CMJ performance in ESP and NSP; (3) investigate differences in CMJ performance between ESP and NSP to establish if such assessments could be used as indicators of soccer playing status.

## **4.2 METHODS**

### **4.2.1 Participants**

Forty-three male soccer players volunteered to take part in this study, which was approved by Liverpool John Moores University Ethics Committee and complied with the Declaration of Helsinki. Participants provided written informed consent prior to being assigned to two groups according to their level of competition. The ESP group (n=23; age,  $18.1 \pm 1.0$  yrs; height,  $182.5 \pm 7.3$  cm; weight,  $77.2 \pm 10.1$  kg) included one goalkeeper, nine defenders, five midfielders and eight forwards from an English Premier League football academy, who regularly participated at U18 and U21 level. The NSP group (n=20; age,  $22.3 \pm 2.7$  yrs; height,  $175.0 \pm 5.8$  cm; weight,  $72.9 \pm 7.3$  kg) included one goalkeeper, five defenders, six midfielders and eight forwards, who participated in at least one hour per week of competitive soccer (11-a-side or five-a-side), and one hour per week of soccer-specific or fitness-based training. Non-elite participants were excluded if they did not meet these inclusion criteria or had previously played soccer at academy, semi-professional, or professional level. Participants were fully familiarised with all testing procedures in a separate session and were asked to complete a physical activity and health questionnaire prior to the study for screening purposes.

#### **4.2.2 Experimental Design**

All participants attended the laboratory on two separate occasions with at least 72 hours between each session. In order to minimise the influence of previous activity, the testing was performed following a period of at least 48 h without any high intensity multi-directional exercise which included any form of soccer match-play activity. The first session enabled the participants to be familiarised with the assessment protocol, which consisted of three unilateral CMJs in the vertical, horizontal-forward and medial directions on each leg, three knee extensor (KE) and three knee flexor (KF) isometric maximal voluntary contractions (iMVCs). This session was also used to determine the superior jumping leg [defined as the limb that produced the highest ground reaction force during a unilateral vertical countermovement jump (UV CMJ)]. During the second session, the participants performed all CMJ and maximal voluntary isometric contraction (iMVC) assessments.

#### **4.2.3 Data acquisition and analysis procedures**

##### *4.2.3.1 Countermovement jumps*

On arrival at the laboratory for the second session, all participants had their height and body mass measured. Prior to the CMJ assessment protocol, a 10 min standardized warm-up consisting of 5 min of jogging at 13 km·h<sup>-1</sup> on a motorised treadmill (LOKO S55, Woodway GmbH, Steinackerstraße, Germany) set at a 0° incline, followed by one practice of each CMJ. Participants performed three trials of each CMJ (with 60 seconds recovery between trials within a single CMJ type, and 180 s between jump types), thus performing a total of 21 CMJs (3 bilateral jumps and 9 unilateral jumps on each leg). During each CMJ, participants were instructed to keep their arms akimbo. Prior to each unilateral CMJ, participants were instructed to flex their alternate contralateral hanging leg to 90 degrees at the hip and knee joints

(Hewitt et al., 2012). Participants were instructed to jump as far as possible in the designated direction (for UV, UH and UM CMJs, participants were instructed to jump upwards, forwards or in the medial direction, respectively) landing on their jumping leg but allowing the contralateral limb to touch the ground to provide balance after the initial landing. A successful unilateral CMJ was registered if the participant performed the jump without allowing their knees to cross (i.e. the femur of the alternate hanging leg was not allowed to cross beyond parallel relative to the femur of the jumping leg). Unilateral CMJs in different directions have previously been shown to have acceptable test-retest reliability (Meylan et al., 2010). All CMJs were visually demonstrated to the participants by the investigator.

Vertical ground reaction force (VGRF), anterior-posterior ground reaction force (HGRF), and mediolateral ground reaction force (MGRF) data were collected using an in-ground 0.9×0.6 m<sup>2</sup> force platform (9287C, Kistler Instruments Ltd., Winterthur, Switzerland), at a sampling rate of 1000 Hz. Using procedures explained in detail elsewhere (Meylan et al., 2010), a custom-designed macro analysis programme (Vanrenterghem, De Clercq and Cleven, 2001) was used to calculate the jump performance variables. For all vertical CMJs, height, vertical take-off velocity, peak vertical power (V-power) and peak VGRF variables were calculated. For the UH CMJ, the resultant take-off velocity, peak VGRF, V-power, peak HGRF and peak horizontal-forward power (H-power) variables were calculated. For the UM CMJ, the resultant take-off velocity, peak VGRF, V-power, peak MGRF and peak medial power (M-power) variables were calculated. Unilateral horizontal-forward and UM CMJ projectile range (PR) were calculated using equations of constant acceleration (Grimshaw et al., 2004). This variable was used as the criterion performance measure for these jumps. To reduce statistical analysis to a meaningful data set and allow comparisons with other research, only performance variables measured in the superior jumping leg were analysed. The jump trial with the best performance

(greatest height or PR) was used for subsequent analysis. All kinetic variables were allometrically scaled to body mass ( $BM^{0.67}$ ) (Jaric, Mirkov and Markovic, 2005).

#### *4.2.3.2 Maximal isometric strength*

Knee extension (KE) and KF iMVCs were assessed on an isokinetic dynamometer (Biodex 3, Medical Systems, Shirley, NY, USA) and analysed using AcqKnowledge data acquisition software (Biopac Systems Inc., Goleta, CA, USA). All measurements were performed on the superior jumping leg only. Muscle activation during these contractions was used to normalize the EMG data during the jump assessment protocol. Participants sat on the rigid chair with their hip angle set to  $85^\circ$  (supine =  $180^\circ$ ) and strapped securely at the hip, chest and distal thigh with inextensible straps to minimise movement. The rotational axis of the dynamometer was aligned with the lateral femoral epicondyle of each participant by adjusting the seat height and length. The lever arm of the dynamometer was firmly secured to the lower leg (the bottom of the padded section was 2 cm above the lateral malleolus) and the knee angle was set to  $90^\circ$  via goniometry. Following a warm-up of 6 submaximal isometric KE and KF contractions, each participant was asked to perform a minimum of three KE iMVCs followed by three KF iMVCs. During all iMVCs, participants were given visual feedback on a projector screen that showed the force-time trace. Consistent verbal encouragement from the researchers was also given to the participant. If the highest iMVC attempt was  $\geq 5\%$  higher than the second highest attempt, the participant would perform further efforts until true iMVC was achieved. This was achieved within 2-3 attempts. Each iMVC lasted 2-3 s with a rest interval of 60 s between contractions. The highest KE and KF iMVCs were used for subsequent analysis.

#### 4.2.3.3 *Electromyography*

During all CMJ and iMVC assessments, surface EMG activity was recorded from the VL and BF muscles of the dominant lower limb using self-adhesive Ag/AgCl bipolar surface electrodes (10 ESP and 9 NSP participants; 2-cm inter-electrode distance, 1-cm circular conductive area; product 72000-S/25, Neuroline 720, Ambu, Denmark). The EMG signal was sampled simultaneously with ground reaction force data at a rate of 1000 Hz, and was transmitted in real time via a wired transmitter (Biopac TEL100M-C 4-CH Transmitter, Biopac Systems Inc., Goletta, USA); or via Motion Lab clinical EMG System with built in wired surface electrodes (13 ESP and 11 NSP participants; MA-300 EMG System, Motion Lab Systems, Inc., Los Angeles, USA). Electrodes were placed on the muscles of the superior jumping leg in accordance with SENIAM guidelines (Freriks et al., 1999) for application, location, and orientation. Reference electrodes were placed on the patella (Biopac Systems EMG transmitter) or on the cervical vertebra 7 (Motion Lab Clinical EMG Systems). To reduce skin impedance, the site of electrode placement was shaved, abraded with fine sandpaper and cleansed with alcohol wipes.

All original raw EMG signals were band-pass filtered (20-500 Hz), then digitally processed using a centred root mean square algorithm with a 50 ms time constant. The peak EMG signal amplitude measured over a 500 ms time epoch centred upon the peak force during the highest of the 3 KE and KF iMVC trials for each muscle was recorded. These data were used to normalize the EMG data during soccer specific assessments of power. For the CMJ assessments, the EMG signals were digitally processed using a centred root mean square algorithm with a 50 ms time constant. Muscle activity was reported as the peak EMG amplitude during the downward and upward phases. Peak amplitudes were normalized to each participant's peak RMS EMG value obtained during the iMVC trials and are reported as a percentage of the iMVC.



### **4.2.3 Statistics**

The mean and standard deviation (s) were calculated for all variables. All data was tested for normality using the Shapiro Wilks normality test. Main effects for CMJ type or muscle activation, and athlete status, and an interaction between the two, were investigated using two separate 2-way mixed ANOVAs [within factor: CMJ type (4 jumps) or muscle activation % iMVC (4 jumps); between factor: athlete status (2 groups)]. Post-hoc analysis was then performed using paired *t*-tests with Bonferroni-correction to determine differences between specific kinetic and temporal variables from different jumps, and muscle activation magnitudes between different jumps.

Multiple linear stepwise regression models were performed between respective jump performance measures (height or PR) and the kinetic and temporal variables. From these analyses, the best multiple predictor model of jump performance in each direction was derived. The forward stepwise linear regression model began with the most significant predictor and continued to add or delete variables until none significantly improved the fit.

To identify which CMJs may be used to distinguish between elite and non-elite athlete status, differences in the dependent variables that were not comparable between jump types (height, PR, H-power, M-power), were assessed using independent samples *t*-tests to assess the difference between the two groups only. Statistical analysis was completed using SPSS version 21 (SPSS Inc., Chicago, IL), and the significance level was set at  $p < 0.05$ .

## **4.3 RESULTS**

Comparisons of peak V-power among the four jumps revealed that there were significant differences between all CMJs (BV > UV > UH; BV > UM; UV > UM;  $p <$

0.001; Table 1) but not between UH and UM CMJ ( $p = 1.000$ ; Table 4.1). The resultant take-off velocity was significantly different ( $p < 0.001$ ; Table 4.1) between all CMJs (BV > UH > UM > UV).

Peak BF EMG was greater during the downward phase of the UH in comparison to BV ( $p < 0.001$ ; Table 4.1), UV ( $p < 0.001$ ; Table 4.1) and UM CMJ ( $p < 0.001$ ; Table 4.1). Similarly, UH CMJ produced significantly greater magnitudes of peak BF EMG during the upward phase in comparison to the BV ( $p < 0.001$ ; Table 4.1), UV ( $p = 0.001$ ; Table 4.1) and UM CMJ ( $p < 0.001$ ; Table 4.1). There were no differences in peak BF EMG or VL EMG between BV, UV and UM CMJ ( $p \geq 0.296$ ; Table 4.1).

**Table 4.1.** Between jump differences in kinetic, kinematic and peak electromyography (EMG) variables in soccer players (n=43); mean  $\pm$  SD.

	BV CMJ	UV CMJ	UH CMJ	UM CMJ
Peak V-power ( $W \cdot Kg^{-1}$ )	220.21 $\pm$ 30.1 <sup>bcd</sup>	144.15 $\pm$ 16.18 <sup>acd</sup>	86.73 $\pm$ 18.28 <sup>ab</sup>	85.48 $\pm$ 13.45 <sup>ab</sup>
Resultant take-off velocity ( $m \cdot s^{-1}$ )	2.666 $\pm$ 0.247 <sup>bcd</sup>	1.926 $\pm$ 0.152 <sup>acd</sup>	2.376 $\pm$ 0.447 <sup>abd</sup>	2.229 $\pm$ 0.431 <sup>abc</sup>
Downward phase duration (s)	0.588 $\pm$ 0.171	0.561 $\pm$ 0.156	0.585 $\pm$ 0.198	0.697 $\pm$ 0.306
Upward phase duration (s)	0.264 $\pm$ 0.031 <sup>c</sup>	0.321 $\pm$ 0.233	0.228 $\pm$ 0.042 <sup>ad</sup>	0.248 $\pm$ 0.048 <sup>c</sup>
Downward phase VL EMG (% iMVC)	114.27 $\pm$ 82.63	105.87 $\pm$ 56.78	121.85 $\pm$ 56.75	106.07 $\pm$ 53.08
Downward phase BF EMG (% iMVC)	44.91 $\pm$ 37.87 <sup>c</sup>	53.56 $\pm$ 28.64 <sup>c</sup>	120.96 $\pm$ 54.20 <sup>abd</sup>	48.94 $\pm$ 30.55 <sup>c</sup>
Upward phase VL EMG (% iMVC)	183.66 $\pm$ 97.23	192.95 $\pm$ 114.99	167.47 $\pm$ 79.15	163.26 $\pm$ 79.02
Upward phase BF EMG (% iMVC)	83.14 $\pm$ 40.66 <sup>c</sup>	89.37 $\pm$ 45.12 <sup>c</sup>	127.05 $\pm$ 60.02 <sup>abd</sup>	81.26 $\pm$ 56.00 <sup>c</sup>

Key: BF, biceps femoris; BV CMJ, bilateral vertical countermovement jump; EMG, electromyography; iMVC, isometric maximal voluntary contraction; UV CMJ, unilateral vertical countermovement jump; UH CMJ, unilateral horizontal-forward countermovement jump; UM CMJ, unilateral medial countermovement jump; VL, vastus lateralis.

*Post hoc bonferroni test:* <sup>a</sup> Significantly different to BV CMJ, <sup>b</sup> Significantly different to UV CMJ, <sup>c</sup> Significantly different to UH CMJ, <sup>d</sup> Significantly different to UM CMJ ( $p < 0.05$ ).

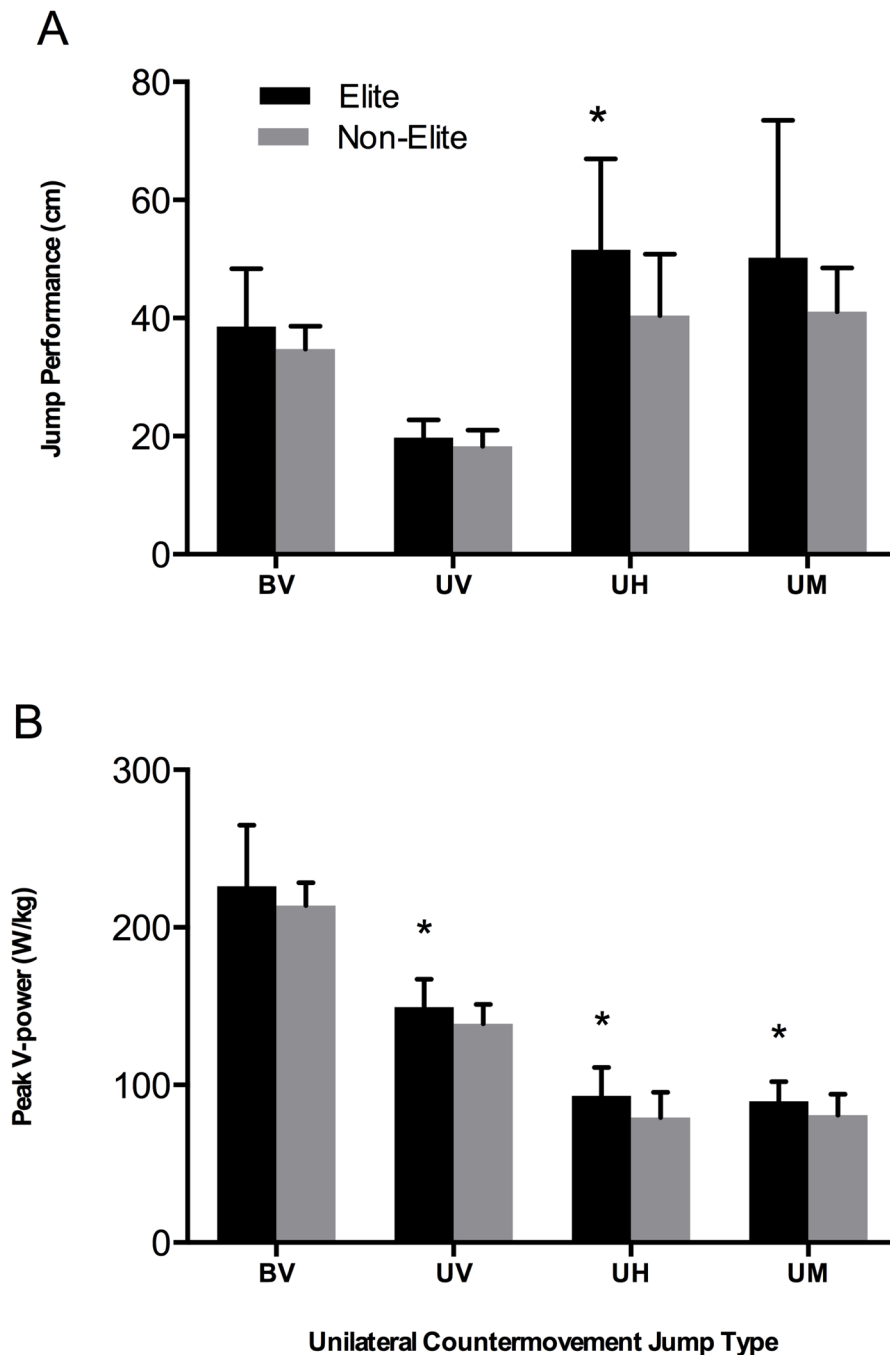
Predictive models for the four different CMJs are shown in Table 4.2. Peak power in the direction of the jump was the best single predictor of jump performance accounting for 61.4%, 64.8%, 54% and 56% of BV CMJ height, UV CMJ height, UH CMJ PR and UM CMJ PR, respectively.

**Table 4.2.** Significant kinetic and kinematic predictors of jump performance in elite (n=23) and non-elite (n=20) players; mean  $\pm$  SD.

Resultant GRF (N)	BV CMJ	UV CMJ	UH CMJ	UM CMJ
Predictor 1	Peak V-power	Peak V-power	Peak H-power	Peak M-power
Model significance	< 0.001	< 0.001	< 0.001	< 0.001
R <sup>2</sup>	0.641	0.648	0.540	0.560
Predictor 2	Duration upward phase	Peak VGRF	Peak V-power	Peak V-power
Model significance	< 0.001	< 0.001	< 0.001	< 0.001
R <sup>2</sup>	0.783	0.896	0.767	0.740
Change in R <sup>2</sup>	0.143	0.248	0.227	0.180
F Change significance	< 0.001	< 0.001	< 0.001	< 0.001
Predictor 3			Peak VGRF	Peak VGRF
Model significance			< 0.001	< 0.001
R <sup>2</sup>			0.901	0.859
Change in R <sup>2</sup>			0.134	0.119
F Change significance			< 0.001	< 0.001
Predictor 4				Duration upward phase
Model significance				0.001
R <sup>2</sup>				0.894
Change in R <sup>2</sup>				0.035
F Change significance				0.001
Predictor 5				Peak Rel. MGRF
Model significance				< 0.001
R <sup>2</sup>				0.907
Change in R <sup>2</sup>				0.013
F Change significance				0.029
Predictor 6				Duration upward phase
Model significance				< 0.001
R <sup>2</sup>				0.920
Change in R <sup>2</sup>				0.013
F Change significance				0.022

BV CMJ, bilateral vertical countermovement jump; UV CMJ, unilateral vertical countermovement jump; UH CMJ, unilateral horizontal countermovement jump; UM CMJ, unilateral medial countermovement jump; V-power, relative vertical power; HGRF, horizontal ground reaction force; H-power, relative horizontal power; MGRF, medial ground reaction force; M-power, relative medial power; VGRF, vertical ground reaction force.

Projectile range was significantly greater in ESP than NSP for UH CMJ ( $p < 0.001$ ; Figure 4.1) only. Peak V-power was significantly greater in ESP than NSP for



**Figure 4.1.** Bilateral vertical (BV) and unilateral vertical (UV) jump height, and unilateral horizontal (UH) and unilateral medial (UM) projectile range (A), and peak V-power (B) of elite (black bars;  $n = 23$ ) and non-elite (grey bars;  $n = 20$ ) soccer players during unilateral countermovement jumps in different directions. Data are mean  $\pm$  SD. \* $p < 0.05$ , \*\* $p < 0.01$ . Peak V-power, peak vertical power allometrically scaled to body mass.

all CMJs ( $p \leq 0.032$ ; Figure 4.1) except for BV ( $p = 0.197$ ; Figure 4.1), which did not show any significant differences in performance variables between ESP and NSP ( $p \geq 0.109$ , Figure 4.1).

#### **4.4 DISCUSSION**

The main aims of our study were to investigate differences in the kinetic, kinematic and EMG variables between unilateral CMJs in different directions, establish the best predictors of unilateral CMJ performance, and investigate differences in CMJ performance between ESP and NSP. This is the first study to report that unilateral CMJs require different BF activation magnitudes and muscular power capabilities, and that the best kinetic predictor of CMJ performance in soccer players is peak power in the direction of the jump. Moreover, BV CMJ performance was similar between ESP and NSP but unilateral jump performance in different directions was greater in ESP, thus demonstrating the potential value of this assessment in elite soccer talent identification and development.

It is important that any series of similar tests selected for elite athlete populations assesses separate physical capabilities and are therefore, able to provide the greatest information linked to performance in the shortest amount of time. In accordance with results in non-elite team sport athletes (Meylan et al., 2010), when peak V-power was compared during the four types of CMJs used in the current study, there were significant differences between CMJs with the exception of the UH and UM CMJ. Furthermore, UH and UM CMJs achieved a greater velocity at take-off than the UV CMJ. This may be because when the body is projected in the horizontal direction, the mechanical constraint of gravity opposing motion is lower than the load represented by body weight during a vertical jump (Samozino et al., 2014, Samozino et al., 2012). The current study is the first to show that UH, UM and UV CMJs assess

direction-specific capabilities in terms of vertical power and take-off velocity in soccer players.

When determining the specificity of different jump assessments, it is also useful to compare muscle activation profiles. Knowledge of muscle activation during unilateral CMJs in different directions can give an insight into the contribution of specific muscles to CMJ performance in each direction. The current results showed that UH CMJ required greater BF activation during the upward and downward phases in comparison to all other CMJs. These results are in line with findings from a previous study investigating horizontal-forward and vertical bilateral CMJs (Fukashiro et al., 2005), and also support previous reports of a greater magnitude of hip joint flexion and more vigorous use of the hip joint during horizontal-forward compared to vertical CMJs (Fukashiro et al., 2005, Nagano, Komura and Fukashiro, 2007). Furthermore, a similar upward phase peak VL activation during UV and UH CMJ is also in accordance with previous research comparing bilateral vertical and horizontal-forward CMJs (Fukashiro et al., 2005). Therefore, the current study is the first to show that the VL has a similar contribution to jump performance in all directions, but the BF plays a greater role in determining UH CMJ performance.

It is useful to establish which muscle groups contribute to jump performance in each direction, but knowledge of which kinetic and kinematic variables best predict unilateral CMJ performance in each direction would give an insight into the specific performance variables to monitor and train for improved unilateral CMJ performance (Meylan et al., 2010). The current study showed that peak V-power explained 61% and 65% of the variability in BV and UV CMJ height, respectively, which is in agreement with previous research (Dowling and Vamos, 1993, Markovic and Jaric, 2007, Meylan et al., 2010). Peak H-power and peak M-power were the best predictors for UH and UM CMJ PR, accounting for 54% and 56% of the shared variance, respectively. Subsequently, the practitioner should aim to assess and

improve peak power in the direction of the jump when monitoring and developing direction-specific jump performance.

Prior to assessing and prescribing training interventions for ESP, it is imperative to determine whether the capabilities assessed are characteristics of elite performance. There was no difference in BV CMJ height and BV CMJ peak V-power between ESP and NSP thus suggesting that this assessment may not be specific enough to differentiate between soccer playing status. Our data, which is in agreement with some (Cometti et al., 2001, Wisloff, Helgerud and Hoff, 1998) but not all previous research (Arnason et al., 2004), therefore questions the inclusion of the BV CMJ in the Premier League's Elite Player Performance Plan fitness testing regulations as an assessment of muscular power (Premier League, 2011). Peak V-power during the UV CMJ was significantly greater in ESP than NSP, thus suggesting that this variable is a determinant of elite soccer performance. Elite soccer players also performed significantly greater UH CMJ PR, UH CMJ peak V-power and UM CMJ peak V-power than NSP. Considering most of the powerful actions performed during elite youth soccer match-play were explosive accelerations directed in the horizontal-forward or mediolateral directions (please see Chapter three), these findings suggest that UH and UM CMJ are specific assessments for ESP. However, it should be noted that our research was performed in ESP recruited from only one EPL club and therefore, a sample size that includes ESP representing a variety of clubs may be needed to confirm these findings.

#### **4.5 CONCLUSION**

Unilateral CMJs assess direction-specific kinetic, kinematic and electromyographic components. The UH CMJ required greater resultant take-off velocity and hamstring activation than UV and UM CMJ. Peak power in the jump direction is the best predictor of unilateral CMJ performance in soccer players. In comparison to NSP,

ESP (performing regularly at U18 and U21 levels) performed better in UV, UH and UM but not in BV CMJ assessments. Thus, UV, UH and UM unilateral CMJs can be considered better indicators of elite soccer performance and should be included in U18 and U21 ESP power profiling assessments. We showed that unilateral CMJs in different directions assess independent leg power qualities, but it has not yet been investigated whether unilateral CMJ performance is underpinned by direction-specific physiological factors.



## **CHAPTER FIVE**

# **THE NEUROMUSCULAR DETERMINANTS OF UNILATERAL JUMP PERFORMANCE IN SOCCER PLAYERS ARE DIRECTION-SPECIFIC**

### STUDY 3: ABSTRACT

#### THE NEUROMUSCULAR DETERMINANTS OF UNILATERAL JUMP PERFORMANCE IN SOCCER PLAYERS ARE DIRECTION-SPECIFIC

**Purpose:** To investigate differences in neuromuscular factors between elite and non-elite players, and to establish which factors underpinned direction-specific unilateral countermovement jump (CMJ) performance. **Methods:** Elite (ESP,  $n=23$ ; age,  $18.1 \pm 1.0$  yrs; BMI,  $23.1 \pm 1.8$  kg/m<sup>2</sup>) and non-elite (NSP,  $n=20$ ; age,  $22.3 \pm 2.7$  yrs; BMI,  $23.8 \pm 1.8$  kg/m<sup>2</sup>) soccer players performed three unilateral vertical (UV), unilateral horizontal-forward (UH) and unilateral medial (UM) CMJs on a force plate. Isometric maximum voluntary contraction knee-extension (KE) torque (iMVT) was assessed using isokinetic dynamometry. Vastus lateralis (VL) fascicle length and angle of pennation (AoP), and quadriceps femoris muscle volume ( $V_m$ ) and physiological cross sectional area (PCSA) were assessed using ultrasonography. VL activation was assessed via EMG. **Results:** ESP presented greater KE iMVT ( $365.7 \pm 66.6$  vs.  $320.1 \pm 62.6$  N·m;  $P=0.045$ ),  $V_m$  ( $2852.5 \pm 507.5$  vs.  $2428.8 \pm 232.1$  cm<sup>3</sup>,  $P=0.001$ ) and PCSA ( $227.2 \pm 42.3$  vs.  $192.6 \pm 25.4$  cm<sup>2</sup>,  $P=0.003$ ) than NSP. In both cohorts, UV and UM CMJ performance correlated with  $V_m$  and PCSA ( $r \geq 0.310$ ,  $P \leq 0.043$ ). In ESP, UV and UM CMJ performance correlated with upward phase VL activation, and VL AoP ( $r \geq 0.478$ ,  $P \leq 0.028$ ). UH CMJ peak V-power did not correlate with any measure of muscle size or activation but correlated inversely with VL AoP ( $r = -0.413$ ;  $P = 0.037$ ). **Conclusions:** Whilst larger and stronger quadriceps differentiated elite from non-elite players, relations between neuromuscular factors and unilateral jump performance was shown to be direction-specific. These findings support a notion that improving direction-specific muscular power in soccer requires working towards a distinct neuromuscular profile.

**Keywords:** *horizontal power, medial power, physiological, volume, architecture.*

## 5.1 INTRODUCTION

Powerful efforts are performed frequently during elite soccer match-play (please see Chapter Three) and often determine the outcome of competitive games (Faude, Koch and Meyer, 2012). Elite soccer players out-performed NSP during maximal unilateral CMJs in the vertical, horizontal-forward and medial directions, thus suggesting unilateral CMJ capabilities may be determinants of elite soccer playing status (please see Chapter Four). An analysis of the kinetic, kinematic and electromyographic variables suggested that unilateral CMJs in different directions assess independent lower-limb power qualities in soccer players (please see Chapter Four). However, no attempt has been made to investigate the neuromuscular factors underpinning direction-specific (soccer-associated) CMJ performance. Such information could be used to inform the specific detail of elite soccer-associated power physiological assessment and performance development protocols.

Muscle volume ( $V_m$ ) is the product of fascicle length ( $L_f$ ) and muscle physiological cross-sectional area (PCSA) (Erskine et al., 2009). The PCSA represents the total area of all fibres within that muscle at right-angles to their long axes, and therefore the maximum force-generating capacity of that muscle (Close, 1972, Degens, Hoofd and Binkhorst, 1995). Muscle fascicle/fibre length, on the other hand, represents the total number of sarcomeres arranged in series and is a major determinant of muscle contraction velocity (Jones, Rutherford and Parker, 1989). Therefore, as power is the product of force x velocity, it follows that  $V_m$  should be a major determinant in maximum muscle power. Indeed, quadriceps femoris  $V_m$  has been shown to be strongly related to mean power produced during bilateral vertical countermovement jumps (BV CMJs) in adults and children (O'Brien et al., 2009a), and moderately related in male children alone ( $r^2 = 0.3$ ) (Temfemo et al., 2009). Nonetheless, BV CMJ performance is not a determinant of elite soccer performance;

instead, unilateral CMJ performance in different directions has been shown to discern ESP from NSP (please see Chapter Four). However, the contribution of  $V_m$ , and its individual components (PCSA and  $L_f$ ), to unilateral CMJ performance in different directions remains unknown.

In addition to  $L_f$ , the angle at which the fascicles insert into the aponeurosis, known as the fascicle pennation angle ( $\theta_p$ ), is also thought to influence maximal power. The  $\theta_p$  is determined by the fibre CSA (the larger the CSA, the greater the  $\theta_p$ ) (Alexander and Vernon, 1975, Degens, Erskine and Morse, 2009). Thus, a greater  $\theta_p$  should lead to an increase in force output, although there is a concomitant reduction in the force resolved at the tendon due to the oblique line of pull of the fascicles (Alexander and Vernon, 1975, Degens, Erskine and Morse, 2009). Furthermore,  $\theta_p$  correlates inversely with the rate of force development (Erskine, Fletcher and Folland, 2014) and has a negative influence on muscle contractile velocity (Degens, Erskine and Morse, 2009, Spector et al., 1980). However, the contribution of  $\theta_p$  to sport-specific actions such as unilateral CMJs in different directions, remains unknown.

Maximal muscular power is not only determined by muscle architecture and size, but also by the ability to recruit motor units and activate all of the fibres in the specific muscles involved in the movement (Cormie, McGuigan and Newton, 2011). Whilst it has been established that unilateral (please see Chapter Four) and bilateral CMJs in different directions require different muscle activation strategies (Fukashiro et al., 2005, Nagano, Komura and Fukashiro, 2007), the role of muscle activation in determining direction-specific unilateral jump performance is not known.

Given the sparse literature in this area, information on the importance of muscle strength, and the neuromuscular determinants underpinning direction-specific unilateral jump performance could impact on soccer talent identification and development programmes. Subsequently, the aims of our study were to: (1)

investigate the differences in muscle size, architecture, activation and isometric strength (maximal and explosive) between ESP and NSP soccer players; and (2) determine the contribution of muscle size, architecture and activation to unilateral CMJ performance in different directions in ESP and NSP.

## **5.2 METHODS**

### **5.2.1 Participants**

Forty-three male soccer players volunteered to take part in this study, which was approved by Liverpool John Moores University Ethics Committee and complied with the Declaration of Helsinki. Participants provided written informed consent prior to being assigned to two groups according to their level of competition. The ESP group (n = 23, mean  $\pm$  SD: age  $18.1 \pm 1.0$  years; height  $182.5 \pm 7.3$  cm; weight  $77.2 \pm 10.1$  kg) included one goalkeeper, nine defenders, five midfielders and eight forwards from an EPL football academy, who regularly participated at U18 and U21 level. The NSP group (n = 20, mean  $\pm$  SD: age  $22.3 \pm 2.7$  years; height  $175.0 \pm 5.8$  cm; weight  $72.9 \pm 7.3$  kg) included one goalkeeper, five defenders, six midfielders and eight forwards, who participated in at least one hour per week of competitive soccer (11-a-side or five-a-side), and one hour per week of soccer specific or fitness based training. Non-elite participants were excluded if they did not meet these inclusion criteria or had previously played soccer at academy, semi-professional, or professional level. Participants were fully familiarised with all testing procedures in a separate session and were asked to complete an activity and health questionnaire prior to the study for screening purposes.

### **5.2.2 Experimental Design**

All participants attended the laboratory on two separate occasions with at least 72 hours between each session. The first session enabled the participants to be

familiarised with the assessment protocol, which consisted of three unilateral CMJs in the vertical, horizontal-forward and medial directions on each leg, three KE and KF iMVCs, five explosive isometric KE contractions and two knee extensor ramp maximum voluntary contractions (RMVCs). This session was also used to determine the superior jumping leg [defined as the limb that produced the highest ground reaction force during a UV CMJ]. During the second session, participants performed all CMJs, KE and KF iMVCs, KE isometric explosive force assessments, and measurements of vastus lateralis (VL) muscle architecture and QF muscle anatomical cross sectional area (ACSA). Electromyographic (EMG) activity in the VL and biceps femoris (BF) was measured throughout the jump and strength assessments. In order to minimise the influence of previous activity, the testing was performed at least 48 h following any high intensity multi-directional exercise which included any form of soccer match-play activity.

### **5.2.3 Data acquisition and analysis procedures**

#### *5.2.3.1 Countermovement jumps.*

Please see section 4.2.3.1 for the detail of the unilateral countermovement jump assessments procedure.

#### *5.2.3.2 Maximal and explosive isometric strength*

Knee extension and KF iMVCs were assessed on an isokinetic dynamometer (Biodex 3, Medical Systems, Shirley, NY, USA) and analysed using AcqKnowledge data acquisition software (Biopac Systems Inc., Goleta, CA, USA). For details of the procedures please see section 4.2.3.2.

Following the iMVCs, participants were asked to perform ten isometric explosive knee extension contractions, each separated by a 20 s rest interval. This method has been explained in detail elsewhere (Erskine, Fletcher and Folland, 2014,

Tillin et al., 2010). Briefly, during each contraction, participants were instructed to extend their knee as 'fast and hard' as possible from a relaxed state for <1 s, while avoiding a countermovement and achieving ~80% quadriceps iMVFs. The three contractions with the greatest peak rate of force development (RFD) were chosen for further analysis which consisted of measuring force output at 50, 100 and 150 ms after force onset, in addition to RFD from 0-50 ms, 50-100 ms, and 100-150 ms after force onset. The mean explosive force and RFD values from the three contractions were used for subsequent analysis. The muscle strength measures were analysed by two raters and the inter-rater reliability for this measure was high [Coefficient of variation (CV) = 2.76%; intraclass correlation coefficient (ICC) = 0.993]. The peak torque values produced during the KE explosive iMVCs were converted to force values by dividing iMVC torque by the patellar tendon moment arm (0.048 m) previously reported for healthy young men at this joint angle (Erskine et al., 2009). Following guidelines proposed by Tillin and colleagues (2013), the explosive iMVCs were analysed using the manual (visual) identification of force onsets. Initially, force signal recordings were viewed on a consistent y-axis scale of ~1 N and an x-axis scale of 500 ms. The pattern of noise in the force signal could be established using these scales. The last peak/trough before the force signal deflected away from the baseline noise was identified and a vertical cursor was placed on the force onset. The force signal was then viewed with a higher resolution (y-axis scale of ~0.5 N and x-axis scale of 25 ms) to verify that the vertical cursor was on the apex of the peak/trough. If required, the cursor was moved accordingly to represent the instant of force onset. The manual identification of force onset is considered the 'gold standard' for identifying force onsets during explosive contractions and has been widely used to validate automated detection methods (Allison, 2003, Pain and Hibbs, 2007, Soda et al., 2010). When analysing multiple noisy surrogate data sets where, the actual force onset was known, this manual identification method was previously reported to

be more accurate (errors of 0 - 9 ms) than automated detection methods (errors of 21 - 90 ms) (Pain, 2003). Subsequent research supports these findings, showing that manual identification methods are considerably more accurate than automated systems for determining force onsets, and detect force and torque onsets 25 (Pain and Hibbs, 2007) to 330 (Soda et al., 2010) ms earlier. The inter-day reliability typical error of measurement for determining force onset time during explosive isometric contractions using these manual force identification methods has previously been reported to be 0.9 ms (Tillin et al., 2010). Moreover, Tillin and colleagues (2013) also documented in their letter to the editor of the *Journal of Electromyography and Kinesiology* that their unpublished research investigating the reliability of the manual force onset detection method during explosive isometric contractions showed that when the same force signal was measured on separate occasions by the same investigator (intra-investigator reliability), and by separate investigators (inter-investigator reliability), the typical error of measurement in the time at which force onset was detected, was 0.97 ms (intra-investigator reliability) and 1.23 ms (inter-investigator reliability), respectively. Considering the error associated with automated systems of force onset detection were  $\geq 25$  ms (Hannah et al., 2012), the manual force onset detection methods used in our study appears to provide the most accurate and reliable method of measuring explosive isometric force production (Tillin, Pain and Folland, 2013).

#### *5.2.3.3 Muscle Volume*

All muscle morphological measurements were conducted with the participant in the seated position (knee joint angle 90° knee flexion). Quadriceps femoris ACSA was measured in the superior jumping leg using methods adapted from Reeves et al. (2004). With the participant in a relaxed position, B-mode ultrasonography (MyLab 30 CV, Esaote Biomedica, Genoa, Italy) was used to locate the distal (lateral femoral



condyle) and proximal (base of greater trochanter) ends of the femur, with the distance between both points providing the femur length. At 40% of femur length, several 2 mm strips of ultrasound-absorbent tape (3M, Neuss, Germany) were placed in axial sections as external reference markers every 3-4 cm. With the 40 mm wide (10- to -15 MHz) linear transducer aligned perpendicular to the VL muscle and oriented in the axial-plane, a single ultrasound movie was taken from the lateral to medial boundaries of the QF. Using the external reference markers as guides, individual frames were exported using freeware video editing software (Windows Movie Maker, Microsoft, Seattle, WA, USA). The individual frames were then realigned using photo-editing software (Photoshop CS5, Adobe Systems Software, San Jose, CA, USA) to reconstruct the QF ACSA (taking care to align the external markers and anatomical reference points between frames) (Reeves, Maganaris and Narici, 2004). Subsequently, the four constituent muscles of the QF were outlined and the individual ACSAs measured using digitizing software (NIH ImageJ, version 1.39b, National Institutes of Health, Bethesda, USA). This method of measuring QF ACSA has previously been shown have sufficient validity when compared to magnetic resonance imaging (MRI) based measurements [intraclass correlation coefficient (ICC) = 0.999]. Moreover, these ultrasound techniques for measuring QF ACSA have previously been shown to demonstrate good inter-day (ICC = 0.998) and inter-rater (coefficient of variation = 2.1%) reliability (Reeves, Maganaris and Narici, 2004).

Using the femur length, QF ACSA at 40% femur length, and a series of regression equations detailed elsewhere (Morse, Degens and Jones, 2007), the volume ( $V_m$ ) of the QF was calculated (Erskine et al., 2009). As this technique has previously been shown to consistently underestimate QF  $V_m$  by 551 cm<sup>3</sup> in young males (Morse, Degens and Jones, 2007), 551 cm<sup>3</sup> was added to the measured QF  $V_m$  of each participant to provide a more accurate estimation (Erskine et al., 2009).

This method has previously been shown to be highly correlated (ICC = 0.84) to gold standard measurements of muscle volume (calculated from eleven magnetic resonance imaging scans at different lengths along the femur) and demonstrated a low level of error (standard error of estimate =  $28.6 \pm 5.2$  %) (Morse, Degens and Jones, 2007). Moreover, these ultrasound techniques for measuring QF  $V_m$  have also previously been shown to demonstrate good inter-day test-retest reliability (CV = 1.73%, ICC = 0.99) (Erskine et al., 2009). Relative QF  $V_m$  was also calculated by dividing  $V_m$  by femur length.

#### 5.2.3.4 Muscle architecture

Vastus lateralis muscle architecture was measured at rest using ultrasonography. The origin and insertion of the VL, and the lateral and medial boundaries at the mid-point of the VL were identified, and the centre of the muscle was marked with a permanent marker pen. This location was used for all architectural measures. Ultrasound-absorbent tape was placed at the centre point of the muscle and 3 cm either side. With the transducer positioned in the sagittal plane, a single movie was taken with the probe being moved from the proximal to the distal tape markings in line with the direction of the muscle fascicles. Individual frames were extracted from the movie and fitted together for analysis using the same method as used for the ACSA analysis detailed above. Muscle thickness,  $L_f$ , and  $\theta_p$  were measured using digitizing software (NIH ImageJ, version 1.39b, National Institutes of Health, Bethesda, USA). Three measurements of each architectural variable were recorded in each image, with the mean of these measurements used to provide the muscle thickness,  $L_f$  and  $\theta_p$  values used for subsequent analyses. To account for skeletal-dependent inter-individual variability in  $L_f$  was also normalised to femur length and referred to as relative fascicle length. The accuracy of ultrasound techniques for measuring muscle architecture has previously been documented by comparing with

those obtained by direct dissection of human cadavers. When compared with direct measurements, the ultrasound methods showed a mean typical error of 0.09-0.14 cm for muscle thickness, 1.01-1.31° for  $\theta_p$ , and 0.92-1.71 cm for  $L_f$ ; while the ICC between the two methods ranged from 0.905 to 0.913. This research therefore suggests that ultrasound is a valid alternative tool for measuring basic architectural parameters (Kellis et al., 2009). Ultrasound techniques for measuring VL architecture have also previously been shown to demonstrate good inter-day test-retest reliability for both  $\theta_p$  (CV = 5.1%, ICC = 0.86) and  $L_f$  (CV = 3.5%, ICC = 0.92) (Erskine et al., 2009).

#### *5.2.3.5 Physiological cross sectional area*

The PCSA of the QF was calculated by dividing QF volume by VL  $L_f$  (Erskine et al., 2009). The inter-day test-retest reliability of such ultrasound techniques for measuring PCSA has previously been shown to be good (CV = 5.0%, ICC = 0.90) (Erskine et al., 2009).

#### *5.2.3.6 Electromyography*

During all CMJ and iMVC assessments, surface EMG activity was recorded from the VL and BF muscles of the superior jumping lower limb using self-adhesive Ag/AgCl bipolar surface electrodes (2-cm inter-electrode distance, 1-cm circular conductive area; product 72000-S/25, Neuroline 720, Ambu, Denmark). The EMG signal was sampled simultaneously with ground reaction force data at a rate of 1000 Hz, and was transmitted in real time via a wired transmitter (10 ESP and 9 NSP participants; Biopac TEL100M-C 4-CH Transmitter, Biopac Systems Inc., Goletta, USA); or via Motion Lab clinical EMG System with built in wired surface electrodes (13 ESP and 11 NSP participants; MA-300 EMG System, Motion Lab Systems, Inc., Los Angeles, USA). Electrodes were placed on the muscles of the superior jumping leg in

accordance with SENIAM guidelines for application, location, and orientation. Reference electrodes were placed on the patella (Biopac Systems EMG transmitter) or on the cervical vertebra 7 (Motion Lab Clinical EMG Systems). To reduce skin impedance, the site of electrode placement was shaved, abraded with fine sandpaper and cleansed with alcohol wipes.

All original raw EMG signals were band-pass filtered at [20-500 Hz according to SENIAM Guidelines (Freriks et al., 1999)], then digitally processed using a centred root mean square algorithm with a 50 ms time constant. The peak and average EMG signal amplitude measured over a 500 ms time epoch centred upon the peak force during the highest of the 3 KE and KF iMVC trials for each muscle was recorded. These data were used to normalize the EMG data during unilateral jump assessments of muscular power. For the jumping assessments, the EMG signals were digitally processed using a centred root mean square algorithm with a 50 ms time constant. Muscle activity was reported as the peak and average EMG amplitude during the downward and upward phases. EMG amplitudes were normalized to each participant's corresponding peak and average RMS EMG values obtained during the iMVC trials and are reported as a percentage of the iMVC. A minimal EMG signal to noise threshold ratio of 3:1 mV was applied and, subsequently, four players EMG data was not included in the final analyses. Surface EMG measurements during single leg jump and landing tasks have previously been shown to demonstrate acceptable inter-day reliability (ICCs: VL = 0.92; BF = 0.94) (Cavanaugh, Aboodarda and Behm, 2016).

#### *5.2.3.7 Antagonist muscle co-activation*

To determine the extent of antagonist muscle co-activation during the leg extension iMVC, the average RMS EMG activity of the BF muscle over a 500 ms epoch around peak torque was recorded during KE and KF iMVC. The ratio of antagonist co-

activation during the KE iMVC was recorded as a percentage of the average RMS EMG activity of the BF during maximal knee flexion contraction.

#### *5.2.3.8 Maximum KE muscle isometric torque (KE iMVT)*

The torque produced by the hamstring muscle group during KE iMVC was estimated, assuming a linear relationship between torque and EMG activity (Erskine et al., 2009). Overall KE iMVT was calculated by the addition of the estimated antagonist torque during KE to the actual torque produced during the KE iMVC (Erskine et al., 2009, Seynnes et al., 2009).

#### *5.2.3.9 QF muscle specific force*

As the force transmitted from the QF muscle fibres to the tendon is reduced according to  $\theta_p$ , a reduced PCSA of the QF was determined by multiplying the PCSA by the cosine of the resting VL  $\theta_p$ , where VL  $\theta_p$  was representative of the mean QF  $\theta_p$  (Erskine et al., 2009). Subsequently, dividing KE iMVT by the patellar tendon moment arm (0.048 m) previously reported for healthy young men provided maximum isometric KE force (KE iMVF). QF specific force was calculated as iMVF divided by the reduced PCSA (Erskine et al., 2009).

### **5.2.4 Statistical analyses**

The mean and standard deviation (s) were calculated for all variables. All data were tested for normality using the Shapiro Wilks normality test. For variables measured at three different time points during explosive isometric contractions (peak force, RFD, RFD relative to iMVF), the influence of time and group was analysed with a mixed repeated measures ANOVA (two groups x number of repeated measures). All other dependent variables were assessed using an independent samples *t*-test. Pearson's correlations were used to determine relations between jump performance variables

(height or PR, peak V-power, peak H-power or peak M-power) and muscle size, morphology and activation. Statistical analysis was completed using SPSS version 14 (SPSS Inc., Chicago, IL), and the significance level was set at  $P \leq 0.05$ .

## 5.4 RESULTS

### 5.4.1 Differences between elite and non-elite soccer players

#### 5.4.1.1 Muscle Strength

Elite and NSP produced similar magnitudes of absolute maximal isometric torque during KE (ESP:  $317.1 \pm 71.3$  N·m; NSP:  $303.9 \pm 64.0$  N·m;  $P = 0.531$ ) and KF ( $P = 0.627$ ) contractions (Table 5.1). Although there was no significant difference in antagonist muscle co-activation between groups during the KE iMVC ( $P = 0.411$ ; Table 5.1), when antagonist muscle co-activation was accounted for, ESP produced significantly greater KE iMVT ( $P = 0.045$ ; Table 5.1). Elite and NSP had similar QF muscle specific force ( $P = 0.912$ ; Table 5.1), absolute ( $P \geq 0.312$ ; Table 5.1) and normalised ( $P \geq 0.423$ ; Table 1) isometric explosive rate of force development (RFD) capabilities in the first 150 ms of the contraction. Moreover, there was no difference between groups in peak RFD ( $P = 0.113$ ; Table 5.1) or time to peak RFD ( $P = 0.453$ ; Table 5.1).

#### 5.4.1.2 Muscle size and architecture

Elite players had greater QF  $V_m$  ( $P = 0.001$ ), relative QF  $V_m$  ( $P = 0.008$ ) and PCSA ( $P = 0.003$ ) than NSP (Table 5.2). However, there was no significant difference in VL muscle architecture ( $\theta_p$ :  $P = 0.724$ ,  $L_f$ :  $P = 0.906$ ; muscle thickness:  $P = 0.698$ ; Table 5.2) between the two groups.

**Table 5.1.** Measured and calculated isometric contraction variables in elite (n = 23) and non-elite (n = 20) players; mean  $\pm$  SD.

Variable	Elite	Non-elite
KE iMVT (N·m)	365.7 $\pm$ 66.6*	320.1 $\pm$ 62.6
KF iMVT (N·m)	121.2 $\pm$ 39.5	116.3 $\pm$ 22.1
Co-activation (%)	27.9 $\pm$ 13.5	23.7 $\pm$ 15.6
Specific force (N · cm <sup>-2</sup> )	36.8 $\pm$ 7.3	36.5 $\pm$ 8.7
Peak RFD (N·s <sup>-1</sup> )	48284 $\pm$ 11689	43045 $\pm$ 9110
Time to peak RFD (ms)	72 $\pm$ 16	68 $\pm$ 16
RFD 0-50 ms (N·s <sup>-1</sup> )	14812 $\pm$ 10113	13666 $\pm$ 6239
RFD 50-100 ms (N·s <sup>-1</sup> )	30226 $\pm$ 9486	28554 $\pm$ 7694
RFD 100-150 ms (N·s <sup>-1</sup> )	22394 $\pm$ 7343	20325 $\pm$ 5644
nRFD 0-50 ms (% MVF·s <sup>-1</sup> )	2.236 $\pm$ 1.582	2.286 $\pm$ 1.176
nRFD 50-100 ms (% MVF·s <sup>-1</sup> )	4.622 $\pm$ 1.148	4.590 $\pm$ 1.195
nRFD 100-150 ms (% MVF·s <sup>-1</sup> )	3.374 $\pm$ 0.608	3.212 $\pm$ 0.659

Key: KE, knee extensor; iMVT, isometric maximal voluntary torque; RFD, rate of force development; nRFD, rate of force development normalised to maximum voluntary force (MVF).

\* Elite significantly greater than non-elite ( $P < 0.05$ )

#### 5.4.1.3 Voluntary Muscle activation

There was a non-significant tendency for ESP to elicit greater peak VL activation during the downward phase of UH CMJ ( $P = 0.056$ ; Table 5.3). Similarly, there was a non-significant tendency for ESP to elicit greater peak VL activation during the upward phase of the UV CMJ ( $P = 0.060$ ; Table 5.3). Peak BF activation was not different between ESP and NSP during any jumping task ( $P > 0.050$ ; Table 5.3).

**Table 5.2.** Quadriceps femoris (QF) muscle morphology and architecture in elite (n=23) and non-elite (n=20) players; mean  $\pm$  SD.

Muscle variable	Elite	Non-Elite
QF $V_m$ (cm <sup>3</sup> )	2852.5 $\pm$ 507.5**	2428.8 $\pm$ 232.1
Relative QF $V_m$ (cm <sup>3</sup> /cm)	61.06 $\pm$ 9.45*	54.67 $\pm$ 4.06
QF PCSA (cm <sup>2</sup> )	227.16 $\pm$ 42.31*	192.57 $\pm$ 25.42
QF ACSA (cm <sup>2</sup> )	80.85 $\pm$ 15.84*	69.80 $\pm$ 6.72
VL Muscle Thickness (mm <sup>2</sup> )	26.41 $\pm$ 2.93	26.06 $\pm$ 3.25
VL $\theta_p$ (°)	14.88 $\pm$ 2.23	14.65 $\pm$ 2.04
VL $L_f$ (mm)	127.20 $\pm$ 18.11	127.84 $\pm$ 17.43
Relative VL $L_f$ (mm/cm)	2.73 $\pm$ 0.40	2.88 $\pm$ 0.37

Key:  $V_m$ , muscle volume; PCSA, physiological cross-sectional area; ACSA, anatomical cross-sectional area; VL, vastus lateralis muscle;  $\theta_p$ , angle of pennation;  $L_f$ , fascicle length.

\* Significantly greater than non-elite ( $P < 0.01$ )

\*\* Significantly greater than non-elite ( $P \leq 0.001$ )

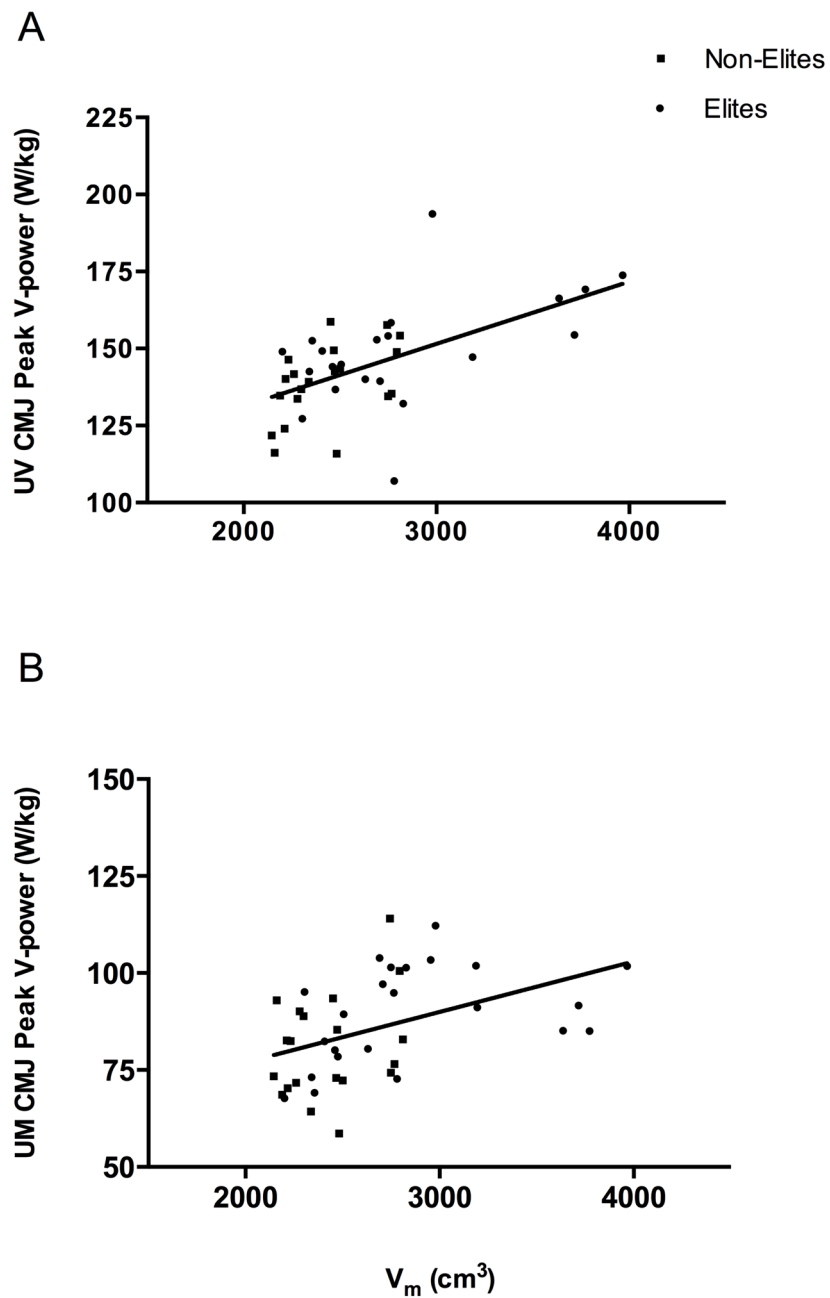
## 5.4.2 The neuromuscular factors contributing to unilateral direction-specific jump performance

### 5.4.2.1 Both groups

UV CMJ height did not correlate significantly with any measure of QF muscle size or VL architecture ( $r \leq 0.290$ ;  $P \geq 0.066$ ). However, UV CMJ peak V-power correlated significantly with QF  $V_m$  (Fig. 5.1A), relative QF  $V_m$  ( $r = 0.539$ ,  $P < 0.001$ ), QF PCSA ( $r = 0.524$ ,  $P < 0.001$ ) and VL muscle thickness ( $r = 0.323$ ,  $P = 0.039$ ). No performance measure of UH CMJ ( $P \geq 0.066$ ), or UM CMJ PR ( $P \geq 0.078$ ), or UM CMJ H-power ( $P \geq 0.429$ ) correlated with any measure of QF muscle size or VL



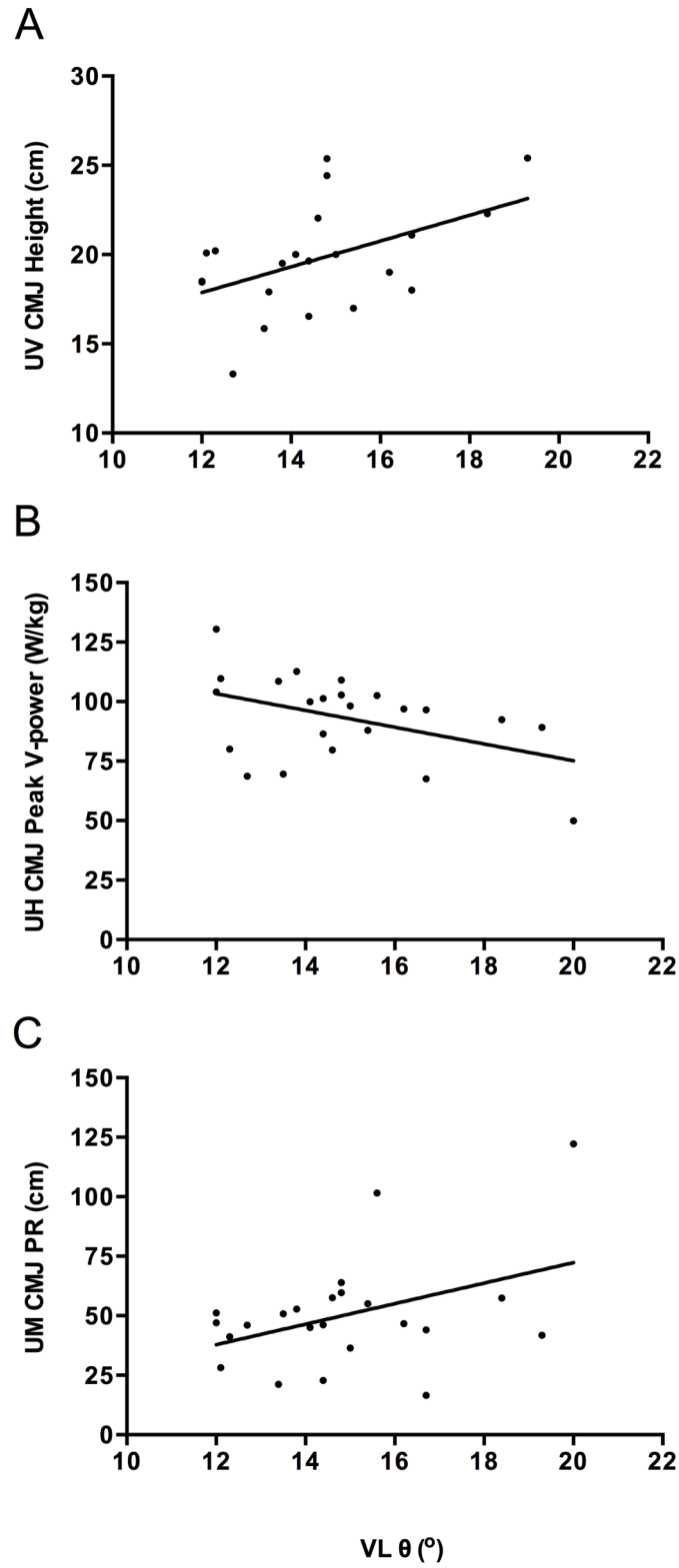
architecture when data from both cohorts were analysed together ( $P \geq 0.066$ ). However, UM CMJ peak V-power correlated significantly with QF  $V_m$  (Fig. 5.1B), relative QF  $V_m$  ( $r = 0.389$ ,  $P = 0.01$ ), QF PCSA ( $r = 0.310$ ,  $P = 0.043$ ) and mean VL activation in the upward phase ( $r = 0.346$ ,  $P = 0.039$ ). No other performance variable in any other jumping task correlated significantly with any muscle activation measurement ( $P > 0.050$ ).



**Figure 5.1.** The relationships between: unilateral vertical (UV) countermovement jump (CMJ) peak V-power and quadriceps femoris (QF) muscle volume ( $V_m$ ) (a;  $r = 0.566$ ,  $P < 0.001$ ); unilateral medial (UM) CMJ peak V-power and QF  $V_m$  (b;  $r = 0.438$ ,  $P = 0.003$ ) in elite ( $n = 23$ ) and non-elite ( $n = 20$ ) players. peak V-power, peak vertical power allometrically scaled to body mass.

#### 5.4.2.2 Elite Group Only

UV CMJ peak V-power correlated significantly with PCSA ( $r = 0.550$ ,  $P = 0.010$ ), QF  $V_m$  ( $r = 0.508$ ,  $P = 0.019$ ) and relative QF  $V_m$  ( $r = 0.500$ ,  $P = 0.021$ ); and UV CMJ height correlated significantly with mean upward phase VL activation ( $r = 0.498$ ,  $P = 0.042$ ) and VL  $\theta_p$  ( $r = 0.478$ ,  $P = 0.028$ ; Fig. 5.2A). However, UH CMJ PR did not correlate with any measure of muscle size, architecture or activation ( $P > 0.050$ ), although UH CMJ peak V-power correlated inversely with VL  $\theta_p$  ( $r = -0.437$ ,  $P = 0.037$ ; Fig. 5.2B). In contrast, UM CMJ PR correlated significantly with VL  $\theta_p$  ( $r = 0.413$ ,  $P = 0.050$ ; Fig. 5.2C), but no other measure of muscle size, activation or architecture ( $P > 0.050$ ). UM CMJ peak V-power correlated significantly with mean VL activation in the upward phase ( $r = 0.471$ ,  $P = 0.042$ ), but not with any measure of muscle size or architecture ( $P > 0.050$ ).



**Figure 5.2.** The relationships between vastus lateralis (VL) pennation angle ( $\theta_p$ ) and: unilateral vertical (UV) countermovement jump (CMJ) height (a;  $r = 0.478$ ,  $P = 0.028$ ); unilateral horizontal (UH) CMJ peak V-power (b;  $r = -0.437$ ,  $P = 0.037$ ); unilateral medial (UM) CMJ projectile range (PR) (c;  $r = 0.413$ ,  $P = 0.050$ ) in elite players ( $n = 23$ ). Peak V-power, peak vertical power allometrically scaled to body mass.

#### 5.4.2.3 Non-elite Group Only

UV CMJ height did not correlate with any measure of muscle size, architecture or activation ( $P > 0.050$ ). However, UV CMJ peak V-power correlated with QF  $V_m$  ( $r = 0.492$ ,  $P = 0.028$ ). UH CMJ PR did not correlate with any measure of muscle size, architecture or activation ( $P > 0.050$ ); however, UH CMJ peak V-power correlated significantly with relative VL  $L_f$  ( $r = 0.482$ ,  $P = 0.031$ ). UM CMJ PR did not correlate with any measure of muscle size, architecture or activation ( $P > 0.050$ ), but UM CMJ peak V-power correlated inversely with mean VL activation in the downward phase ( $r = -0.532$ ,  $P = 0.034$ ).

## 5.5 DISCUSSION

The aims of our study were to investigate the differences in neuromuscular characteristics between ESP and NSP, and determine which neuromuscular factors contributed to unilateral CMJ performance in different directions. We have shown for the first time that ESP presented with greater peak isometric QF iMVT, QF  $V_m$  (absolute and relative to femur length), and QF PCSA than NSP. Correlations between jump performance variables and neuromuscular factors in both cohorts revealed that absolute and relative QF  $V_m$ , and PCSA contribute to UV CMJ and UM CMJ, but not UH CMJ performance. In ESP only, VL  $\theta_p$  correlated positively with UV CMJ and UM CMJ, but correlated inversely with UH CMJ performance. Moreover, upward VL activation correlated only with UV CMJ height and UM CMJ peak V-power in ESP. Our data suggests that QF size ( $V_m$  and PCSA) and maximal isometric force can therefore be considered characteristics of elite soccer playing status. Having established in Chapter Four that unilateral CMJs in different directions assess separate muscular power qualities, our current data builds on these findings by documenting that the neuromuscular factors underpinning unilateral CMJ

performance are direction-specific. This information suggests that assessment protocols and training interventions for improving maximal power in ESP should be direction-specific targeting a separate combination of neuromuscular factors to assess/develop UV and UM, in comparison to UH CMJ performance.

It is imperative that physiological assessment protocols for ESP evaluate characteristics considered important for high-level soccer performance. If the presentation of performance or physiological factors differ between ESP and NSP, these characteristics may be considered important for performance at the elite level (Cometti et al., 2001, Wisloff, Helgerud and Hoff, 1998). Within this context, ESP presented with greater QF iMVT but similar KF iMVT and KE isometric explosive force capabilities, compared to NSP. Previous research has shown differences between elite and amateur players in KF isokinetic strength (Cometti et al., 2001) but the current results are the first to suggest that QF isometric strength may be an indicator of elite soccer playing status. Interestingly, despite frequent performance of explosive actions during elite soccer match-play (Faude, Koch and Meyer, 2012), our data also suggest that the ability to produce force in the first 150 ms of an isometric explosive contraction is not a determinant of soccer playing status. As the level of neural activation at the onset of explosive contractions is thought to determine RFD capabilities (De Ruyter et al., 2004, De Ruyter et al., 2006, Tillin et al., 2010), it appears that ESP do not have a greater ability to achieve higher levels of neural drive at the onset of explosive contractions than NSPs. However, more compliant patellar tendons have previously been associated with greater sprint performance (Kubo et al., 2000b, Stafilidis and Arampatzis, 2007) but have also been shown to increase electromechanical delay (the time delay between the onset of electrical activity at the muscle and the generation of force (Winter and Brookes, 1991a)) and therefore, reduce isometric rate of force development capabilities during the early stages of an explosive contraction (Kubo et al., 2001). Subsequently, considering the

link with tendon compliance and sprint performance (Kubo et al., 2000b, Stafilidis and Arampatzis, 2007), it may be that soccer players have more compliant patellar tendons but also have greater neural activation at the onset of explosive contractions compared to NSP, with the trade-off between these two physiological factors resulting in similar isometric RFD capabilities between the two groups. However, the tendon properties in elite soccer players have never been investigated and such theories remain speculative. We do show for the first time that ESP have greater QF isometric peak force capacity than NSP.

As the maximum force-generating capacity of the muscle is primarily determined by the total area of all fibres within that muscle at right-angles to their long axes (Close, 1972, Degens, Hoofd and Binkhorst, 1995), it is unsurprising that the ESP in our study presented with significantly QF PCSA than NSP. While ESP also displayed greater absolute and relative QF  $V_m$  than NSP, there was no difference in muscle architecture (VL  $\theta_p$ ,  $L_f$  and muscle thickness). Similarly, muscle specific force (maximum force per unit PCSA) was not different between groups, thus suggesting that muscle quality is similar between ESP and NSP. Elite soccer players had a tendency to achieve greater mean VL activation during the downward phase of the UH CMJ and the upward phase of the UV CMJ, indicating that VL activation capability during ballistic movements may be an indicator of elite soccer performance. As 12 weeks of recreational soccer training has been shown to result in a 12% increase in muscle fibre cross sectional area and a 14% increase in peak rate of rise in VL EMG activity in untrained participants (Jakobsen et al., 2012), it is possible that greater QF size and muscle activation capabilities in ESP could be attributed to eliciting regular high force muscle actions during soccer training. Alternatively, as QF  $V_m$ , strength and power in healthy young men are associated with a variation of the alpha-actinin-3 gene (Erskine et al., 2014), and ESP have been shown to have a higher frequency of this particular genotype compared to

endurance athletes and control participants (Santiago et al., 2008), it is possible that the differences in QF muscle morphology reported here are associated with genetic variation. Whilst further research is needed to test this hypothesis, we are the first to show that QF muscle size and muscle activation during unilateral CMJs in different directions may be important for elite soccer performance.

Investigating the physiological mechanisms that underpin soccer performance characteristics can inform the specific detail of performance enhancement programmes. Unilateral jump performance in different directions has been shown to be an indicator of elite soccer playing status (please see Chapter Four) and QF muscle size ( $V_m$  and PCSA) was related to UV CMJ and UM CMJ peak V-power, but not to any measure of UH CMJ performance in ESP and NSP. These findings are somewhat in accordance with previous research that reported a positive relationship between BV CMJ and QF muscle volume (O'Brien et al., 2009a, Temfemo et al., 2009). Horizontal-forward CMJs have previously been shown to require greater hamstring activation (Fukashiro et al., 2005, Nagano, Komura and Fukashiro, 2007), and a greater motion and more vigorous utilization of the hip joint (please see Chapter Four) (Fukashiro et al., 2005, Nagano, Komura and Fukashiro, 2007) than vertical CMJs. Therefore, it may be that properties of the hamstring muscle group, rather than the QF, determine UH CMJ performance. Vertical CMJs, on the other hand, produce greater knee joint moments (Fukashiro et al., 2005, Nagano, Komura and Fukashiro, 2007) and therefore, larger PCSA and  $V_m$  of the QF muscle group appear to be more important for UV CMJ peak V-power production. The positive effect of a large QF muscle group on UM CMJ performance may also suggest that UM CMJs require high moments at the knee joint, although this has not yet been investigated. Nevertheless, these findings may suggest that training interventions to enhance UV and UM, but not UH CMJ performance in soccer players could focus on increasing QF  $V_m$ . However, as the significant relationships between QF  $V_m$  and both



UV and UM CMJ performance variables produced moderate coefficients of determination, other physiological factors may also influence UV and UM CMJ performance.

In addition to muscle size, the architecture of the muscle is thought to be important in determining the power output of the whole muscle (Sacks and Roy, 1982, Spector et al., 1980). The VL  $\theta_p$  measurements in soccer players in the current study were similar to values previously reported in youth ESP (Enright et al., 2015). The current study is the first to show that VL  $\theta_p$  was positively related to UV CMJ height and UM CMJ peak V-power, but was inversely related to UH CMJ peak V-power in ESP. Presuming the geometry of the VL is representative of the total QF muscle architecture (Erskine et al., 2009), the greater VL  $\theta_p$  and in theory, greater number of fascicles aligned in parallel (Aagaard et al., 2001, Degens, Erskine and Morse, 2009), could allow the QF muscle to extend the knee joint with more force (Aagaard et al., 2001), thus increasing UV and UM CMJ performance in ESP. However, greater  $\theta_p$  has been associated with reduced muscle contraction velocity (Degens, Erskine and Morse, 2009, Spector et al., 1980), and as the UH CMJ requires greater take-off velocities than UV and UM CMJs, a greater VL  $\theta_p$  may reduce the QF contraction velocity and therefore, reduce peak V-power during UH propulsion. In support of these findings, increments in  $\theta_p$  after a period of resistance training were associated with reductions in elbow flexor RFD in the first 150 ms of an isometric contraction (Erskine, Fletcher and Folland, 2014). In contrast to findings in ESP, VL  $\theta_p$  had no association with any jump performance measure in NSP, but VL relative  $L_f$  was positively related to UH CMJ peak V-power. Non-elite soccer players are less effective at performing horizontal-forward CMJs (please see Chapter Four) and the increased muscle shortening velocity associated with greater  $L_f$  (Wickiewicz et al., 1983) appears to have a greater contribution to fast multi-joint ballistic performance, such as the UH CMJ in these players. Thus, we have demonstrated

that the contribution of QF muscle architecture to unilateral CMJ performance in soccer players is specific to the direction of the jump.

Maximal power production is not only governed by muscle size and architecture, but by the ability of the nervous system to activate the specific muscle groups during ballistic actions (Cormie, McGuigan and Newton, 2011). Mean upward phase VL activation was positively related to vertical (UV CMJ height) and medial (UM CMJ peak V-power) jump performance in ESP, but downward phase VL activation was inversely related to UM CMJ peak V-power in NSP. Previous research has documented a relationship between BV CMJ performance and knee extensor muscle activation during the first 100ms of the rise in ground reaction force (De Ruyter et al., 2006), and between BV CMJ and drop jump peak concentric force and downward phase VL activation (McBride, McCaulley and Cormie, 2008). These studies support our findings with the ESP, but are in contrast to our findings in NSP. The less competent jumpers in the NSP cohort may not have been able to coordinate the downward phase during a UM CMJ, which may result in greater VL activation. Therefore, rather than the force capabilities of the lengthened muscle increasing due to greater downward phase activation (Brown, Cheng and Loeb, 1999), a negative energy balance may have decreased concentric propulsive performance. There were no relationships between UH CMJ performance and VL activation or BF activation in either cohort. Despite previously reporting greater peak BF activation during UH CMJ in comparison to BV, UV and UM CMJs (please see Chapter Four), higher magnitudes of BF activation do not appear to directly contribute to enhanced horizontal-forward jump performance in ESP and NSP. These findings suggest that the morphological properties of the hamstring muscle group could underpin horizontal-forward jump performance but additional research is required to test this hypothesis. Our study demonstrates that BF activation does not contribute to unilateral CMJ performance in different directions, but greater VL

activation enhances UV and UM, but not UH CMJ performance in ESP.

## **5.6 CONCLUSION**

By comparing neuromuscular characteristics in ESP (performing regularly at U18 and U21 levels) and NSP, we have demonstrated that greater peak isometric QF force and QF size ( $V_m$  and PCSA) are important characteristics of U18 and U21 elite soccer performance. Moreover, we show that the size of the QF muscle group contributes to UV and UM CMJ, but not UH CMJ performance. In ESP, greater VL neural drive and VL pennation angle appear to enhance jump performance in the vertical and medial directions, but a larger VL pennation angle reduces UH CMJ performance. Together these findings suggest that jump performance in the vertical and medial directions are underpinned by similar neuromuscular characteristics, which are in contrast to the UH CMJ. Our findings could have implications for the detail of soccer-associated power related physiological assessment and direction-specific performance enhancement protocols in U18 and U21 ESP. However, as it is currently unknown if the properties of the tendon influence unilateral CMJ performance in different directions, the combination of physiological factors relating to the muscle-tendon unit that underpin soccer-associated power, still remain to be elucidated.

## **CHAPTER SIX**

**PATELLAR TENDON ELONGATION IS ASSOCIATED  
WITH HORIZONTAL, BUT NOT VERTICAL POWER IN  
ELITE SOCCER PLAYERS**

#### STUDY 4: ABSTRACT

### PATELLAR TENDON EXTENSIBILITY IS ASSOCIATED WITH HORIZONTAL, BUT NOT VERTICAL POWER IN ELITE SOCCER PLAYERS

**Purpose:** The aims our study were to investigate differences in tendon properties between elite and non-elite soccer players, and to establish whether tendon properties were related to power during soccer-associated tasks. **Methods:** Elite (ESP; n=16; age,  $18.1 \pm 1.0$  yrs) and non-elite (NSP; n=13; age,  $22.3 \pm 2.7$  yrs) soccer players performed three unilateral vertical (UV), unilateral horizontal-forward (UH) and unilateral medial (UM) countermovement jumps (CMJs) on a force plate. Patellar tendon cross sectional area (CSA), elongation, stiffness and Young's modulus were assessed with ultrasonography and isokinetic dynamometry. **Results:** ESP presented greater elongation ( $6.83 \pm 1.87$  vs.  $4.92 \pm 1.88$  mm,  $P=0.011$ ) and strain ( $11.73 \pm 3.25$  vs.  $8.38 \pm 3.06\%$ ,  $P=0.009$ ) than NSP. Tendon elongation correlated with peak horizontal power during UH ( $r=0.693$ ,  $P<0.001$ ) and UM CMJ peak medial power ( $r=0.658$ ,  $P<0.001$ ). Tendon stiffness correlated inversely with peak horizontal power during UH CMJ ( $r=-0.409$ ,  $P=0.028$ ) and peak medial power during UM CMJ ( $r=-0.368$ ,  $P=0.050$ ). Young's modulus correlated inversely with peak horizontal power during UH CMJ ( $r=-0.402$ ,  $P=0.031$ ) but no tendon property correlated with UV CMJ performance ( $r \leq 0.339$ ;  $P \geq 0.078$ ). **Conclusions:** Patellar tendon strain was greater in ESP vs. NSP players and can therefore be considered an indicator of elite soccer performance. More specifically, a more compliant patellar tendon facilitates UH and UM, but not UV CMJ performance in soccer players. These findings should be considered when prescribing talent identification and development protocols to improve direction-specific power in elite soccer players.

**Keywords:** *horizontal power, medial power, Young's modulus, unilateral jump.*

## 6.1 INTRODUCTION

The powerful activity profile of elite soccer [comprising of 68 accelerations, 8 sprints, and 6 vertical jumps (please see Chapter Three)] implies that the most common type of explosive actions elicited involve the successive combination of eccentric and concentric actions, known as the stretch-shortening cycle (SSC) (Cavanagh and Komi, 1979). Indeed, ESP have been previously shown to outperform NSP during unilateral jump tasks oriented in different directions, which induce SSC actions in the muscle-tendon complex of the lower limb (please see Chapter Four). The viscoelastic properties of the tendon affect the interaction between the contractile and elastic elements of the muscle-tendon unit and are thought to influence performance during SSC activities (Bojsen-Møller et al., 2005, Kubo et al., 2007). In Chapter Five, we showed that the KE iMVT and QF size ( $V_m$  and PCSA) are indicators of elite soccer playing status, and the neuromuscular factors underpinning soccer-associated power are specific to the direction of the jump. However, the importance of tendon properties for elite soccer performance, and their contribution to soccer-associated power capabilities, has not yet been investigated.

A comparison of tendon properties in populations of well trained and untrained, or different sporting performance levels, may provide an insight into the importance of these characteristics for high level sports performance (Tillin et al., 2010). Within this context, high (Kubo et al., 2011) and intermediate (Kubo et al., 2000b) level sprinters have a more compliant vastus lateralis (VL) aponeurosis than untrained individuals. More specifically, significant correlations have been reported between 100 m race performance and VL aponeurosis compliance (Kubo et al., 2000b) and maximal elongation (Stafilidis and Arampatzis, 2007). This suggests that greater elongation of the VL tendon-aponeurosis complex allows the utilisation of greater energy storage and increases the shortening velocity of the knee extensor muscle-tendon unit during sprint running. Results from some jump studies are in

accordance with these findings, and report that VL aponeurosis stiffness correlated inversely with differences between bilateral countermovement jump and squat jump height thus suggesting the increased compliance of the VL tendon-aponeurosis complex facilitates the augmentation in jump performance with a countermovement (Kubo et al., 2000a, Kubo, Kawakami and Fukunaga, 1999). In contrast, Bojsen-Møller and colleagues (2005) demonstrated that VL aponeurosis stiffness correlated positively with bilateral vertical countermovement ( $r = 0.55$ ,  $P < 0.05$ ) jump height and knee extensor isometric rate of torque development (RTD), thus suggesting that a stiffer tendon-aponeurosis complex contributes to enhanced muscle output during high force isometric and dynamic bilateral vertical jumping tasks (Bojsen-Møller et al., 2005). However, previous studies measured from the VL aponeurosis and corrected to calculate an estimation of tendon elongation (Bojsen-Møller et al., 2005, Kubo et al., 2011, Kubo et al., 2000b, Stafilidis and Arampatzis, 2007). Hence, the contribution of tendon properties to dynamic sports-specific performance remains unknown and future studies should utilise direct *in vivo* assessments of tendon properties, as exemplified by other researchers (Hansen et al., 2006, Seynnes et al., 2009).

Unilateral CMJs in different directions are indicators of elite soccer performance and can be used as a specific performance assessment of soccer-associated muscular power (please see Chapter Four). They assess independent power qualities (please see Chapter Four) and are underpinned by discrete neuromuscular factors (please see Chapter Five). However, the importance of tendon properties in elite soccer and their contribution to unilateral jump performance in different directions is unknown. Such information may inform the specific detail of soccer maximal muscular power talent identification and development protocols. Therefore, the aims of our study were (i) to investigate whether patellar tendon properties differed between ESP and NSP; (ii) to establish if relationships existed

between the morphological, mechanical and material properties of the patella tendon and unilateral jump performance in different directions in ESP and NSP.

## **6.2 METHODS**

### **6.2.1 Participants**

Twenty-nine male soccer players volunteered to take part in this study, which was approved by Liverpool John Moores University Ethics Committee and complied with the Declaration of Helsinki. Participants provided written informed consent prior to being assigned to two groups according to their level of competition. The ESP group (n = 16; age,  $18.3 \pm 1.3$  yrs; height,  $1.81 \pm 0.07$  m; body mass,  $76.2 \pm 9.7$  kg) consisted of players from an EPL football academy, who regularly participated at U18 and U21 level training and matches. The NSP group (n = 13; age,  $22.4 \pm 1.7$  yrs; height,  $1.74 \pm 0.06$  m; body mass,  $72.6 \pm 6.6$  kg) consisted of players, who participated in at least one hour per week of competitive soccer (11-a-side or five-a-side), and one hour per week of soccer-specific or fitness-based training. Non-elite participants were excluded if they did not meet these inclusion criteria or had previously played soccer at academy, semi-professional, or professional level. Participants were fully familiarised with all testing procedures in a separate session and were asked to complete a physical activity and health questionnaire prior to the study for screening purposes.

### **6.2.2 Experimental Design**

All participants attended the lab on two separate occasions with at least 72 hours between each session. The first session enabled the participants to be familiarised with the assessment protocol, which consisted of three unilateral CMJs in the vertical, horizontal-forward and medial directions on each leg, three KE and KF iMVCs, five explosive isometric KE contractions and two knee extensor ramp



maximum voluntary contractions (RMVCs). This session was also used to determine the superior jumping leg [defined as the limb that produced the highest ground reaction force during a UV CMJ]. During the second session, the participants performed all assessments for CMJ and tendon properties. In order to minimise the influence of previous activity, the testing was performed at least 48 h following any high intensity exercise.

### **6.2.3 Data acquisition and analysis procedures**

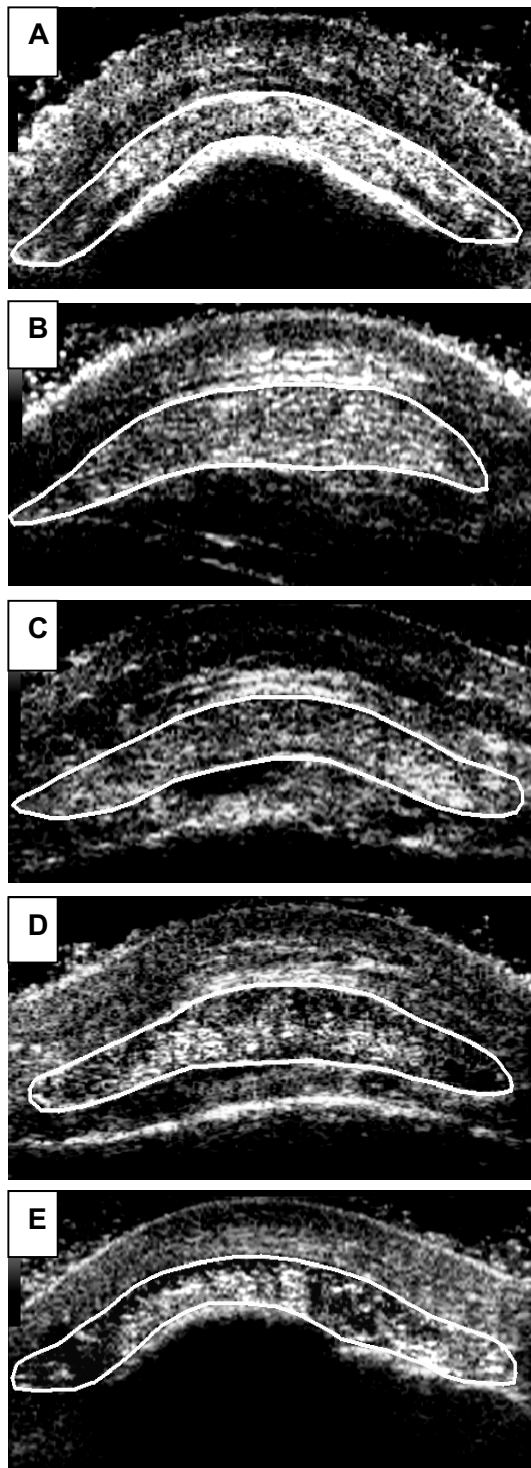
#### *6.2.3.1 Counter movement jumps (CMJs)*

Please see section 4.2.3.1 for the detail of the unilateral countermovement jump assessments procedure.

#### *6.2.3.2 Tendon properties*

##### *6.2.3.2.1 Tendon morphology*

Patellar tendon length, cross sectional area (CSA) and elongation measurements were performed using ultrasonography (MyLab30, Esaote, Genoa, Italy) with the knee joint set at 90° knee flexion (full extension = 0°) (Seynnes et al., 2009) and the hip joint set at 85° (supine = 180°). The patellar tendon resting length, defined as the distance between the patella apex and the point at which the tendon inserts into the tibial tuberosity, was determined by positioning the ultrasound transducer in the sagittal plane and marking the location of the patella apex (0% tendon length) and tibial tuberosity (100% tendon length) on the skin with a permanent marker pen. Three more locations were then marked on the skin over the tendon (25, 50 and 75% tendon length) to enable CSA of the patellar tendon to be measured at these five locations. Axial scans of the patellar tendon were then performed by positioning the ultrasound transducer in the frontal plane over the five points marked along the tendon length. Patellar tendon CSA was measured from these axial images of the

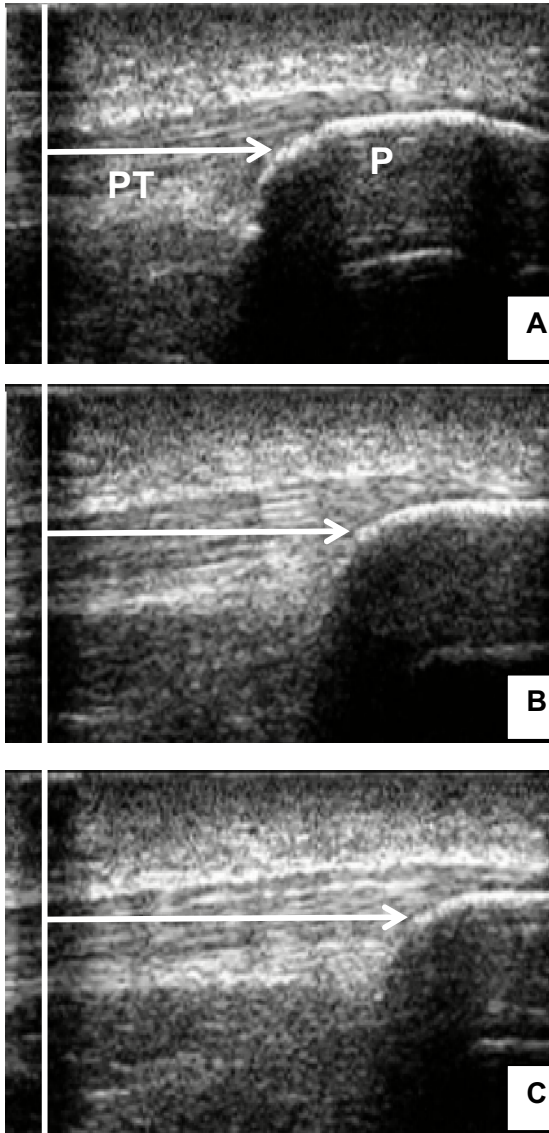


**Figure 6.1.** An example of a transverse plane ultrasound scan of the patellar tendon cross sectional area (CSA) outlined at 0% (A) 25% (B) 50% (C) 75% (D) and 100% (E) of the tendon length from proximal to distal end.

tendon at each point along the length (Fig. 6.1) using image analysis software (ImageJ V.1.45s, National Institute of Health, Maryland, USA). All tendon CSA measurements were allometrically scaled to body mass ( $BM^{0.67}$ ) (Seynnes et al., 2011). These ultrasound procedures have previously been shown to demonstrate acceptable inter-day reliability for measurements of tendon length (ICC = 0.99, typical error = 0.6 mm) and CSA (ICC = 0.99, typical error =  $1.5 \text{ mm}^2$ ) (Reeves, Maganaris and Narici, 2003).

#### 6.2.3.2.2 Tendon mechanical properties

The details of the measurements have been documented previously (Hansen et al., 2006, Seynnes et al., 2009). The mechanical properties of the tendon were assessed by measuring the elongation of the patellar tendon during RMVCs. Prior to performing two RMVCs, a 2 mm wide strip of surgical tape (3M, Neuss, Germany) acted as an echo-absorbent marker and was placed transversely on the skin over the tendon as a reference point at ~30% tendon length from the proximal end (Fig.



**Figure 6.2.** An example of a sagittal plane ultrasound image used to measure tendon elongation/stiffness during a ramped maximum voluntary contraction (RMVC) showing the distance from the echo-absorbent marker (drawn over with white line), patella (P) and patellar tendon (PT), at rest (A), at 50% RMVC (B) and at 100% RMVC (C). The white arrow shows the measurement taken in each position.

6.2). The 40-mm wide, 10-15 MHz linear transducer was placed in the sagittal plane over the patellar tendon (~1 cm of the probe above the patellar apex and ~3 cm below). During the RMVCs, participants were instructed to extend their knee with a gradual increase in force from rest to 100% of their iMVC and then a decrease to rest. The contractions lasted 6 s in total with 2 minutes rest between each contraction. Visual feedback of force production was displayed in front of the participants to ensure all RMVCs were performed at a constant loading rate. Trials were discarded when the torque trace deviated from the required linear pattern upon visual inspection (Helland et al., 2013). Torque data during the RMVC was sampled using data acquisition software (AcqKnowledge, Biopac Systems Inc., Goleta, CA, USA). Ultrasound video sequences were recorded at 25 Hz during the RMVC and were synchronised with the RMVC torque data via the administration of a square wave pulse, which was visible simultaneously on the AcqKnowledge software and the ultrasound monitor (ECG

signal).

#### 6.2.3.2.3 Analysis of tendon property data

Tendon elongation was recorded as the distance the patella moved from the external marker every 10% RMVC (Fig. 6.2). The video frame that corresponded to each 10% RMVC was exported as a portable network graphics (.png) file and the distance from the patella apex to the external marker was measured using image analysis software (ImageJ v. 1.47, National Institute of Health, Maryland, USA). Patellar tendon force was calculated by dividing knee extension moment by the patellar tendon moment arm, which was assumed to be 0.048 m based on MRI measurements in young healthy men (Erskine et al., 2009). Individual force-elongation curves were fitted with a second order polynomial ( $R^2 > 0.95$  in all cases). The linear region of force-elongation data from *in vivo* testing may always not be clear (Reeves, Maganaris and Narici, 2003). Subsequently, when comparing tendon stiffness values between participants producing different tendon forces, e.g. ESP vs. NSP soccer players, it is recommended that stiffness is calculated in a common force region dictated by the weakest participant (Reeves et al., 2005). Therefore, tendon stiffness ( $\Delta F/\Delta L$ ) values were obtained over the highest 20% common force interval in the weakest participant with the lowest maximal RMVC peak force (2599 - 3248 N). Patellar tendon stress for each participant was calculated by dividing the maximum tendon force of the weakest participant, with the mean tendon CSA of each participant, respectively. Tendon elongation was calculated as the change in tendon length at the highest common RMVC force in comparison to resting length. Tendon strain was calculated as the change in tendon length at the highest common RMVC force relative to the original tendon length ( $\Delta L/L_0$ ), and expressed as a percentage. Young's modulus ( $E$ ) was calculated by multiplying stiffness ( $k$ ) with the ratio of the resting tendon length ( $l_0$ ) to mean tendon CSA, i.e.  $E = k \times (l_0/CSA)$ . These ultrasound procedures have

previously been shown to demonstrate acceptable inter-day reliability for measurements of PT stiffness ( $r = 0.94$ , typical error = 8.7%), strain ( $r = 0.98$ , typical error = 3.7%) and Young's modulus ( $r = 0.86$ , typical error = 9.6%) (Hansen et al., 2006).

#### **6.2.4 Statistical analyses**

The mean and standard deviation ( $s$ ) were calculated for all variables. All data was tested for normality using the Shapiro Wilks normality test. For tendon CSA and tendon CSA allometrically scaled to body mass (CSA Rel.  $BM^{0.67}$ ), a two-way mixed ANOVA was used to determine a main effect of athlete status (between factor: ESP vs. NSP), tendon location (within factor: 0, 25, 50, 75, and 100% tendon length), or an athlete status x tendon location interaction. For tendon force, length, stiffness, elongation, strain, stress, Young's modulus, mean CSA and mean CSA Rel.  $BM^{0.67}$ , independent t-tests were used to determine differences between ESP and NSP. Pearson's correlations were used to determine relations between jump performance variables (height or PR, peak V-power, peak H-power or peak M-power) and mean tendon CSA, mean tendon CSA Rel.  $BM^{0.67}$ , stress, strain, stiffness and Young's modulus. Statistical analysis was completed using SPSS version 21 (SPSS Inc., Chicago, IL), and the significance level was set at  $P \leq 0.05$ .

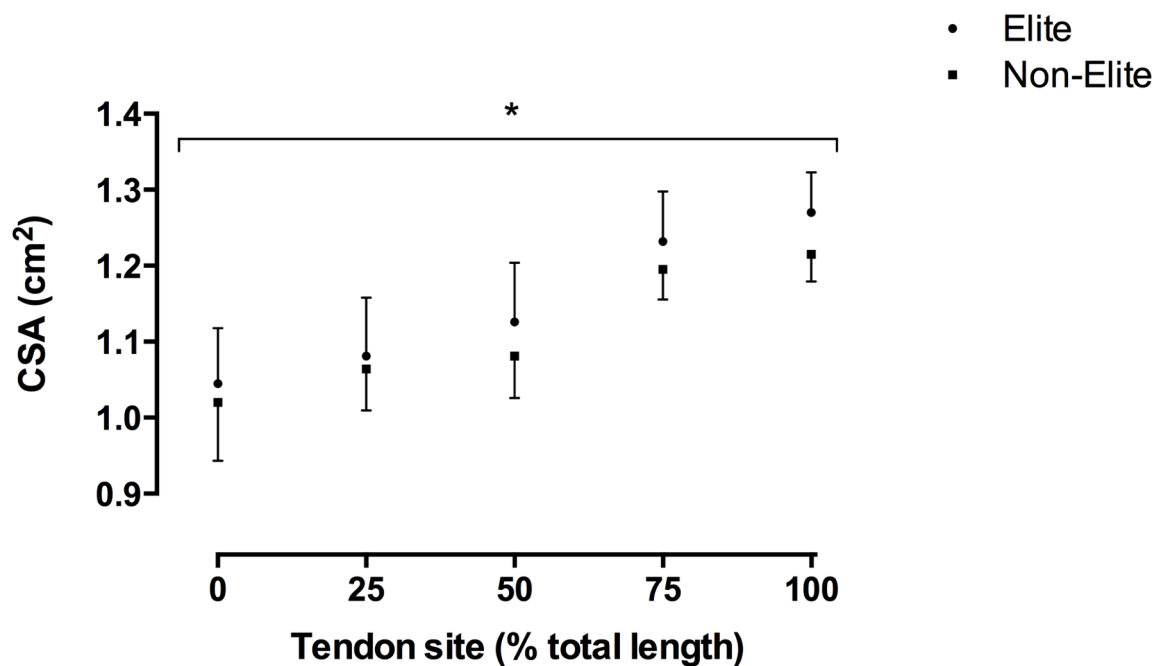
### **6.3 RESULTS**

#### **6.3.1 Differences in patellar tendon properties between elite and non-elite players**

##### *6.3.1.1 Tendon morphology*

Elite soccer players were significantly taller ( $P = 0.009$ ) and had significantly greater femur length ( $46.8 \pm 2.1$  vs.  $44.0 \pm 1.7$ ;  $P = 0.001$ ) than non-elite players. However, there was no difference in body mass between ESP and NSP ( $P = 0.267$ ). For

tendon CSA, there was a main effect of athlete status, with elite players demonstrating greater CSA ( $F_{1,27} = 4.439$ ,  $P = 0.045$ ; Fig. 6.3). There was also a main effect of tendon location ( $F_{4,108} = 106.07$ ,  $P < 0.001$ ), with post hoc analyses showing significant differences in CSA between different locations along the tendon length (0% vs. 25%,  $P = 0.032$ ; 0% vs. 50%,  $P < 0.001$ ; 0% vs. 75%,  $P < 0.001$ ; 0% vs. 100%,  $P < 0.001$ ; 25% vs. 75%,  $P < 0.001$ ; 25% vs. 100%,  $P < 0.001$ ; 50% vs. 75%,  $P < 0.001$ ; 50% vs. 100%,  $P < 0.001$ ; 75% vs. 100%,  $P = 0.043$ ; Fig. 6.3), except between locations at 25% vs. 50% of tendon length ( $P = 0.165$ ; Fig. 6.3). There was no interaction between athlete status and tendon location for CSA ( $F_{4,108} = 0.720$ ,  $P = 0.580$ ). For tendon CSA rel. BM<sup>0.67</sup>, there was no main effect of athlete



**Figure. 6.3** Patellar tendon cross-sectional area (CSA) along its length at 25% intervals in elite ( $n = 16$ , circles, mean + SD) and non-elite ( $n = 13$ , squares, mean - SD) players. \* Elite players significantly greater CSA than non-elite players:  $P < 0.05$ .

status ( $F_{1,27} = 0.006$ ,  $P = 0.951$ ; Fig. 6.3). There was a main effect of tendon location for tendon CSA rel. BM<sup>0.67</sup> ( $F_{4,108} = 106.07$ ,  $P < 0.001$ ), with post hoc analyses showing significant differences in CSA rel. BM<sup>0.67</sup> between different locations along the tendon length (0% vs. 25%,  $P = 0.024$ ; 0% vs. 50%,  $P < 0.001$ ; 0% vs. 75%,  $P < 0.001$ ; 0% vs. 100%,  $P < 0.001$ ; 25% vs. 75%,  $P < 0.001$ ; 25% vs. 100%,  $P < 0.001$ ; 50% vs. 75%,  $P < 0.001$ ; 50% vs. 100%,  $P < 0.001$ ; 75% vs. 100%,  $P = 0.031$ ), except between locations at 25% vs. 50% of tendon length ( $P = 0.185$ ). There was no interaction between athlete status and tendon location for CSA rel. BM<sup>0.67</sup> ( $F_{4,108} = 0.417$ ,  $P = 0.796$ ). Tendon resting length did not differ between groups ( $P = 0.906$ ; Table 6.1).

#### 6.3.1.2 Tendon mechanical and material properties

Elite soccer players demonstrated significantly greater tendon elongation ( $P = 0.011$ ; Table 6.1) and strain ( $P = 0.009$ ; Table 6.1). Non-elite soccer players presented with greater tendon stress ( $P = 0.049$ ; Table 6.1) but there were no differences regarding tendon stiffness ( $P = 0.104$ ; Table 6.1). There was a non-significant tendency for Young's modulus ( $P = 0.075$ ; Table 6.1) and maximum tendon force ( $P = 0.069$ ; Table 6.1) to be higher in ESP compared to NSP.

### 6.3.2 Relationships between patellar tendon properties and unilateral CMJ performance

#### 6.3.2.1 Both Groups

Patellar tendon elongation correlated with UH CMJ PR ( $r = 0.657$ ,  $P < 0.001$ ), UH CMJ peak H-power ( $r = 0.693$ ,  $P < 0.001$ ; Fig. 6.4A), UM CMJ PR ( $r = 0.496$ ,  $P = 0.006$ ) and UM CMJ peak M-power ( $r = 0.658$ ,  $P < 0.001$ ; Fig. 6.5A). Patellar tendon strain correlated with UH CMJ PR ( $r = 0.698$ ,  $P < 0.001$ ), UH CMJ peak H-power ( $r = 0.674$ ,  $P < 0.001$ ), UM CMJ PR ( $r = 0.409$ ,  $P = 0.027$ ) and UM CMJ peak M-power ( $r = 0.658$ ,  $P < 0.001$ ).

**Table 6.1.** Patellar tendon properties in elite (n=16) and non-elite (n=13) players; mean  $\pm$  SD.

Patellar Tendon Properties	Elite	Non-Elite
Mean CSA, mm <sup>2</sup>	115 $\pm$ 6*	112 $\pm$ 3
Mean CSA Rel. BM <sup>0.67</sup> , mm <sup>2</sup> /Kg <sup>0.67</sup>	6.35 $\pm$ 0.44	6.41 $\pm$ 0.02
Resting Tendon Length, mm	58.5 $\pm$ 7.1	58.2 $\pm$ 4.4
Stiffness, N/mm	1269 $\pm$ 607	1707 $\pm$ 792
Elongation, mm	6.83 $\pm$ 1.87*	4.92 $\pm$ 1.88
Strain, %	11.73 $\pm$ 3.25**	8.38 $\pm$ 3.06
Stress, MPa	28.29 $\pm$ 1.34*	29.15 $\pm$ 0.72
Young's Modulus, GPa	0.64 $\pm$ 0.31	0.88 $\pm$ 0.39
MVC tendon force, N	5728 $\pm$ 1522	4800 $\pm$ 989

Key: CSA, cross sectional area; Rel. BM<sup>0.67</sup>, allometrically scaled to body mass; MVC, maximal voluntary contraction; \* denotes a significant difference between elite and non-elite ( $P < 0.05$ );

\*\* denotes a significant difference between elite and non-elite ( $P < 0.01$ ).

= 0.616,  $P < 0.001$ ; Fig. 6.5B). Tendon stiffness correlated inversely with UH CMJ peak H-power ( $r = -0.409$ ,  $P = 0.028$ ; Fig. 6.4B) and with UM CMJ peak M-power ( $r = -0.368$ ,  $P = 0.050$ ; Fig. 6.5C). Young's modulus correlated inversely with UH CMJ PR ( $r = -0.376$ ,  $P = 0.044$ ) and UH CMJ peak H-power ( $r = -0.402$ ,  $P = 0.031$ ; Fig. 6.4C). Patellar tendon mean CSA correlated with UH CMJ peak V-power ( $r = 0.381$ ,  $P = 0.041$ ) and with UM CMJ peak V-power ( $r = 0.401$ ,  $P = 0.031$ ). Tendon stress correlated inversely with UH CMJ peak V-power ( $r = -0.383$ ,  $P = 0.040$ ) and with UM CMJ peak V-power ( $r = -0.388$ ,  $P = 0.037$ ). No patellar tendon property correlated with height or peak V-power during BV or UV CMJ ( $r \leq 0.339$ ;  $P \geq 0.078$ ).

### 6.3.2.2 Elite Players

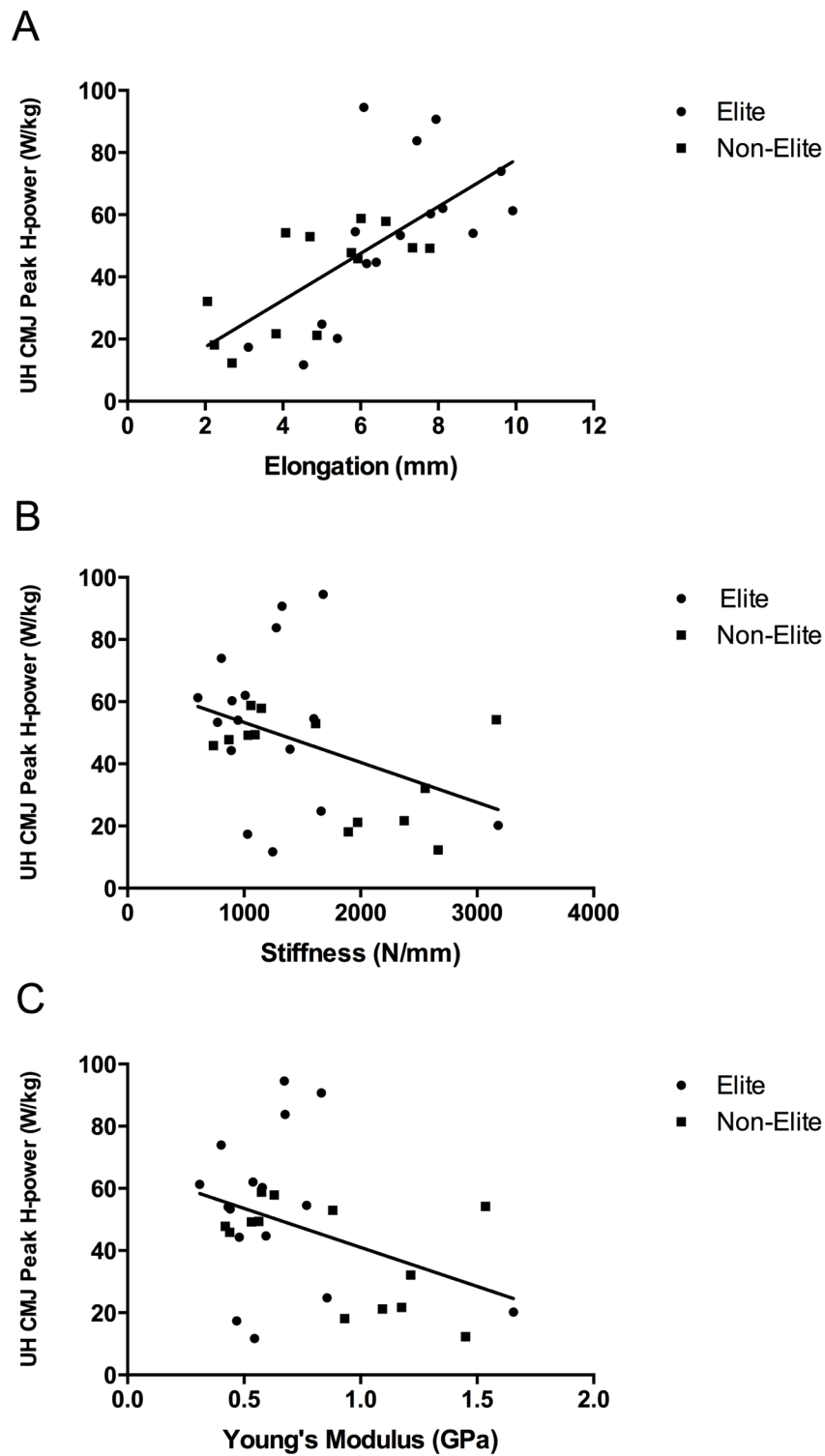
Resting tendon length correlated inversely with UV CMJ height ( $r = -0.484$ ,  $P = 0.026$ ). Tendon strain correlated with UH CMJ PR ( $r = 0.695$ ,  $P = 0.003$ ), UH CMJ



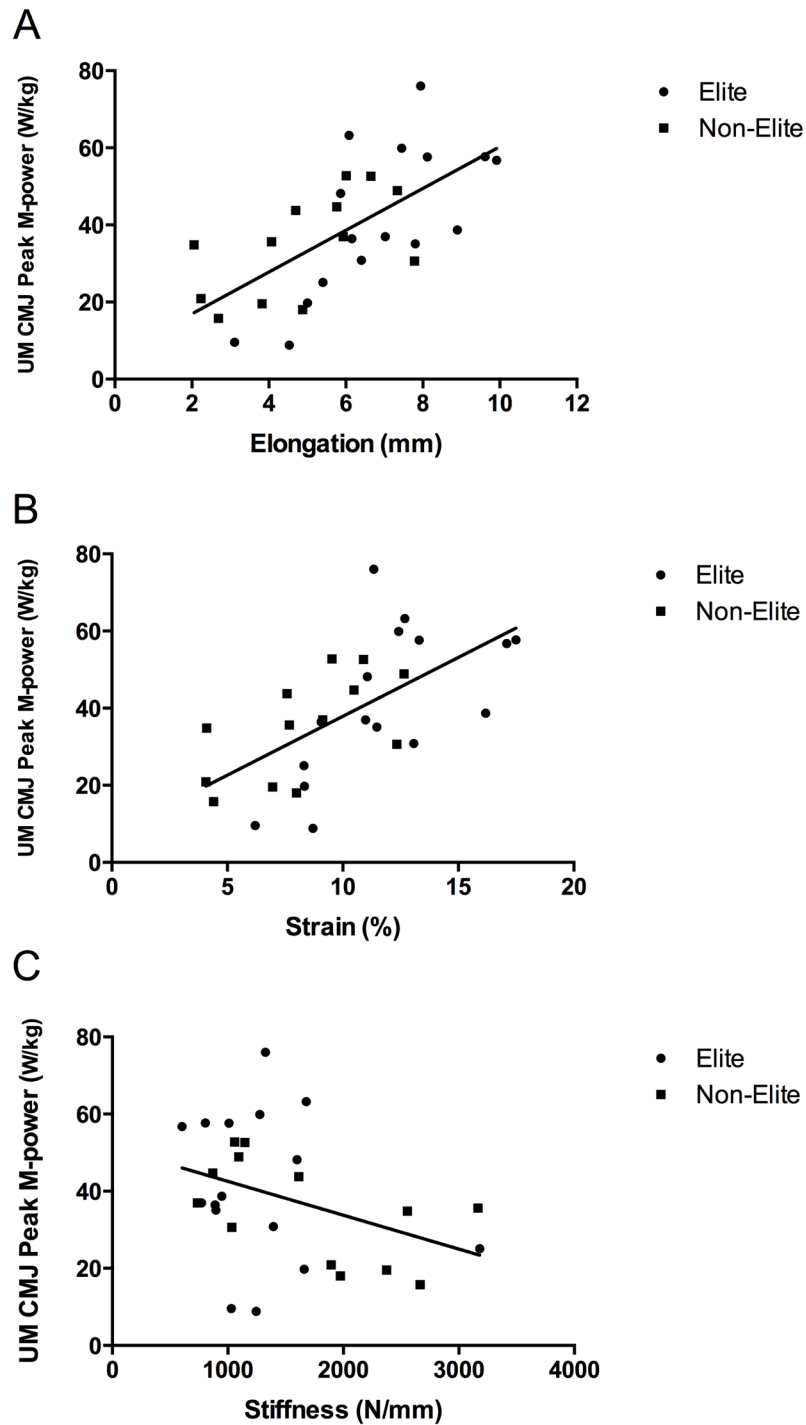
peak H-power ( $r = 0.618$ ,  $P = 0.011$ ) and UM CMJ peak M-power ( $r = 0.636$ ,  $P = 0.008$ ). Tendon elongation correlated with UH CMJ PR ( $r = 0.654$ ,  $P = 0.006$ ), UH CMJ peak H-power ( $r = 0.656$ ,  $P = 0.006$ ), UM CMJ PR ( $r = 0.519$ ,  $P = 0.040$ ) and UM CMJ peak M-power ( $r = 0.709$ ,  $P = 0.002$ ).

#### *6.3.2.3 Non-Elite Players*

Tendon strain correlated with UH CMJ peak H-power ( $r = 0.698$ ,  $P = 0.008$ ) and UM CMJ peak M-power ( $r = 0.582$ ,  $P = 0.037$ ). Tendon elongation correlated with UH CMJ peak H-power ( $r = 0.701$ ,  $P = 0.008$ ) and UM CMJ peak M-power ( $r = 0.595$ ,  $P = 0.032$ ). Tendon stiffness ( $r = -0.579$ ,  $P = 0.038$ ) and Young's modulus ( $r = -0.613$ ,  $P = 0.026$ ) correlated inversely with UM CMJ peak M-power.



**Figure 6.4.** The relationship between unilateral horizontal (UH) countermovement jump (CMJ) peak H-power and: tendon elongation (a,  $r = 0.693$ ,  $P < 0.001$ ), stiffness (b,  $r = -0.409$ ,  $P = 0.028$ ), and Young's Modulus (c,  $r = -0.402$ ,  $P = 0.031$ ) in elite ( $n = 16$ , circles) and non-elite ( $n = 13$ , squares) players. Peak H-power, peak horizontal power allometrically scaled to body mass.



**Figure 6.5.** The relationship between unilateral medial (UM) countermovement jump (CMJ) peak M-power and: tendon elongation (a,  $r = 0.658$ ,  $P < 0.001$ ), strain (b,  $r = 0.616$ ,  $P < 0.001$ ), and stiffness (c,  $r = -0.368$ ,  $P = 0.050$ ) in elite ( $n = 16$ , circles) and non-elite ( $n = 13$ , squares) players. Peak M-power, peak medial power allometrically scaled to body mass.

## 6.4 DISCUSSION

The aims of our study were to compare patellar tendon properties between ESP and NSP, and to establish if these properties were related to unilateral jump performance in different directions. Our results showed that tendon elongation and strain were greater in ESP than NSP. These specific tendon properties may therefore be considered indicators of elite soccer playing status. Tendon elongation and strain also correlated positively with peak H-power and M-power during UH and UM CMJ, respectively; while tendon stiffness and Young's modulus correlated inversely with H-power during UH CMJ. No tendon property was related to UV CMJ height or peak vertical power. The current study suggests that a more compliant patellar tendon facilitates greater unilateral jump performance in the horizontal-forward and medial directions, but patellar tendon stiffness does not contribute to vertical jump performance.

Comparing the physiological capabilities in soccer players competing at different performance levels may provide an insight into the physiological factors underpinning elite soccer performance. While tendon CSA was significantly greater in ESP compared to NSP, when normalised to body size, there was no significant difference between cohorts. Subsequently, whilst it is possible that the greater tendon CSA presented by players is a result of the higher volume of soccer training ESP are exposed in comparison to NSP (Couppe et al., 2008, Magnusson and Kjaer, 2003), it is more likely that ESP demonstrated tendons with larger CSA as they were significantly taller than NSP. Despite greater absolute CSA, tendon elongation and strain were significantly higher in ESP compared to NSP. This illustrates that ESP have more extensible patellar tendon structures than NSP at a given tendon force (highest common tendon force = 3248 N). Interestingly, patellar tendon stiffness of ESP did not differ from NSP. However, comparing tendon stiffness measurements in populations with tendons of different dimensions may not provide the best

comparison of *in vivo* tendon function and Young's modulus (i.e. the relation between stress and strain), which represents the material properties of the tendon independent of its dimensions, may provide a more accurate representation of the *in vivo* function of the patellar tendon when comparing ESP and NSP (Foster et al., 2014). Our findings showed that there was a non-significant tendency for ESP to display lower Young's modulus than NSP. The greater elongation and strain demonstrated by ESP in comparison to NSP may therefore be due to differences in the microstructure of the tendon, including a decreased collagen fibril diameter (Diamant et al., 1972), a decreased fibril packing (Reed and Iozzo, 2002), a decreased collagen cross-linking (Birch, Bailey and Goodship, 1998), and an increased collagen crimping (Kastelic, Palley and Baer, 1980). However, given the non-significant difference in Young's modulus, this theory remains speculative. Considering the maximal acceleration and sprint demands of elite soccer match-play [elite soccer match-play requires ~68 maximal accelerations and ~8 sprints (please see Chapter Three)], our findings of ESP displaying more extensible patellar tendons than NSP are consistent with previous cross sectional studies reporting that elite sprinters have more extensible VL tendon-aponeurosis complex structures than both inferior sprinters (Stafilidis and Arampatzis, 2007) and untrained participants (Kubo et al., 2011, Kubo et al., 2000b). It has been well documented that resistance and plyometric training interventions will not enhance the extensibility of the tendon structures (Burgess et al., 2007, Reeves, Maganaris and Narici, 2003, Seynnes et al., 2009), and only bed rest (Reeves et al., 2005) or detraining (Kubo et al., 2010) can induce these changes. Therefore, as variations in certain collagen genes have been associated with tendon properties (Kubo, Yata and Tsunoda, 2013), it is possible that ESP players have a genetic predisposition to more extensible tendon structures than NSP.

Knowledge of the specific tendon properties that are related to certain physical predictors of soccer performance can inform elite soccer talent identification and development protocols. Unilateral jump tasks oriented in different directions have been suggested to represent a measurement of soccer-associated power (please see Chapter Four) and the relationship between unilateral jump performance in different directions and tendon properties are therefore of interest for the assessment and development of muscular power in ESP. The current study showed that in soccer players, patellar tendon elongation and strain were both positively related to UH CMJ H-power and UM CMJ M-power, while tendon stiffness was inversely related to UH CMJ H-power and UM CMJ M-power. Our findings suggest a more extensible and compliant patellar tendon facilitates UH and UM CMJ performance. Moreover, Young's modulus was inversely related with UH CMJ projectile range and H-power, thus suggesting a tendon with more elastic material properties enhances UH CMJ performance. As acceleration and sprinting activities require the production of high magnitudes of horizontal-forward power (Buchheit et al., 2014), these findings are in accordance with previous studies reporting that 100 m sprint performance is positively related to VL aponeurosis compliance (Kubo et al., 2000b) and maximal elongation (Stafilidis and Arampatzis, 2007). Real-time ultrasonography observing the behaviour of the tendon *in vivo* has shown that, during high intensity jumping movements whereby the range of joint motion is small, the VL muscle fascicles lengthen only marginally, if at all during the eccentric phase (Finni et al., 2001, Finni et al., 2003), and are thought to function quasi-isometrically. Horizontal-forward CMJs have been shown to require  $\sim 10^\circ$  less knee flexion than vertical CMJs (Fukashiro et al., 2005). Hence, UH and possibly UM CMJs, may require a quasi-isometric contraction of the knee extensor muscle group which could induce greater tendon lengthening (Reeves and Narici, 2003), therefore allowing the tendon to store more potential energy and recoil at greater speeds thus acting as a power amplifier

during horizontal-forward and medial CMJs (Nagano, Komura and Fukashiro, 2004). Moreover, it has also been reported that during the initial concentric phase of SSC exercises, the rapid shortening of the tendon contributes to lowering the shortening velocity of the muscle fibres to near isometric conditions (Kawakami et al., 2002, Kubo et al., 2000c). Therefore, a more compliant patellar tendon will have a capacity for greater elongation, allowing the knee extensor muscle fibres more time to develop greater forces during the concentric propulsive phase of sprinting (Kubo et al., 2011), UH CMJ and UM CMJ activities. Hence, our data demonstrate that more compliant patellar tendon structures enhance UH and UM CMJ performance in soccer players.

As greater knee flexion range and extension moments are required during vertical CMJs compared to horizontal-forward CMJs (Fukashiro et al., 2005), the neuromuscular properties of the knee extensors may play a greater role in determining vertical jump performance than the properties of the patellar tendon. Indeed, we have previously shown in ESP that UV CMJ peak V-power and height are related to quadriceps femoris muscle size, and vastus lateralis muscle fascicle pennation angle and activation, respectively (please see Chapter Five). The lack of direct relationships between patellar tendon properties and UV CMJ performance in soccer players is in accordance with some (Kubo et al., 2000a, Kubo et al., 2007), but not all previous research (Bojsen-Møller et al., 2005). Bojsen-Møller and colleagues (2005) found that a stiffer VL tendon-aponeurosis complex contributes to enhanced muscle output during high intensity isometric and dynamic bilateral vertical jumping tasks. Although we have only reported the relationship between tendon properties and UV CMJ variables, unpublished data from our lab also showed no relationship between tendon properties and bilateral vertical jump performance variables. Discrepancies between the study by Bojsen-Møller and colleagues (2005) and the present results may have been due to methodological disparities. Whilst the current study analysed ultrasound images of the patellar tendon, Bojsen-Møller and

colleagues (2005) measured the VL aponeurosis and therefore approximated tendon elongation. It is therefore possible that their stiffness measurements do not account for total displacement of the tendon and may underestimate tendon compliance (Hansen et al., 2006). Nevertheless, the current study is the first to investigate the influence of patellar tendon properties on UV CMJ performance. When considering the results of our previous research (please see Chapter Five), it appears that the neuromuscular properties of the QF muscle group, rather than patellar tendon properties, play a primary role in determining unilateral vertical jump performance, while the patellar tendon plays a greater role in tasks requiring the application of horizontal-forward or medial power.

Despite no relationship between tendon properties and vertical jump capability, mean tendon CSA was related to UH and UM CMJ peak vertical power. With everything else remaining constant, greater CSA will increase tendon stiffness. Subsequently, as tendon stiffness has previously been related to bilateral squat jump and CMJ performance peak vertical power (Bojsen-Møller et al., 2005), the CSA of the tendon could potentially stiffen the tendon and allow greater peak vertical power to be produced during the UH and UM CMJ. However, in the absence of an association between tendon stiffness and vertical jump performance, or tendon stiffness and UH and UM CMJ peak V-power, this hypothesis remains speculative and more research is required to investigate the effect of tendon CSA on peak vertical power during UH and UM CMJs.

## **6.5 CONCLUSION**

Our study has shown for the first time that patellar tendon elongation and strain are greater in ESP vs. NSP, and are therefore indicators of U18 and U21 elite soccer playing status. A more compliant patellar tendon appears to enhance H-power and M-power achieved during UH and UM CMJs, respectively. Moreover, a lower



Young's modulus facilitates greater UH CMJ performance. In contrast, patellar tendon properties were not related to UV CMJ performance thus documenting that patella tendon properties only influence unilateral CMJ performance in the horizontal-forward and mediolateral directions. Our findings from the current chapter suggest that soccer talent identification and training intervention protocols should aim to recruit, and develop, players with more elastic patella tendons.

When we consider the data from the current chapter, together with our findings documented in Chapters Four and Five, we show that unilateral jumps in different directions assess independent muscular power qualities (please see Chapter Four) and are underpinned by specific combinations of knee extensor neuromuscular (please Chapter Five) and tendon properties in post-PHV ESP and NSP. This novel information should inform the detail of soccer-associated muscular power related physiological assessment criteria in post-PHV soccer players, and should also allow practitioners to target a definitive combination of physiological factors when aiming to enhance unilateral soccer-associated power performance in a specific direction. However, it should be noted that our research thus far (please see Chapters Three, Four, Five and Six) has been performed with U18 and U21 ESP and NSPs, and due to the significant changes in the muscle-tendon unit that occur during maturation (Malina, Bouchard and Bar-Or, 2004, O'Brien et al., 2010b, Viru et al., 1999), may not be applicable in younger ESP at different stages of maturation.

## **CHAPTER SEVEN**

MUSCULAR POWER IS IMPORTANT IN MID- AND  
POST- BUT NOT PRE-PEAK HEIGHT VELOCITY ELITE  
YOUTH SOCCER PLAYERS

## STUDY 5: ABSTRACT

### MUSCULAR POWER IS IMPORTANT IN MID- AND POST- BUT NOT PRE-PEAK HEIGHT VELOCITY ELITE YOUTH SOCCER PLAYERS

**Purpose:** Maturation status is a confounding factor when identifying talent in elite youth soccer players (ESP). By comparing performance of ESP and control participants (CON) matched for maturation status, the aims of our study were to establish the importance of acceleration, sprint, horizontal-forward jump and vertical jump capabilities at different stages of maturation in elite youth soccer. **Methods:** ESP (n=213; age, 14.0±3.5 yrs) and CON (n=113; age, 15.0±4.4 yrs) were grouped using years from/to predicted peak height velocity (PHV) to determine maturation status (ESP: pre-PHV, n=100; mid-PHV, n=25; post-PHV, n=88; CON: pre-PHV, n=44; mid-PHV, n=15; post-PHV, n=54). Participants performed three reps of: 10 m and 20 m sprint, bilateral vertical countermovement jump (BV CMJ) and bilateral horizontal-forward countermovement jump (BH CMJ). **Results:** ESP demonstrated faster 10 m (ESP vs. CON; Pre-PHV: 2.00±0.10 vs. 2.05±0.15 s; mid-PHV: 1.83±0.20 vs. 1.94±0.13 s; post-PHV: 1.74±0.08 vs. 1.80±0.13 s; P<0.001) and 20 m sprint (P<0.001) performance than CON at all stages of maturation. Mid-PHV and post-PHV ESP achieved greater BV CMJ height (P<0.001) and BH CMJ distance (P<0.001) compared to CON but there was no difference in BV or BH CMJ between pre-PHV ESP and CON (BV CMJ: 22.7±4.04 vs. 22.8±4.31 cm; BH CMJ: 136.5±15.4 vs. 133.1±18.0, respectively; P>0.880). **Conclusions:** Our data suggest that 10 and 20 m and sprint performance may be determinants of elite soccer playing status at all stages of maturation. However, lower limb muscular power (horizontal-forward and vertical jumping) capabilities only discriminate ESP from CON participants at mid- and post-PHV thus suggesting that soccer talent identification protocols for pre-PHV players should include sprint, but not jump assessments.

**Keywords:** *horizontal power, acceleration, sprint, maturation status.*

## **7.1 INTRODUCTION**

Identifying predictors of long-term success is an extremely important process for elite soccer clubs competing at the highest level. We previously documented that the ability to perform powerful actions in different directions is critical for elite soccer performance (please see Chapters Three and Four). Indeed, professional U18 and U21 ESP demonstrated greater performance than NSP in unilateral CMJ assessments in different directions (please see Chapter Four), which are underpinned by separate combinations of physiological factors in this cohort ESP and NSP (please see Chapters Five and Six; and Table 6.2). However, significant morphological and neural changes occur during growth and maturation (Malina, Bouchard and Bar-Or, 2004) and the physiological factors underpinning muscular speed and power may be specific to maturation status (Martin et al., 2003, Meylan et al., 2014). Subsequently, our findings presented in Chapters Four, Five and Six may only be applicable in U18 and U21 professional ESP and the relative importance of muscular power for younger EPL ESP at different stages of maturation, remains unknown.

Youth ESP have been shown to outperform NSP in acceleration, speed and power assessments at various youth age groups including 14-17 yrs (Gil et al., 2007), U13-U15 (Deprez et al., 2015) and U14 (Waldron and Murphy, 2013). However, cross sectional data consistently show that from the age of ~13 years, boys that are advanced in physical maturity status (sexual and skeletal maturation) are better represented in elite youth soccer teams (Figueiredo et al., 2009, Malina et al., 2007, Pena Reyes, Cardenas-Barahona and Malina, 1994, Wrigley et al., 2014). As the adolescent growth spurt varies in timing and rate, and is closely associated with improvements in speed and power performance in youth soccer players (Malina

et al., 2004, Philippaerts et al., 2006), the difference in performance between youth ESP and NSP may be somewhat confounded by failure to account for differences in maturation status (Vandendriessche et al., 2012).

During the pre-PHV phase, running speed and power are thought to be underpinned by neural factors such as inter-muscular coordination and intra-muscular synchronisation (Lloyd and Oliver, 2012, Rabinowickz, 1986, Viru et al., 1999). In contrast, the mid-PHV phase is characterised by a surge in growth hormones and testosterone (Boisseau and Delamarche, 2000, Fragala et al., 2011), which stimulates pubertal muscle growth (Malina, 1969, Malina, Bouchard and Bar-Or, 2004, Viru et al., 1999). The large increase in maximal power and speed during the mid-PHV phase is thought to be underpinned primarily by increments muscle volume (Martin et al., 2003, Meylan et al., 2014, Round et al., 1999). Whilst lean muscle mass continues to increase during the post-PHV phase, and increments in peak force capabilities are evident (Martin et al., 2003, Meylan et al., 2014), the increase in speed and power from mid-PHV to post-PHV is driven primarily by enhancements of contraction velocity and underpinned by qualitative factors including increased fascicle length (O'Brien et al., 2010a, Van Praagh and Dore, 2002), transformation of type I to type II fibres (Lexell et al., 1992, Metaxas et al., 2014), increased motor unit recruitment (Dotan et al., 2012, O'Brien et al., 2010a), stiffening in the tendon-aponeurosis structures (O'Brien et al., 2010b) and increased ability to utilize supra-spinal feed-forward input and stretch latency reflexes (Lloyd et al., 2012, Rumpf et al., 2013). Hence, the importance of certain speed and power characteristics throughout growth and maturation may depend on the developmental stage of the physiological determinants underpinning these specific traits.

Acceleration and sprint performance have been shown to be independent capabilities in ESP (Little and Williams, 2005). While early acceleration is associated with longer ground contact times [(0.12-0.20 s (Wild et al., 2011))] and relies on

contractile force capabilities (Mero, 1988), sprinting is associated with shorter ground contact times [(0.09-0.12 s (Wild et al., 2011))] and therefore relies more on the ability of the muscle-tendon unit to perform fast stretch-shortening cycle actions (HENNESSY and KILTY, 2001, Young, McLean and Ardagna, 1995). Similarly, vertical and horizontal-forward CMJ capabilities are independent qualities (please see Chapter Four) and are controlled by different co-ordination strategies (Jones and Caldwell, 2003, Nagano, Komura and Fukashiro, 2007), with horizontal-forward CMJs requiring significantly more biceps femoris electromyographic activity (please see Chapter Four) (Fukashiro et al., 2005). Moreover, vertical and horizontal-forward unilateral CMJs are underpinned by different neuromuscular-tendon properties, and while tendon elasticity is positively associated with UH CMJ H-power (please see Chapter Six), UV CMJ V-power is related to quadriceps femoris muscle volume, vastus lateralis (VL) pennation angle and VL electromyographic activation (please see Chapter Five). Subsequently, considering the biological changes that occur during growth and maturation (Malina, Bouchard and Bar-Or, 2004), certain physical assessments may be better predictors of elite soccer performance at different stages of maturation. However, no study to date has assessed and compared soccer-associated speed and power performance in large cohorts of youth ESP and CON, grouped according to maturation status. Thus, the importance and relevance of acceleration, speed and power qualities at different stages of maturation in elite soccer remains unknown.

Considering the physiological changes that occur during growth and maturation, the talent identification process needs to be dynamic and perhaps specific to the stage of biological development. Hence, the aim of our cross sectional study was to compare acceleration, speed, BV CMJ and bilateral horizontal-forward CMJ (BH CMJ) performance in pre-, mid- and post-PHV ESP and maturity matched

CON to establish which performance assessments may be indicators of elite soccer playing status at specific stages of maturation.

## **7.2 METHODS**

### **7.2.1 Participants**

Three-hundred and twenty-six males volunteered to take part in this study, and formed two cohorts: ESP (n = 213) and CON (n = 113). The ESP were members of an EPL football academy and regularly participated at U9 to U21 level. The control participants were recruited under the inclusion criteria that they were young healthy males who had not previously played soccer at EPL academy or professional level. The control participants consisted of individuals with a range of habitual activity levels. During the recruitment process, all individuals interested in taking part in the study completed a health questionnaire which included questions about previous injury history. The inclusion criteria for all potential participants were that the individual had been free of any injury to the lower body within the previous three months and had not previously sustained a serious knee or ankle injury which may be aggravated during testing procedures, or cause an adverse effect on performance. Participant characteristics are displayed in Table 7.1. All participants and their parents/guardians (if participants were <16 years old) provided written informed consent prior to participating in the study, which was approved by Liverpool John Moores University Ethics Committee and complied with the Declaration of Helsinki.

### **7.2.2 Experimental Design**

This study examined BV CMJ, BH CMJ, 10 m acceleration and 20 m sprint performance in pre-, mid- and post-peak height velocity (PHV) elite youth soccer

players and non-elite control participants. To avoid any systematic bias between performance tests, assessments were completed in a random order. Performance tests were completed either on the same day, or in a small number of the control participants, within a 3-week period (jump tests on one day and sprint tests on another day) due to logistical reasons dependent on their respective school schedules. All tests were performed during the in-season period and testing sessions were scheduled > 48 h after competition or a high intensity training session to minimise the influence of training. Participants performed all tests in soccer shirt/t-shirt, shorts and soccer boots, except for the BV CMJ, for which participants removed their boots.

### **7.2.3 Testing procedures**

#### *7.2.3.1 Anthropometric measurements*

Standing stature was measured with a fixed stadiometer ( $\pm 0.1$  cm; Holtain Limited, Crosswell, UK), seated height with a fixed sitting height table ( $\pm 0.1$  cm; Holtain Limited, Crosswell, UK) and body mass with a digital balance scales ( $\pm 0.1$  kg; ADE Electronic Column Scales, Hamburg, Germany). Pubertal timing was estimated according to the estimated biological age (age at peak height velocity (PHV)) of each individual using calculations described by Mirwald et al. (2002). The estimated age at which peak linear growth in stature occurs (age at PHV) is an indicator of somatic maturity and is calculated using prediction equations based on the interaction between stature, sitting height, body mass and chronological age. The use of stature and sitting height in the prediction takes into consideration the differential timing of the adolescent spurt in body dimensions and also their interactions with chronological age (Mirwald et al., 2002). The biological maturity age was calculated by subtracting the chronological age at the time of testing from the estimated chronological age at PHV. Participants were split into three maturity groups based on



biological age: Pre-PHV (< -1.0 years), Mid-PHV (-0.99 to 0.5 years) and Post-PHV (> 0.51 years) (Meylan et al., 2014, Rumpf et al., 2012). This method of estimating biological maturity age was previously cross-validated in 221 boys who were had their height and sitting height measured longitudinally. The mean difference between predicted years from PHV and estimated years from PHV was 0.243 ( $\pm$  0.650) years. The authors subsequently concluded that this method of estimating biological maturity age has been shown to be have an error of  $\pm$  1 yr 95% of the time (Mirwald et al., 2002). Previous research that included young soccer players (age range: 12.1-17.3 years) also showed this method of estimating age from/to PHV to be well correlated [ $r = 0.69$  (90% confidence limits: 0.59; 0.77)] with skeletal age (estimated from hand and wrist radiograph) in (Gilsanz and Ratib, 2005). Moreover, estimated age to/from PHV was reported to have acceptable absolute (the noise occurring from trial-to-trial, which might confound the assessment of real changes in repeated measures; CV = 0.6% (Hopkins, 2000)), and relative (the ability of the test to differentiate between individuals; ICC = 0.98) reliability, when measurements were repeated twice within a month in youth soccer players at pre-, mid- and post-PHV (Buchheit and Mendez-Villanueva, 2013).

#### *7.2.3.2 Warm up protocol*

After the anthropometric measurements were performed, the participants undertook a standardised 10-minute warm up procedure that consisted of 5 minutes of dynamic movements (e.g. high knees, skips, lunges). After this, CMJ, and sprint performance assessment procedures were demonstrated to the participants, after which, participants practiced each assessment (5 x BH CMJs, 5 x BV CMJs, and 3 x 20 m sprints).

### 7.2.3.3 *Jump assessments*

Participants performed a minimum of 3 trials of the BH CMJ and BV CMJ with approximately 30 seconds of recovery between trials and 120 s between jump types. If the third jump measurement (height or distance) was higher than the first or second, the participant performed a fourth trial. The highest or longest jump was selected for analysis. To isolate the lower limbs, and eliminate the contribution of technique and arm swing (Hara et al., 2008), participants were asked to keep their arms akimbo during all CMJs. Participants were instructed to jump as high, or as far as possible and no specific instructions were given regarding depth of countermovement. Upon landing, participants were required to remain in a position with both feet fixed on the ground, and if they lost balance, the jump was disqualified. The BH CMJ testing was performed on an artificial grass surface. Participants placed both feet behind a line and jumped as far as possible, while landing on two feet. The distance from the line to the player's closest heel was measured with a measuring tape. The BV CMJ assessment was carried out on a hard, flat surface according to previously described methods (Oliver, Armstrong and Williams, 2008) and using a portable photoelectric cell system (Optojump, Microgate, Bolzano, Italy). The inter-day test-retest reliability of this equipment for measuring jump height has previously been shown to be excellent, with ICCs ranging from 0.982 to 0.989, low coefficients of variation (2.7%), and low random errors ( $\pm 2.81$  cm). The Optojump photoelectric cell system has also been shown to demonstrate strong concurrent validity when compared to gold standard force plate derived measurements of vertical jump performance. Indeed, the ICCs for validity were very high (0.997–0.998), even if a systematic difference was consistently observed between force plate and Optojump ( $-1.06$  cm;  $p = 0.001$ ) (Glatthorn et al., 2011). It should also be noted that the inter-day test-retest reliability of BV and BH CMJ performance has previously been shown to be acceptable in pre (BV CMJ: CV = 5.8%, ICC = 0.93; BH CMJ: CV = 6.1%, ICC

= 0.83), mid- (BV CMJ: CV = 5.4%, ICC = 0.97; BH CMJ: CV = 4.8%, ICC = 0.91) and post- (BV CMJ: CV = 5.1%, ICC = 0.95; BH CMJ: CV = 3.8%, ICC = 0.96) PHV male and female athletic children (Meylan et al., 2012).

#### *7.2.3.4 Speed assessments*

A photocell timing system (Brower Timing System, Salt Lake City, UT, USA) was used to assess sprints to the nearest 0.001 s. Participants were required to perform three maximal sprints in which they were instructed to run 24 m as quickly as possible. The first, second and third timing gates were positioned 1 metre, 11 metres and 21 metres from the start line. After assuming a split stance crouch position, with their front foot behind the start line, participants were instructed to sprint past the final marker which was situated 3 metres from the third timing gate to ensure that participants did not slow down. The time taken for the participants to run between the first and second (10 m), and first and third (20 m) timing gates was recorded using a hand held wireless controller. The best 10 m and 20 m times of the three sprints were recorded and represented acceleration and sprint performance, respectively. Participants received verbal encouragement and were given feedback on performance throughout. Participants performed the speed tests on an artificial grass surface. The inter-day test-retest reliability of 10 m sprint time and maximal linear speed (fastest 10 m split time over 40 m) using timing gates has previously been shown to be acceptable in pre (10 m speed: CV = 2.2%, ICC = 0.48; maximal speed: CV = 1.6%, ICC = 0.90), mid- (10 m speed: CV = 2.2%, ICC = 0.76; maximal speed: CV = 1.4%, ICC = 0.96) and post- (10 m speed: CV = 2.2%, ICC = 0.70; maximal speed: CV = 1.2%, ICC = 0.97) PHV male soccer players (Buchheit and Mendez-Villanueva, 2013).

## 7.2.4 Statistics

The mean and standard deviation (*s*) were calculated for all variables. All data was tested for normality using the Shapiro Wilks normality test. Main and interaction effects between maturation status (Pre-, Mid and Post-PHV) and athlete status (ESP vs. CON) on performance (BH and BV CMJ, 10 m acceleration and 20 m sprint) were analysed using 2-way between factor ANOVAs (between factor 1: maturation status; between factor 2: athlete status). Post-hoc analyses were then performed using paired *t*-tests with Bonferroni-correction to determine differences in performance between ESP and CON at different stages of maturation. Percent changes in jump and sprint performances were calculated from pre- to mid- to post-PHV. Simple effect size, estimated from the ratio of the mean difference to the pooled standard deviation, was also calculated. Effect size ranges of < 0.20, 0.21-0.60 and 0.61-1.20, 1.21-2.00 and > 2.00 were considered to represent trivial, small, moderate large and very large differences, respectively (Hopkins, 2006). Statistical analysis was completed using SPSS version 21 (SPSS Inc., Chicago, IL), and the significance level was set at  $p < 0.05$ .

## 7.3 RESULTS

### 7.3.1 Anthropometric analyses

Stature. As expected, there was a main effect of maturation status ( $F = 729.641$ ,  $P < 0.001$ ; Table 7.1), with post-PHV being taller than mid-PHV ( $P < 0.001$ ), which was taller than pre-PHV ( $P < 0.001$ ). There was no main effect of athlete status ( $F = 2.723$ ,  $P = 0.100$ ; Table 7.1) but there was an interaction between athlete status and maturation status ( $F = 6.173$ ,  $P = 0.002$ ; Table 7.1). There was no difference in stature between ESP and CON at pre-PHV ( $F = 0.643$ ,  $P = 0.423$ ; Table 7.1), or at

mid-PHV ( $F = 0.096$ ,  $P = 0.757$ ; Table 1), but at post-PHV, ESP was taller than CON ( $F = 17.382$ ,  $P < 0.001$ ; Table 7.1).

Body mass. As expected, there was a main effect of maturation status ( $F = 643.233$ ,  $P < 0.001$ ; Table 7.1), with post-PHV having a greater mass than mid-PHV ( $P < 0.001$ ), which was greater than pre-PHV ( $P < 0.001$ ). There was no main effect of athlete status ( $F = 0.195$ ,  $P = 0.659$ ; Table 7.1), but there was a significant interaction between athlete status and maturation status ( $F = 3.937$ ,  $P = 0.020$ ; Table 7.1). There was no difference between ESP and CON at pre-PHV ( $F = 1.283$ ,  $P = 0.258$ ; Table 7.1) or at mid-PHV ( $F = 1.329$ ,  $P = 0.250$ ; Table 7.1), but at post-PHV, body mass was greater in ESP than CON ( $F = 5.465$ ,  $P = 0.020$ ; Table 7.1).

Leg length. As expected, there was a main effect of maturation status ( $F = 317.569$ ,  $P < 0.001$ ; Table 7.1) with post-PHV having greater leg length than mid-PHV ( $P < 0.001$ ), which was longer than pre-PHV ( $P < 0.001$ ). There was no main effect of player status ( $F = 0.445$ ,  $P = 0.505$ ; Table 7.1) but there was an interaction between athlete status and maturation status ( $F = 4.953$ ,  $P = 0.008$ ; Table 7.1). There was no difference between ESP and CON at pre-PHV ( $F = 2.418$ ,  $P = 0.121$ ; Table 7.1), or at mid-PHV ( $F = 0.009$ ,  $P = 0.926$ ; Table 7.1), but at post-PHV, ESP had a longer leg length than CON ( $F = 8.242$ ,  $P = 0.004$ ; Table 7.1).

**Table 7.1.** Participant characteristics in pre-PHV (ESP: n = 99; CON: n = 44) mid-PHV, (ESP: n = 25, CON: n = 15) and post-PHV (ESP: n = 87, CON: n = 54) maturation groups.

	Age (years)		Stature (cm)		Leg length (m)		Body mass (kg)	
	ESP	CON	ESP	CON	ESP	CON	ESP	CON
<b>Pre-PHV</b>	10.9 ± 1.3	11.2 ± 1.3	144.1 ± 7.6	145.1 ± 7.6	68.2 ± 5.3	69.5 ± 5.1	35.9 ± 5.2	37.5 ± 5.8
<b>Mid-PHV</b>	13.8 ± 0.8	13.6 ± 0.6	163.3 ± 5.8	162.6 ± 5.2	79.8 ± 3.9	79.6 ± 3.9	48.3 ± 5.8	51.2 ± 8.1
<b>Post-PHV</b>	17.5 ± 2.1	18.6 ± 3.7	180.0 ± 6.5*	175.0 ± 6.2	85.6 ± 4.5*	83.0 ± 4.4	72.0 ± 9.6*	69.3 ± 8.9

Key: ESP, elite youth soccer player group; CON, control group; PHV, peak height velocity.

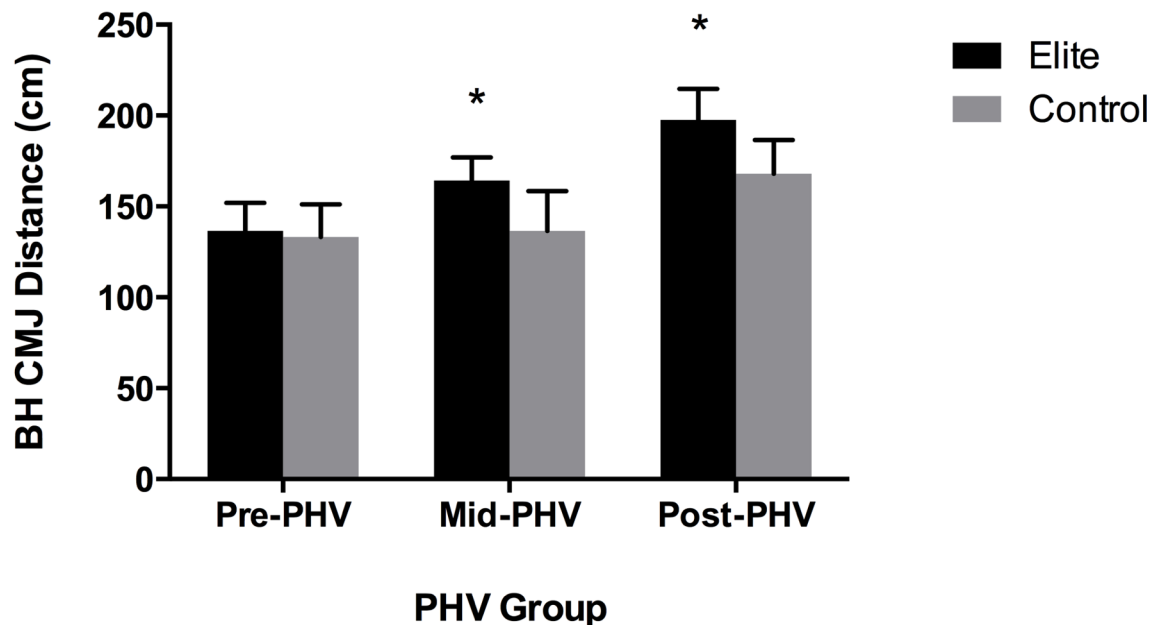
\* Significantly greater than CON ( $P \leq 0.02$ ).

Age. As expected, there was a main effect of maturation status ( $F = 364.090$ ,  $P < 0.001$ ), with post-PHV being older than mid-PHV ( $P < 0.001$ ), which was older than pre-PHV ( $P < 0.001$ ). There was no main effect of athlete status ( $F = 1.840$ ,  $P = 0.176$ ; Table 1). There was no interaction between player status and PHV status for age ( $F = 0.1838$ ,  $P = 0.161$ ).

### 7.3.2 Bilateral Horizontal-forward Countermovement Jump (BH CMJ)

As expected, there was a significant main effect of maturation status for ( $F = 214.453$ ,  $P < 0.001$ ; Fig. 7.1), with post-PHV performing better than mid-PHV ( $P < 0.001$ ), which performed better than pre-PHV ( $P < 0.001$ ). There was a main effect of athlete status ( $F = 71.237$ ,  $P < 0.001$ ; Fig. 7.1), with ESP performing better than CON ( $161.7 \pm 32.1$  vs.  $146.5 \pm 24.9$  cm, respectively). There was also an interaction between athlete status and maturation status ( $F = 18.337$ ,  $P < 0.001$ ; Fig. 7.1). ESP jumped further than CON at both mid-PHV ( $P < 0.001$ ; Fig. 7.1) and post-PHV ( $P < 0.001$ ; Fig. 7.1) but there was no difference between ESP and CON at pre-PHV ( $P = 0.273$ ; Fig. 7.1). Large effect sizes were associated with differences in BH CMJ

performance between ESP and CON at post-PHV ( $d = 1.32$ ) and mid-PHV ( $d = 1.30$ ) maturation status. However, only small effect sizes were associated with differences in BH CMJ performance between ESP and CON at pre-PHV status ( $d = 0.21$ ).

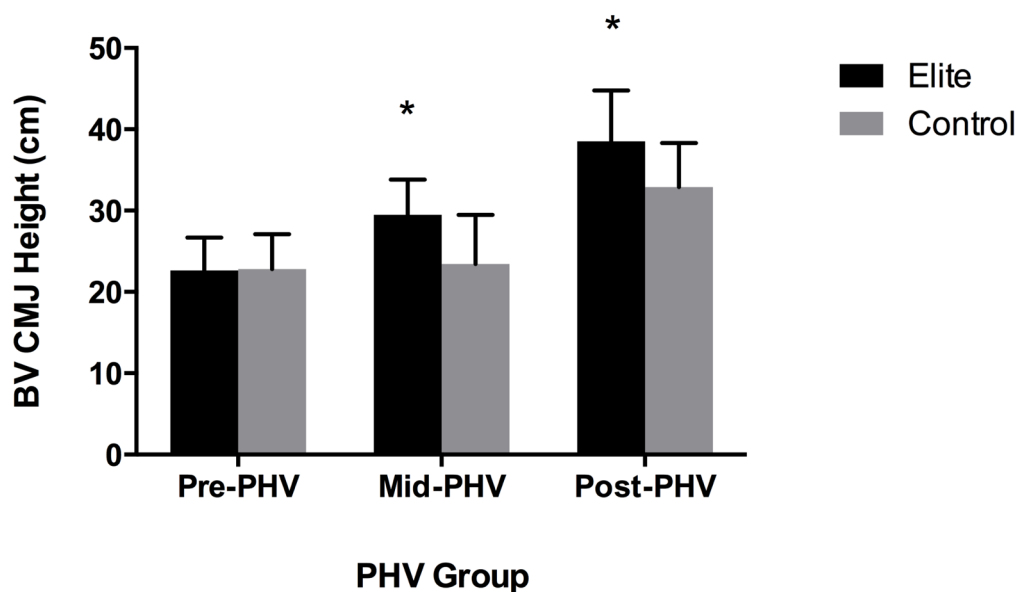


**Figure 7.1.** Bilateral horizontal-forward countermovement jump (BH CMJ) performance in pre-PHV (ESP:  $n = 99$ ; CON:  $n = 44$ ), mid-PHV (ESP:  $n = 25$ ; CON:  $n = 15$ ) and post-PHV (ESP:  $n = 68$ ; CON:  $n = 34$ ) maturation groups. \* Significant difference between ESP and CON ( $P < 0.001$ ). ESP, elite soccer players; CON, control participants; PHV, peak height velocity.

### 7.3.3 Bilateral Vertical CMJ (BV CMJ)

As expected, there was a main effect of maturation status ( $F = 199.399$ ,  $P < 0.001$ ; Fig. 7.2), with post-PHV performing better than mid-PHV ( $P < 0.001$ ), which performed better than pre-PHV ( $P = 0.001$ ). There was also a main effect of athlete status ( $F = 28.503$ ,  $P < 0.001$ ; Fig. 7.2), with ESP jumping higher than CON ( $29.9 \pm 9.0$  vs.  $28.0 \pm 7.1$  cm, respectively). There was also an interaction between athlete status and maturation status ( $F = 10.939$ ,  $P < 0.001$ ; Fig. 7.2), with ESP jumping

higher than CON at both mid-PHV ( $P < 0.001$ ; Fig. 7.2) and post-PHV ( $P < 0.001$ ; Fig. 7.2) but there was no difference between ESP and CON at pre-PHV ( $P = 0.880$ ; Fig. 7.2). Moderate effect sizes were associated with differences in BV CMJ performance between ESP and CON at post-PHV ( $d = 0.86$ ) and mid-PHV ( $d = 1.05$ ) status. However, only trivial effect sizes were associated with differences in BV CMJ performance between ESP and CON at pre-PHV status ( $d = 0.04$ ).



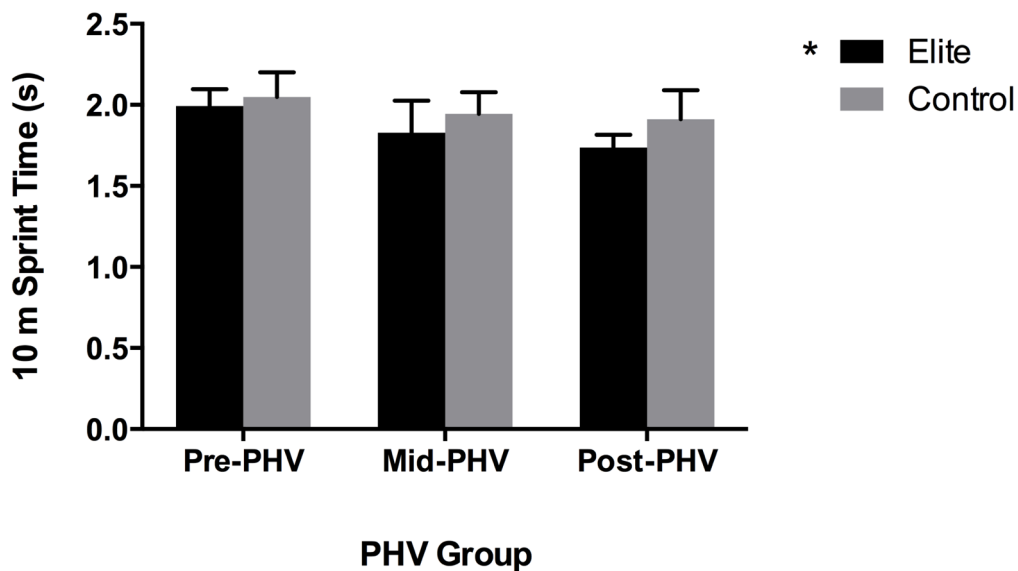
**Figure 7.2.** Bilateral vertical countermovement jump (BV CMJ) performance in pre-PHV (ESP:  $n = 99$ ; CON:  $n = 38$ ), mid-PHV (ESP:  $n = 25$ ; CON:  $n = 14$ ) and post-PHV (ESP:  $n = 85$ ; CON:  $n = 54$ ) maturation groups. \* Significant difference between ESP and CON ( $P < 0.001$ ). ESP, elite soccer players; CON, control participants; PHV, peak height velocity.

#### 7.3.4 10 m Sprint

As expected, there was a main effect of maturation status ( $F = 92.019$ ,  $P < 0.001$ ), with post-PHV accelerating faster than mid-PHV ( $P < 0.001$ ), which performed better than pre-PHV ( $P < 0.001$ ; Fig. 7.3). There was also a main effect of athlete status ( $F = 18.540$ ,  $P < 0.001$ ), with ESP able to accelerate quicker than CON ( $1.877 \pm 0.164$



vs.  $1.918 \pm 0.178$  s, respectively). There was no interaction between athlete status and maturation status for 10 m sprint performance ( $F = 0.770$ ,  $P = 0.464$ ), demonstrating that ESP performed better than CON at all three stages of maturation. Moderate effect sizes were associated with differences in 10m-sprint performance between ESP and CON in the post-PHV ( $d = 0.63$ ) and mid-PHV ( $d = 0.63$ ) groups. However, only small effect sizes were associated with differences in 10m-sprint performance between ESP and CON in the pre-PHV group ( $d = 0.48$ ).

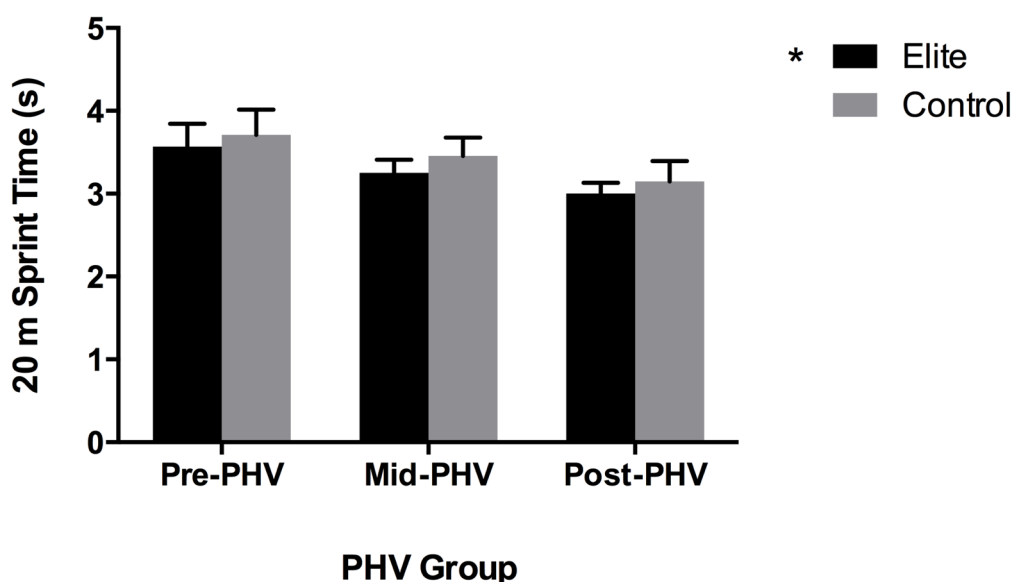


**Figure 7.3.** 10 m sprint performance in pre-PHV (ESP:  $n = 97$ ; CON:  $n = 26$ ), mid-PHV (ESP:  $n = 24$ ; CON:  $n = 14$ ) and post-PHV (ESP:  $n = 70$ ; CON:  $n = 32$ ) maturation groups. \* Significant main effect between elite players and controls ( $P < 0.001$ ). ESP, elite soccer players; CON, control participants; PHV, peak height velocity.

### 7.3.5 20 m Sprint

Unsurprisingly, there was a main effect of maturation status for 20 m sprint performance ( $F = 124.514$ ,  $P < 0.001$ ), with post-PHV sprinting faster than mid-PHV ( $P < 0.001$ ), which was faster than pre-PHV ( $P < 0.001$ ; Fig. 7.4). There was also a

main effect of athlete status ( $F = 21.395$ ,  $P < 0.001$ ; Fig. 7.4), with ESP able to sprint faster than CON ( $3.321 \pm 0.344$  vs.  $3.410 \pm 0.365$  s, respectively). There was no interaction between player status and PHV status for 20 m sprint performance ( $F = 0.256$ ,  $P = 0.774$ ), showing that ESP performed better than CON at all three stages of maturation. Moderate effect sizes were associated with differences in 20m-sprint performance between ESP and CON in the post-PHV ( $d = 0.78$ ) and mid-PHV ( $d = 0.99$ ) groups. However, only small effect sizes were associated with differences in 20m-sprint performance between ESP and CON in the pre-PHV group ( $d = 0.49$ )



**Figure 7.4.** 20 m sprint performance in pre-PHV (ESP:  $n = 97$ ; CON:  $n = 26$ ), mid-PHV (ESP:  $n = 24$ ; CON:  $n = 14$ ) and post-PHV (ESP:  $n = 69$ ; CON:  $n = 32$ ) maturation groups. \* Significant main effect between elite players and controls ( $P < 0.001$ ). ESP, elite soccer players; CON, control participants; PHV, peak height velocity.

## 7.4 DISCUSSION

The aim of our study was to investigate whether acceleration, sprint, horizontal-forward CMJ and vertical CMJ capabilities were important for elite youth soccer at different stages of maturation. The main findings were that, whilst ESP outperformed

the CON group in acceleration and sprint tasks at all stages of maturation, they only outperformed CON in BH and BV CMJ tasks at mid-PHV and post-PHV maturation status. More specifically, the difference in BH CMJ performance between ESP and CON participants for both mid-PHV and post-PHV groups was associated with a large practical magnitude, whereas only moderate practical magnitudes were associated with the difference between ESP and CON participants in both mid-PHV and post-PHV groups for acceleration, sprint and BV CMJ performance. These results suggest that, when identifying pre-PHV soccer talent, acceleration and sprint assessments, rather than jump assessments, should be employed. However, when identifying elite soccer talent from mid-PHV and post-PHV maturation groups, elite soccer clubs should prioritise BH CMJ performance over BV CMJ, acceleration and sprint performance.

When evaluating physical performance tests for soccer talent identification, growth and maturation are considered to be the main confounding factors (Pearson, Naughton and Torode, 2006, Vandendriessche et al., 2012). By grouping ESP and CON according to maturation status, we attempted to overcome this limitation and establish the predictors of elite soccer performance at different stages of maturation. As many previous studies did not group players into maturation groups, it is difficult to compare the performance scores in the current study with those from others. Moreover, different criteria and equipment utilized for testing protocols also made comparisons difficult (Stolen et al., 2005). Nevertheless, pre-PHV ESP in our study demonstrated similar BV CMJ performance (22.7 cm jump height) compared to U10, U11 and U12 (mean age 10.3 years old) elite Belgian youth soccer players (22.4 cm jump height) (Deprez et al., 2015). Similarly, our mid-PHV ESP BV CMJ height performance ( $29.5 \pm 4.3$  cm) was comparable with elite youth Portuguese soccer players aged between 13-15 years (mean age  $14.3 \pm 0.6$  years; jump height  $29.3 \pm 4.6$  cm) (Malina et al., 2004). In addition, our post-PHV ESP demonstrated similar BV

CMJ scores to U17 elite Belgian youth soccer players ( $38.5 \pm 6.3$  vs.  $37.0 \pm 4.6$  cm, respectively) (Deprez et al., 2015) and elite Norwegian players aged 16-18 yr ( $38.6 \pm 5.1$  cm) (Haugen, Tønnessen and Seiler, 2013). Subsequently, the EPL ESP seem to have similar BV CMJ capabilities to elite youth players in different leagues around Europe, thus suggesting our elite cohort may be representative of European elite youth soccer players at different stages of maturation.

Comparing the physical capabilities of ESP and CON participants who have never been selected to play at the elite level, may provide an insight into which physical capabilities are potentially important for elite performance (Cometti et al., 2001). Within this context, pre-PHV ESP achieved significantly greater acceleration and sprint performance compared to CON, thus illustrating that these capabilities may be indicators of pre-PHV elite youth soccer playing status. These findings are somewhat in agreement with a study that compared soccer players who dropped out, with players retained, in a high level soccer development programme. Players retained at age groups U10 and U11, and U10 and U12, demonstrated significantly greater 5 m acceleration and 30 m sprint performance, respectively, compared to those players who dropped out (Deprez et al., 2015). However, although our data shows that there was a significant difference ( $P < 0.05$ ) between pre-PHV ESP and CON in acceleration and sprint performance assessments, the effect size of this difference was classified as small (acceleration:  $d = 0.48$ ; sprint:  $d = 0.49$ ). Subsequently, our data shows that the difference in acceleration and sprint performance between pre-PHV ESP and CON was only small, and therefore these capabilities may not be considered important indicators of playing status in pre-PHV elite soccer. It has previously been shown that the magnitude of speed gains were similar for pre-PHV soccer players involved in straight line sprint training or co-ordination training (Venturelli, Bishop and Pettene, 2008), which suggests that motor co-ordination plays a key role in speed development in pre-PHV children. In support

of this, it has been reported that the neuromuscular system undergoes a rapid development during the pre-PHV years (Borms, 1986), with peak rates of brain maturation being reported to occur between 6 and 8, and 10 and 12 years of age (Rabinowickz, 1986). The greater acceleration and speed capabilities demonstrated by pre-PHV ESP compared to controls in the current study, may therefore be a reflection of better motor co-ordination skills (Vandendriessche et al., 2012, Venturelli, Bishop and Pettene, 2008). Subsequently, it appears that EPL pre-PHV ESP may be selected based on demonstrating better inter-muscular and intra-muscular co-ordination (Lloyd and Oliver, 2012, Viru et al., 1999), which underpin greater acceleration and speed performance.

In contrast to the pre-PHV period, the surge in hormone concentrations (e.g. testosterone and growth hormone) during the mid-PHV period (Forbes et al., 2009, Round et al., 1999), and the associated anthropometric (stature, body mass, muscle mass, etc.) (Malina, Bouchard and Bar-Or, 2004) and physiological changes in the muscle and tendon structures, are thought to underpin developments in running speed capabilities during maturation (Rumpf et al., 2013). Acceleration and sprint performance was greater in the ESP in the current study compared to maturity matched control participants in the mid-PHV and post-PHV groups. This somewhat concurs with findings from Waldron and Murphy (2013), who reported better 30 m sprint performances in elite compared with sub-elite English U14 youth soccer players. However, they did not account for maturation, so it is possible that ESP outperformed NSP due to being physically more mature. Nonetheless, when maturation was accounted for and included as a covariate, Vaeyens and colleagues (2006) reported that youth ESP demonstrated greater 30 m performance in comparison to age matched non-elite players (U13-U16). In contrast, a retrospective analysis in French U14-U16 soccer players contradicts these findings, reporting no difference in sprint performances amongst players reaching future international,

professional or amateur status (le Gall et al., 2010). Due to the different demands associated with competing in various European Leagues (Dellal et al., 2011), it appears that the speed requirements of elite youth soccer may be specific to the demands of the senior league. Within this context, the results of our study reflect the demands of EPL youth soccer and it appears acceleration and sprint performance can discriminate between EPL ESP and CON at all stages of maturation.

In contrast to the small practical difference between acceleration and sprint performance in the pre-PHV ESP and CON, differences between ESP and CON participants at mid-PHV and post-PHV maturation stages were associated with a moderate practical magnitude, thus suggesting the acceleration and sprint demands are greater in mid-PHV and post-PHV elite soccer. In EPL academies, the current competitive match-play format progressively increases in the number of players and absolute size of the pitch until U13 age group, when senior football is simulated on a large pitch in 11 vs. 11 format (Pover, 2016). Consequently, a greater pitch area leads to an increase in both sprint frequency and sprint distances achieved during competitive match-play (Casamichana, Castellano and Castagna, 2012). This may explain the larger effect size when comparing sprint performance between ESP and CON at mid-PHV (~14 years of age) vs. pre-PHV maturation status. Thus, acceleration and sprint capabilities appear to become more important at mid- and post-PHV compared to pre-PHV elite youth soccer. The results of our study may therefore suggest that EPL elite soccer academies recruit footballers with superior acceleration and sprint qualities, especially during the mid- and post-PHV periods.

Whilst muscular power is a component of acceleration and sprint performance (Rumpf et al., 2013), unilateral horizontal-forward and vertical CMJs are thought to assess separate leg power qualities (please see Chapter Four) and have previously been shown to have different development patterns during adolescence in elite youth soccer players (Philippaerts et al., 2006). It was therefore deemed

important to determine the importance of these independent capabilities at different stages of maturation. We found no difference in BH CMJ or BV CMJ performance between ESP and CON participants in the pre-PHV groups. In contrast, mid-PHV and post-PHV ESP achieved greater BV CMJ and BH CMJ performance than maturity-matched control participants. These data therefore suggest that vertical and horizontal-forward power performance may be determinants of elite soccer playing status during the mid-PHV and post-PHV periods, but are not important in during the pre-PHV period. As it has been reported that the percentage of muscle mass increased by 0.6% and 29% per year from the age of 7 to 13.5, and 13.5 to 15 years, respectively (Malina, 1969), the large increase in muscular power from the beginning of the mid-PHV period (Meylan et al., 2014) could be largely attributed to the increase in muscle volume during growth and its direct relationship with peak power (Jones, Rutherford and Parker, 1989, Martin et al., 2003, Meylan et al., 2014, O'Brien et al., 2009b). It therefore appears that vertical and horizontal-forward power only become determinants of elite youth soccer during the mid- and post-PHV periods when the individual begins to develop his phenotypic muscle mass profile.

The significant difference in BH CMJ and BV CMJ between EPL ESP and CON participants at mid-PHV and post-PHV were associated with large (BH CMJ) and moderate (BV CMJ) practical magnitudes. Hence, it appears that, during the mid-PHV and post-PHV periods, BH CMJ performance is a more important determinant of elite youth soccer than BV CMJ, and should be prioritised in talent identification and development protocols. These findings are supported by our previous results showing no difference in unilateral vertical CMJ height between elite and non-elite professional soccer players, but a significant difference for unilateral horizontal-forward CMJ projectile range (please see Chapter Four). However, in contrast to the current study, we reported in Chapter Three that there was no difference in any BV CMJ performance variable between ESP and NSP. In Chapter

Four ESP were compared with non-elite players (players who participated in at least one hour per week of competitive soccer (eleven-a-side or five-a-side), and one hour per week of soccer-specific or fitness-based training), whereas the current study compared ESP and CON participants (a range of active male volunteers who never represented an elite soccer club). Hence, it appears that the BV CMJ can distinguish between ESP and CON, but not NSP practicing soccer on a regular basis. Our findings would therefore agree with previous longitudinal research which compared players who dropped out or were retained in an elite soccer development programme, and documented that horizontal-forward CMJ capability was the key physical factor at a young age influencing future contract status and playing minutes after reaching professional status (Deprez et al., 2015).

Attempting to identify the physical determinants of EPL youth soccer in our cross sectional study by comparing ESP and CON may have limitations. We cannot discount that this population of players developed greater physical capabilities from exposure to an elite soccer development training programme, and were therefore perhaps not initially selected based on a superior physical profile. Indeed, a longitudinal study suggested that U12-U16 EPL youth soccer players exposed to an elite training programme over three years developed speed and power capabilities at greater rates than control participants when controlling for maturation (Wrigley et al., 2014). However, in agreement with our findings, the EPL academy players in the aforementioned study demonstrated greater acceleration, sprint and jump performance at baseline, which was associated with a large effect size (representative of the practical magnitude difference) (Wrigley et al., 2014). Moreover, currently unpublished, recent data from our research group demonstrates that the majority of training time for players selected at the EPL academy in our study was spent performing technical and tactical training, and only U15-U21 players performed resistance training for an average of  $45 \pm 18$  min per week (Brownlee,



2016). It was also shown that there was no improvement in isometric mid-thigh pull strength [previously correlated with 10-m sprint time and BV CMJ performance (Thomas et al., 2015, West et al., 2011)] after 8 weeks of exposure to in-season soccer training in ESP at all three stages of maturation (Brownlee, 2016). Subsequently, it appears that the ESP who participated in our study may have been selected based on demonstrating greater physical performance and a large proportion of their physical capacities could have been inherited, rather than developed from partaking in an elite soccer training programme. In support of this theory, previous longitudinal research showed large variations in the rank scores in speed and power performance measures for ESPs (age: 12 yrs) exposed to the same training programme (players only included if they attended over 90% of training sessions) over a four-year period (ICC values, 10 m sprint time: 0.66; BV CMJ: 0.66) (Buchheit and Mendez-Villanueva, 2013). This research therefore documents that during adolescence, ESPs may respond differently to the same training environment and develop physical speed and power capacities at different rates thus achieving contrasting performance levels relative to their original ranking amongst the elite cohort at baseline. Subsequently, it may be that the ESP's physical development during maturation is in fact, largely determined by their genetic profile rather than the elite soccer training environment they are exposed to.

Elite soccer players have previously been associated with more favorable genetic profiles in comparison to CON (Egorova et al., 2014, Juffer et al., 2009, Santiago et al., 2008). As our findings suggest that muscular power becomes more important in elite youth soccer at mid- and post-PHV [when anabolic hormone-stimulated muscle growth becomes a major factor (Malina et al., 2004)], candidate gene variations that may contribute to the differences in power seen here include the *ACTN3* R577X polymorphism, which has previously been associated with testosterone concentration in elite Russian athletes (Ahmetov, Donnikov and

Trofimov, 2014), and muscle volume, strength and power in young, healthy men (Erskine et al., 2014). However, the genetic profile in EPL players and its relationship to acceleration, sprint and power performance at different stages of maturation has never been investigated and this area requires more research to determine the influence of genetic variation on elite soccer player status and physical performance.

## **7.5 CONCLUSION**

Our study provides evidence that talent identification in elite youth soccer needs to be dynamic and specific to maturation status. Acceleration and sprint performance appear to be determinants of elite soccer at all stages of maturation but more so at mid- and post-PHV. Vertical and horizontal-forward power, on the other hand, only appear to be important during mid-PHV and post-PHV periods, thus suggesting that jump assessments may be unnecessary for pre-PHV talent identification protocols. The large effect size (practical magnitude of difference) in BH CMJ performance (compared to acceleration, sprint and BV CMJ performance) between ESP and CON participants at mid- and post-PHV suggests this assessment should be prioritised in soccer talent identification and development protocols in mid-PHV and post-PHV players only. It is currently unknown whether differences in speed and power capabilities between ESP and CON are primarily due to environmental or genetic factors.

## **CHAPTER EIGHT**

# **THE GENETIC ASSOCIATION WITH SPRINT AND POWER PERFORMANCE IN ELITE YOUTH SOCCER IS SPECIFIC TO MATURATION STATUS**

## STUDY 6: ABSTRACT

### THE GENETIC ASSOCIATION WITH SPRINT AND POWER PERFORMANCE IN ELITE YOUTH SOCCER IS SPECIFIC TO MATURATION STATUS

**Purpose:** We aimed to investigate the role of *ACTN3* R577X (rs1815739), *BDNF* G>A (rs6265), *COL5A1* C>T (rs12722), and *COL2A1* C>T (rs2070739) single nucleotide polymorphisms (SNPs) in determining athlete status, and speed and power capabilities, in elite youth soccer players (ESP) and control participants (CON) at different stages of maturation. **Methods:** ESP (n=208; age, 14.0±3.5 yrs) and CON (n=114; age, 15.0±4.4 yrs) were genotyped for four SNPs and grouped using years from/to predicted peak height velocity (PHV) to determine maturation status. Participants performed three reps of: 10m and 20m sprint, bilateral vertical countermovement jump (BVCMJ) and bilateral horizontal-forward countermovement jump (BHCMJ). **Results:** The *ACTN3* R- and *BDNF* G-allele frequencies, and *BDNF* GG genotype frequencies, were more common in post-PHV ESP than in pre-PHV ESP ( $P \leq 0.034$ ). The *COL2A1* CC genotype was associated with greater BHCMJ and 20 m sprint performance compared to T-allele carriers in all participants (BHCMJ: 159.1±32.2 vs. 145.4±29.9 cm;  $P=0.024$ ; 20 m sprint: 3.316±0.334 vs. 3.449±0.441 s;  $P=0.040$ ). The *BDNF* GG genotype was associated with faster 20 m sprint performance compared to the A-allele in pre-PHV participants only (3.556±0.249 vs. 3.644±0.219 s;  $P=0.048$ ). **Conclusions:** *ACTN3* R- and *BDNF* G-allele frequencies are more important in determining post-PHV, than pre-PHV, elite soccer playing status. The *COL2A1* CC genotype association with greater horizontal-forward power was probably related to genotype-dependent tendon properties. *BDNF* GG genotype appears to influence 20 m sprint performance only during the pre-PHV period, suggesting that neuromuscular control is a pre-determinant of sprint performance in pre-pubertal children.

**Keywords:** *talent identification, genotype, polymorphism, polygenic.*

## 8.1 INTRODUCTION

The physical determinants of elite youth soccer playing status may be specific to the stage of maturation (please see Chapter Seven) (Vaeyens et al., 2006, Vandendriessche et al., 2012). While we have previously demonstrated that acceleration and sprint performance were greater in ESP compared to CON at all stages of maturation (pre-, mid- and post-PHV), BV and BH CMJ capabilities only discriminated between mid- and post-PHV ESP and CON (please see Chapter Seven). Human physical capabilities are influenced by a number of environmental and genetic factors (De Moor et al., 2007). However, it is unknown if genetic variation may account for the differences in speed and power capacities between ESP and CON, or if specific gene polymorphisms may be more advantageous to elite soccer performance at different stages of maturation. Such information could help inform genetic screening criteria in ESP, which could potentially help applied practitioners identify physical deficiencies earlier in a player's career (i.e. before maturation).

The majority of previous soccer genetics research consisted of case control studies, which reported that adult ESP were associated with more favorable genetic profiles in comparison to CON (Egorova et al., 2014, Ginevičienė et al., 2010, Juffer et al., 2009, Micheli et al., 2011, Santiago et al., 2008). However, case control studies are of limited use to the applied practitioner as, unlike cross-sectional association studies, they do not reveal the relationship between specific genetic polymorphisms and physical performance parameters. There is a paucity of cross sectional genetic association studies in soccer (Coelho et al., 2015, Pimenta et al., 2013) and the contribution of genetic variation to speed and power performance in ESP remains unknown.

The genetic association with speed and power is likely due to certain gene variants influencing the protein product(s), which in turn, affect(s) the physiological determinants of speed and power. From Chapter Six, we demonstrated that the main determinant of UH CMJ performance in elite U18 and U21 soccer players was patellar tendon elasticity. Elite U18 and U21 ESP also presented with more extensible patellar tendons compared to NSP (Chapter Six). Nearly 85% of the dry mass of a tendon consists of collagen, and the mechanical and physiological characteristics of the collagenous tissue dictate the qualities of the tendon (Kirkendall and Garrett, 1997). The *COL5A1* gene encodes the alpha 1 chain of procollagen type V, a quantitatively minor fibrillar collagen that may have regulatory roles in controlling fibril diameter in connective tissue such as tendon (Birk et al., 1990, Wenstrup et al., 2011). The *COL5A1* (rs12722) single nucleotide polymorphism (SNP) has been associated with the extensibility of the tendon-aponeurosis structures of the knee extensors in some (Kirk et al., 2016, Kubo, Yata and Tsunoda, 2013), but not all studies (Foster et al., 2014). However, the *COL5A1* (rs12722) SNP has never been investigated in ESP.

Another gene related to collagen formation is *COL2A1*, which encodes the alpha 1 chain of procollagen type II. A SNP has been identified in the *COL2A1* gene (rs2070739) which involves a C>T missense substitution on human chromosome 12 (Nishimura et al., 2005). *COL2A1* gene (rs2070739) may regulate the concentration of procollagen type II produced (Donoso et al., 2003, Tarpey et al., 2013). Collagen type II forms strong fibrils, is the major component found in adult cartilage (Eyre, 2002), and is also located in the tendon at the cartilaginous zone of the tendon-bone interface (Adamczyk et al., 2008, Buckley et al., 2013, Waggett et al., 1998). Subsequently, it could be hypothesised that the *COL2A1* gene (rs2070739) may affect the capacity of the tendon to store and release mechanical energy (Kirkendall and Garrett, 1997), which could potentially influence concentric power production

during stretch shortening cycle actions (Kubo et al., 2011, Kubo, Kanehisa and Fukunaga, 2005). However, the *COL2A1* rs2070739 SNP has never been investigated in an athletic population and its association with physical performance remains unknown.

As well as the patella tendon influencing horizontal-forward power in soccer players, we demonstrated in Chapter Five that quadriceps femoris (QF) muscle volume was the main determinant of concentric vertical power in ESP. In addition, we showed in Chapter Five that elite U21 and U18 ESP had greater QF muscle volume compared to NSP. A common SNP in the human alpha-actinin-3 (*ACTN3*) gene results in either an arginine (R) or a stop codon (X) at amino acid 577 of exon 16 on chromosome 11 (North and Beggs, 1996). This results in an individual being one of three genotypes for this SNP: RR, RX or XX. Previously, XX homozygotes have been found to have smaller QF volume in young healthy men (Erskine et al., 2014), and a greater composition of type I skeletal muscle fibres (Ahmetov et al., 2011, Vincent et al., 2007) than individuals of RR or RX genotype. The *ACTN3* R577X SNP has also been associated with speed and power in Brazilian professional senior soccer players (Pimenta et al., 2013), although these findings were not consistent (Coelho et al., 2015). Moreover, it is not known if the *ACTN3* R577X SNP is associated with ESP of varying maturation status.

Maximal power is not only governed by the morphology and size of the muscle, but also by the ability to activate the muscles involved in the action (Cormie, McGuigan and Newton, 2011). Indeed, we demonstrated in Chapter Five that neuromuscular activation of the *vastus lateralis* was associated with vertical jump performance in ESP. Brain derived neurotrophic factor (BDNF) is a neurotrophin that regulates neuronal survival, growth, maintenance, neurogenesis and synaptic plasticity (McAllister, Katz and Lo, 1999). The *BDNF* G>A (rs6265) SNP has been associated with serum concentration of BDNF in response to exercise (Egan et al.,

2003), i.e. individuals homozygous for the G-allele produce more BDNF than individuals of either GA or AA genotype. It is possible, therefore, that the *BDNF* G>A SNP could influence neuromuscular activation and, therefore, maximal power and speed performance in elite youth soccer players. However, the association between this SNP and soccer performance has never been investigated.

Establishing if certain genetic variants are associated with elite soccer playing status and specific measures of power and speed performance could inform future genetic screening criteria at elite clubs. Such information could potentially allow soccer practitioners to predict future power and speed capacities from an early age (i.e. before maturation) and thus, implement detailed and specific long term training intervention programmes that aim to eradicate or develop, predicted physical deficiencies or strengths, respectively. The ability to use genetic profiling to predict a player's future speed and power capacities may also provide valuable information on which positional role they may be best suited to in the future. The first aim of our study was therefore, to investigate the association of the *ACTN3* R577X (rs1815739), *COL5A1* C>T (rs12722), *COL2A1* C>T (rs2070739) and *BDNF* G>A (rs6265) SNPs with elite soccer playing status, at different stages of maturation. The second aim was to investigate associations between the aforementioned SNPs and acceleration, sprint, BH CMJ and BV CMJ performance in youth ESP and control participants at different stages of maturation.

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## **8.2 METHODS**

### **8.2.1 Participants**

Three-hundred and twenty-six males volunteered to take part in this study, and formed two cohorts: ESP (n = 213) and CON (n = 113). The ESP were members of an EPL football academy and regularly participated at U9 to U21 level. The control participants were recruited under the inclusion criteria that they were young healthy males who had not previously played soccer at EPL academy or professional level. The control participants consisted of individuals with a range of habitual activity levels. During the recruitment process, all individuals interested in taking part in the study completed a health questionnaire which included questions about previous injury history. The inclusion criteria for all potential participants were that the individual had been free of any injury to the lower body within the previous three months and had not previously sustained a serious knee or ankle injury which may be aggravated during testing procedures, or cause an adverse effect on performance. Participant characteristics are displayed in Table 7.1. All participants and their parents/guardians (if participants were <16 years old) provided written informed consent prior to participating in the study, which was approved by Liverpool John Moores University Ethics Committee and complied with the Declaration of Helsinki.

### **8.2.2 Experimental Design**

We investigated associations between *ACTN3* R577X (rs1815739), *BDNF* G>A (rs6265), *COL5A1* C>T (rs12722), and *COL2A1* C>T (rs2070739) SNPs, and BV CMJ, BH CMJ, 10 m acceleration and 20 m sprint performance, in ESP and CON of different maturation status [i.e. pre-, mid- and post-peak height velocity (PHV)]. Performance tests were completed in a random order, either on the same day, or within a 3-week period. All tests were performed during the in-season period and

testing sessions were scheduled >48 h after competition or a high intensity training session to minimise the influence of training. Participants performed all tests in soccer shirt/t-shirt, shorts and soccer boots, except for the BV CMJ, for which participants removed their boots.

### **8.2.3 Testing procedures**

#### *8.2.3.1 Anthropometric measurements*

Please see section 7.2.3.1 for the detail of the anthropometric measurements procedure.

#### *8.2.3.2 Warm up protocol*

Please see section 7.2.3.2 for the detail of the warm up procedure.

#### *8.2.3.3 Jump assessments*

Please see section 7.2.3.3 for the detail of the jump assessments.

#### *8.2.3.4 Speed assessments*

Please see section 7.2.3.4 for the detail of the speed assessments.

#### *8.2.3.5 Blood and saliva sampling*

Participants' DNA was obtained from either blood (n = 83) or saliva (n = 243) samples. For blood sampling, a 10-mL blood sample was drawn from a superficial forearm vein into a 10-mL EDTA vacutainer (BD Vacutainer Systems, Plymouth, UK). The whole blood was then aliquoted into 2-mL cryotubes (Eppendorf AG, Hamburg, Germany) and stored at -80°C until DNA extraction. For saliva samples, the participants were required to provide 2 mL saliva into a Genefix tube (Isohelix Ltd., Harrietsham, UK), having not eaten or drunk anything (or chewed gum) for at least

30 min prior to saliva sampling. After collection, the saliva tubes were closed and gently shaken to mix the saliva with 2 mL of non-toxic stabilization buffer contained within the tube. Samples were then incubated at 56°C for 60 min prior to aliquotting into 2 mL cryotubes (Eppendorf AG), and storing at -80°C until DNA extraction.

#### 8.2.3.6 DNA extraction and determination of *ACTN3* R/X (*rs1815739*), *BDNF* G>A (*rs6265*), *COL5A1* C>T (*rs12722*), and *COL2A1* C>T (*rs2070739*) genotypes

DNA purification from blood and saliva samples was performed manually using a QIAamp® DNA Blood Mini Kit (Qiagen Ltd., Manchester, UK), following the manufacturer's guidelines. Briefly, 20 µL proteinase K was pipetted into a 1.5 mL microcentrifuge tube (Fisher Scientific Ltd., Loughborough, UK), followed by 200 µL of sample and 200 µL of lysis buffer AL, which was then incubated at 56°C for 10 min to maximise DNA yield. Following incubation, 200 µL ethanol was added and the mixture was then transferred to a QIAamp Mini spin column (Qiagen Ltd.) and centrifuged at 6000 *g* for 1 min before the mini spin column was transferred to a clean 2 mL collection tube. 500 µL of wash buffer AW1 was then added to the mini spin column before being centrifuged again at 6000 *g* for 1 min. The spin column was again placed into a new 2 mL collection tube and 500 µL wash buffer AW2 was added before centrifuging at 20,000 *g* for 3 min, and again for 1 min after replacing the collection tube. Finally, the spin column was placed in a 1.5 mL microcentrifuge tube (Fisher Scientific Ltd.), and 200 µL elution buffer AE was added to the column, which was centrifuged at 6000 *g* for 1 min after a 2 min incubation period at room temperature. DNA samples were then stored at 4°C until subsequent genotyping.

We performed real-time polymerase chain reaction (RT-PCR) to establish the genotypes of the *ACTN3* R/X (*rs1815739*), *BDNF* G>A (*rs6265*), *COL5A1* C>T (*rs12722*), and *COL2A1* C>T (*rs2070739*) SNPs for each participant. Each 10-µL reaction volume contained 5 µL Genotyping Master Mix (Applied Biosystems, Foster

City, USA), 3.5  $\mu$ L nuclease-free H<sub>2</sub>O (Qiagen Ltd.), 0.5  $\mu$ L genotyping assay mix (Applied Biosystems, Foster City, USA), plus 1  $\mu$ L DNA sample. For control tubes, 1 $\mu$ L nuclease-free H<sub>2</sub>O (Qiagen, Manchester, UK) replaced the DNA template. RT-PCR (Rotor-Gene Q, Qiagen, Manchester, UK) was performed using the following protocol: denaturation at 95°C for 10 min, followed by 50 cycles of incubation at 92°C for 15 s, then annealing and extension at 60°C for 1 min. Genotypes were determined using Rotor-Gene Q Pure Detection 2.1.0 software (Qiagen Ltd.). All samples were analysed in duplicate and there was 100% agreement between genotype calls for samples from the same participant. Genotyping was performed in accordance with published genotyping and quality control recommendations (Chanock et al., 2007).

#### **8.2.4 Data Analysis**

Due to the small number of individuals in the total cohort homozygous for *COL2A1* TT (0.95 %) and *BDNF* AA (3.15 %), *COL2A1* TT homozygotes were combined with *COL2A1* CT heterozygotes and compared with *COL2A1* CC homozygotes, while *BDNF* AA homozygotes were combined with *BDNF* GA heterozygotes and compared with *BDNF* GG homozygotes. All ESP (n = 208), pre-PHV ESP (n = 94) and post-PHV ESP (n = 90) soccer player genotype and allele frequency distributions were compared with all CON (n = 114) genotype and allele frequency distributions (Table 1). Moreover, in order to investigate the importance of genotype at different stages of elite soccer player development, we also compared genotype and allele frequency distributions between pre-PHV (n = 94) and post-PHV (n = 90) soccer players (due to the low sample size of mid-PHV: ESP, n = 25; CON, n = 15), mid-PHV players were excluded from these analyses).

An algorithm proposed by Williams and Folland (2008) was used to estimate the combined influence of these four SNPs on speed/power performance. All

favourable genotypes were placed into a simple additive model whereby each specific favourable genotype polymorphism was given a “score” based on which genotype is associated with “favourable” phenotype (i.e. soccer playing status and/or power performance). Favourable homozygous genotypes were allocated a score of 2, a heterozygous genotype with a score of 1 and the remaining “unfavourable” homozygote with a score of 0. The total genotype score (TGS) was then calculated to lie in the range of 0-100, with 100 representing a perfect genotype profile and 0 representing the worst possible profile.

### **8.2.5 Statistics**

The mean and standard deviation (s) were calculated for all performance variables. All data was tested for normality using the Shapiro Wilks normality test.

Genotype frequencies of the all elite soccer players, pre-PHV elite soccer players, post-PHV elite soccer players and controls were tested for compatibility with Hardy-Weinberg equilibrium (HWE) using  $\chi^2$  goodness of fit tests. Genotype and allele frequency distribution for each SNP were compared between ESP and CON using Pearson's  $\chi^2$  tests. Post-hoc analyses were conducted according to previous recommendations (Beasley and Schumacker, 1995).

For each SNP, three-way between-subjects ANOVAs [between factor 1: player status (ESP vs. CON); between factor 2: maturation status (pre- vs. post-PHV); between factor 3: genotype (*ACTN3* and *COL5A1*, three levels; *COL2A1* and *BDNF*, 2 levels)] were used to determine main effects of athlete status, maturation status, genotype, and interactions between athlete status and maturation status, between athlete status and genotype, between maturation status and genotype, and between athlete status, maturation status and genotype. If a significant three-way interaction occurred, simple simple main effects and simple simple pairwise comparisons with Bonferroni adjustment revealed significant differences. If a

significant two-way interaction occurred, simple main effects and pairwise comparisons with Bonferroni adjustment were performed to reveal differences. If a significant genotype main effect existed, Bonferroni post-hoc tests were used to locate the genotype difference in test performance scores.  $P$ -values  $< 0.05$  (after correcting for multiple comparisons) were considered statistically significant.

Differences in TGS between pre-PHV elite soccer players, post-PHV elite soccer players and all controls were analysed using a one-way ANOVA. Post-hoc analyses were then performed using independent sample  $t$ -tests with Bonferroni-correction to determine differences between groups. Statistical analyses were completed using SPSS version 21 (SPSS Inc., Chicago, IL), and the significance level was set at  $P < 0.05$ .

## **8.3 RESULTS**

### **8.3.1 Genotype and allele frequency distributions**

#### *8.3.1.1 Hardy-Weinberg equilibrium (HWE)*

Genotype frequency distributions of the four SNPs in CON and ESP were in HWE except for the *ACTN3* R577X in ESP (Table 8.1). When ESP were segregated according to maturation status, pre-PHV genotype distributions for all four SNPs were in HWE except for the *ACTN3* R577X SNP (Table 8.1). ESP post-PHV genotype frequency distribution was in HWE for all four SNPs (Table 8.1).

#### *8.3.1.2 Genotype and allele frequency distribution*

*ACTN3* R577X

There was a non-significant tendency for pre-PHV ESP to present with different *ACTN3* genotype frequencies compared to CON ( $\chi^2 = 5.652$ ,  $P = 0.059$ ; Table 8.1). Post-hoc analyses revealed a greater frequency of XX genotype in pre-PHV ESP ( $P = 0.021$ , Table 8.1). There were no differences between *ACTN3* genotype frequencies when comparing any other groups ( $\chi^2 \leq 4.537$ ,  $P \geq 0.103$ ; Table 8.1). The frequency distribution of the *ACTN3* R-allele was higher in post-PHV ESP compared the pre-PHV ESP ( $\chi^2 = 5.644$ ,  $P = 0.018$ ).

**Table 8.1.** Allele and genotype frequency distributions of *ACTN3* R577X (rs 1815739), *BDNF* G>A (rs 6265), *COL5A1* C>T (rs 12722) and *COL2A1* C>T (rs 2070739) SNPs among elite soccer players (ESP) and control (CON) participants.

Cohort		ESP			CON
Groups		All	Pre-PHV	Post-PHV	All
Group size, <i>n</i>		208	94	90	114
<b><i>ACTN3</i></b>					
Allele, <i>n</i> (%)	R	238 (57.5)	93 (50.5)*	112 (62.9)	133 (58.3)
	X	176 (42.5)	91 (49.5)*	66 (37.1)	95 (41.7)
Genotype, <i>n</i> (%)	RR	82 (39.4)	31 (33.0)	40 (44.4)	39 (34.2)
	RX	76 (36.5)	34 (36.2)	34 (37.8)	55 (48.2)
	XX	50 (24.0)	29 (30.9)	16 (17.8)	20 (17.5)
<b><i>BDNF</i></b>					
Allele, <i>n</i> (%)	G	347 (82.2)	143 (77.7)*	156 (87.6)	184 (81.4)
	A	75 (17.8)	41 (22.3)*	22 (12.4)	42 (18.6)
Genotype, <i>n</i> (%)	GG	140 (67.6)	57 (61.3)*	68 (75.6)	75 (66.4)
	GA/AA	67 (32.4)	36 (38.7)*	22 (24.4)	38 (33.6)
<b><i>COL5A1</i></b>					
Allele, <i>n</i> (%)	C	214 (52.2)	98 (53.3)	93 (52.8)	102 (45.5)
	T	196 (47.8)	86 (46.7)	83 (47.2)	122 (54.5)
Genotype, <i>n</i> (%)	CC	54 (26.1)	28 (29.8)	24 (27.0)	24 (21.1)
	CT	107 (51.7)	43 (45.7)	47 (52.8)	56 (49.1)
	TT	46 (22.2)	23 (24.5)	18 (20.2)	34 (28.9)
<b><i>COL2A1</i></b>					
Allele, <i>n</i> (%)	C	377 (92.0)	163 (89.6)	166 (94.3)	202 (90.2)
	T	33 (8.0)	19 (10.4)	10 (5.7)	22 (9.8)
Genotype, <i>n</i> (%)	CC	175 (85.0)	75 (80.6)	79 (88.8)	91 (81.3)
	CT/TT	31 (15.0)	18 (19.4)	10 (11.2)	21 (18.8)

\* Significantly different to post-PHV elite cohort ( $P < 0.050$ ).

Key: SNP, single nucleotide polymorphism.



### *BDNF G>A*

Post-PHV ESP presented with greater *BDNF* GG genotype frequency than pre-PHV ESP ( $\chi^2 = 4.487$ ,  $P = 0.034$ ; Table 8.1). However, there were no differences in *BDNF* genotype frequency distribution between any other group ( $\chi^2 \leq 2.029$ ,  $P \geq 0.154$ ; Table 8.1). The frequency distribution of the *BDNF* G-allele was higher in post-PHV ESP compared to pre-PHV ESP ( $\chi^2 = 6.918$ ,  $P = 0.018$ ; Table 8.1). There was also a non-significant tendency for a higher *BDNF* G-allele frequency in post-PHV ESP compared with CON ( $\chi^2 = 2.894$ ,  $P = 0.089$ ; Table 8.1).

### *COL5A1 C>T and COL2A1 C>T*

There were no differences in *COL5A1* C/T ( $\chi^2 \leq 2.671$ ,  $P \geq 0.263$ ; Table 1) and *COL2A1* C/T ( $\chi^2 \leq 2.208$ ,  $P \geq 0.114$ ; Table 8.1) genotype frequency distributions between any groups. There was a non-significant tendency for higher *COL2A1* C-allele frequency ( $\chi^2 = 2.721$ ,  $P = 0.099$ ; Table 8.1) in post-PHV ESP compared to pre-PHV ESP.

## **8.3.2 Associations between genotype and speed/power performance**

As the main effects of maturation status and athlete status, as well as interactions between maturation status and athlete status for BH CMJ, BV CMJ, 10 m acceleration and 20 m sprint performance, have previously been reported in Chapter Seven, these are not reported in the results section below.

### *8.3.2.1 ACTN3 R577X (rs1815739)*

#### *BH CMJ performance*

There was no main effect of genotype ( $F = 0.593$ ,  $P = 0.553$ ). There was also no two-way interaction between genotype and athlete status ( $F = 1.287$ ,  $P = 0.278$ ), or

genotype and maturation status ( $F = 0.728, P = 0.484$ ). There was no three-way interaction between genotype, athlete status and maturation status ( $F = 0.115, P = 0.892$ ).

#### *BV CMJ performance*

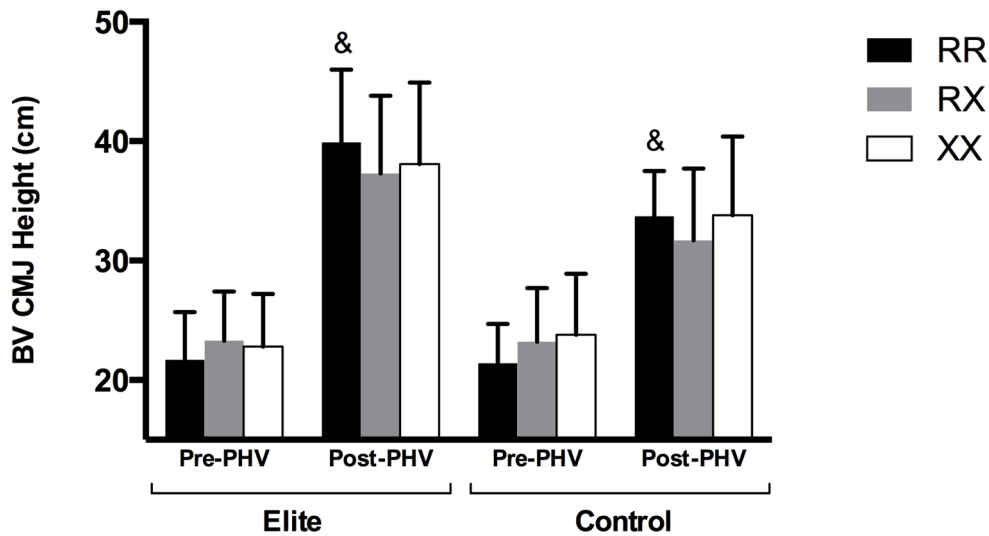
There was no main effect of genotype ( $F = 0.363, P = 0.696$ ). There was also no two-way interaction between genotype and athlete status ( $F = 0.369, P = 0.693$ ). There was, however, a two-way interaction between genotype and maturation status ( $F = 3.241, P = 0.041$ ), with BV CMJ height being greater in post-PHV RR vs. RX genotype (Fig. 1). There was no simple main effect of genotype on BV CMJ performance in pre-PHV participants ( $F = 1.230, P = 0.294$ ; Fig. 8.1). There was no significant three-way interaction between genotype, athlete status and maturation status ( $F = 0.014, P = 0.986$ ).

#### *10 m acceleration performance*

There was no main effect of genotype ( $F = 1.329, P = 0.267$ ). There was also no two-way interaction between genotype and athlete status ( $F = 0.763, P = 0.467$ ), or between genotype and maturation status ( $F = 1.137, P = 0.323$ ). There was no three-way interaction between genotype, athlete status and PHV status ( $F = 0.069, P = 0.933$ ).

#### *20 m sprint performance*

There was no main effect of genotype ( $F = 1.216, P = 0.299$ ). There was no two-way interaction between genotype and athlete status ( $F = 1.807, P = 0.167$ ), or between genotype and maturation status ( $F = 1.329, P = 0.267$ ). There was no three-way interaction between genotype, athlete status and maturation status ( $F = 0.136, P = 0.873$ ).



**Figure 8.1.** The association between *ACTN3* R577X (rs1815739) genotype and bilateral vertical countermovement jump (BV CMJ) performance in pre-peak height velocity (PHV) and post-PHV elite soccer players (pre-PHV:  $n = 94$ ; post-PHV:  $n = 90$ ) and control participants (pre-PHV:  $n = 44$ ; post-PHV:  $n = 54$ ). & Non-significant tendency for a difference in BV CMJ performance between post-PHV RR and RX genotypes ( $P = 0.075$ ).

### 8.3.2.2 *BDNF* G>A (rs6265)

#### *BH CMJ performance*

There was no main effect of genotype ( $F = 3.959$ ,  $P = 0.048$ ). There was a two-way interaction between genotype and athlete status ( $F = 4.547$ ,  $P = 0.034$ ), with CON GG genotype achieving greater jump distance than A-allele carriers ( $151.7 \pm 26.1$  vs.  $140.5 \pm 21.2$  cm;  $F = 4.247$ ,  $P = 0.040$ ). There was no two-way interaction between genotype and maturation status ( $F = 1.207$ ,  $P = 0.273$ ). There was a three-way interaction between genotype, athlete status and maturation status ( $F = 4.899$ ,  $P =$

0.028), with post-PHV CON GG genotype achieving greater BH CMJ distance than post-PHV CON A-allele carriers ( $F = 9.011$ ,  $P = 0.003$ ; Fig. 8.2A).

#### *BV CMJ performance*

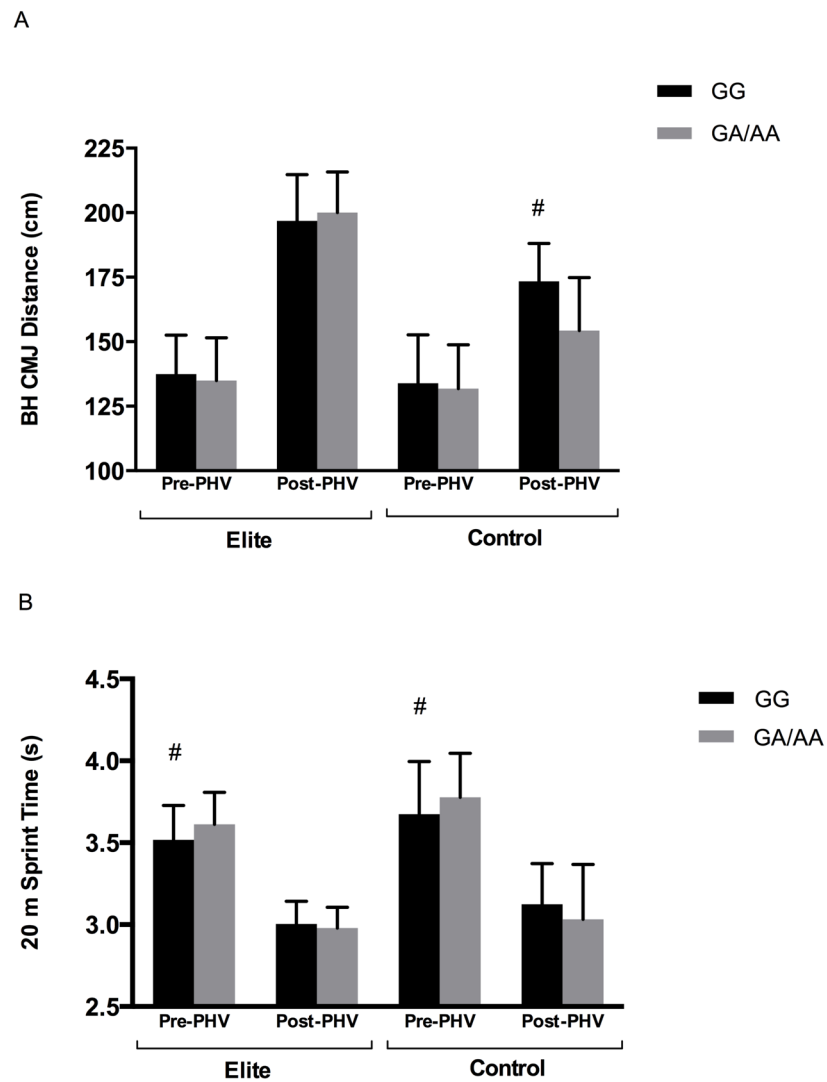
There was a non-significant tendency for a main effect of genotype, with GG genotype achieving greater BV CMJ height than A-allele carriers ( $F = 3.527$ ,  $P = 0.072$ ). There was no two-way interaction between genotype and maturation status ( $F = 0.297$ ,  $P = 0.586$ ) or between genotype and athlete status ( $F = 0.007$ ,  $P = 0.935$ ). There was no three-way interaction between genotype, athlete status and maturation status ( $F = 2.876$ ,  $P = 0.091$ ).

#### *10 m acceleration performance*

There was no significant main effect for genotype ( $F = 2.170$ ,  $P = 0.142$ ). There were no two-way interactions between genotype and maturation status ( $F = 1.624$ ,  $P = 0.204$ ), or between genotype and athlete status ( $F = 0.666$ ,  $P = 0.415$ ). Further, there was no three-way interaction between genotype, athlete status and maturation status ( $F = 0.001$ ,  $P = 0.970$ ).

#### *20 m sprint performance*

There was no main effect for genotype ( $F = 0.302$ ,  $P = 0.583$ ). However, there was a two-way interaction between genotype and maturation status ( $F = 4.591$ ,  $P = 0.033$ ), with pre-PHV *BDNF* GG homozygotes achieving greater sprint performance compared to pre-PHV A-allele carriers ( $F = 3.951$ ,  $P = 0.048$ ; Fig. 8.2B). There was no two-way interaction between genotype and player status ( $F = 0.158$ ,  $P = 0.692$ ), and no three-way interaction between genotype, athlete status and maturation status ( $F = 0.264$ ,  $P = 0.608$ ).



**Figure 8.2.** The association between *BDNF* G/A (rs6265) genotype and: (A) Bilateral horizontal-forward countermovement jump (BH CMJ) performance, and (B) 20 m sprint performance in pre-peak height velocity (PHV) and post-PHV elite soccer players (pre-PHV: n = 94; post-PHV: n = 90) and control participants (pre-PHV: n = 44; post-PHV: n = 54). # Significant difference between GG and GA+AA genotypes ( $P < 0.050$ ).

### 8.3.2.3 COL5A1 C>T (rs12722)

#### *BH CMJ performance*

There was no main effect for genotype ( $F = 1.967$ ,  $P = 0.141$ ). However, there was a two-way interaction between genotype and athlete status ( $F = 5.857$ ,  $P = 0.003$ ; Fig. 8.3A), with CON COL5A1 TT homozygotes achieving greater BH CMJ performance than CON individuals of CT genotype ( $P = 0.004$ ; Fig 8.3A), and a tendency for greater BH CMJ performance than individuals of CON CC genotype ( $P = 0.065$ ; Fig 8.3A). There was no two-way interaction between genotype and maturation status ( $F = 0.255$ ,  $P = 0.775$ ), and no three-way interaction between genotype, athlete status and maturation status ( $F = 0.038$ ,  $P = 0.963$ ).

#### *BV CMJ performance*

There was no main effect for genotype ( $F = 0.075$ ,  $P = 0.928$ ), although there was a two-way interaction between genotype and athlete status ( $F = 3.460$ ,  $P = 0.033$ ; Fig. 8.3B), with ESP COL5A1 CC homozygotes jumping higher than ESP COL5A1 TT homozygotes ( $P = 0.058$ ; Fig 8.3B). However, there was no difference in BV CMJ performance between ESP COL5A1 CC and CT genotype ( $P = 0.215$ ; Fig 8.3B). There was no two-way interaction between genotype and maturation status ( $F = 1.335$ ,  $P = 0.265$ ), and there was no three-way interaction between genotype, athlete status and maturation status ( $F = 0.710$ ,  $P = 0.493$ ).

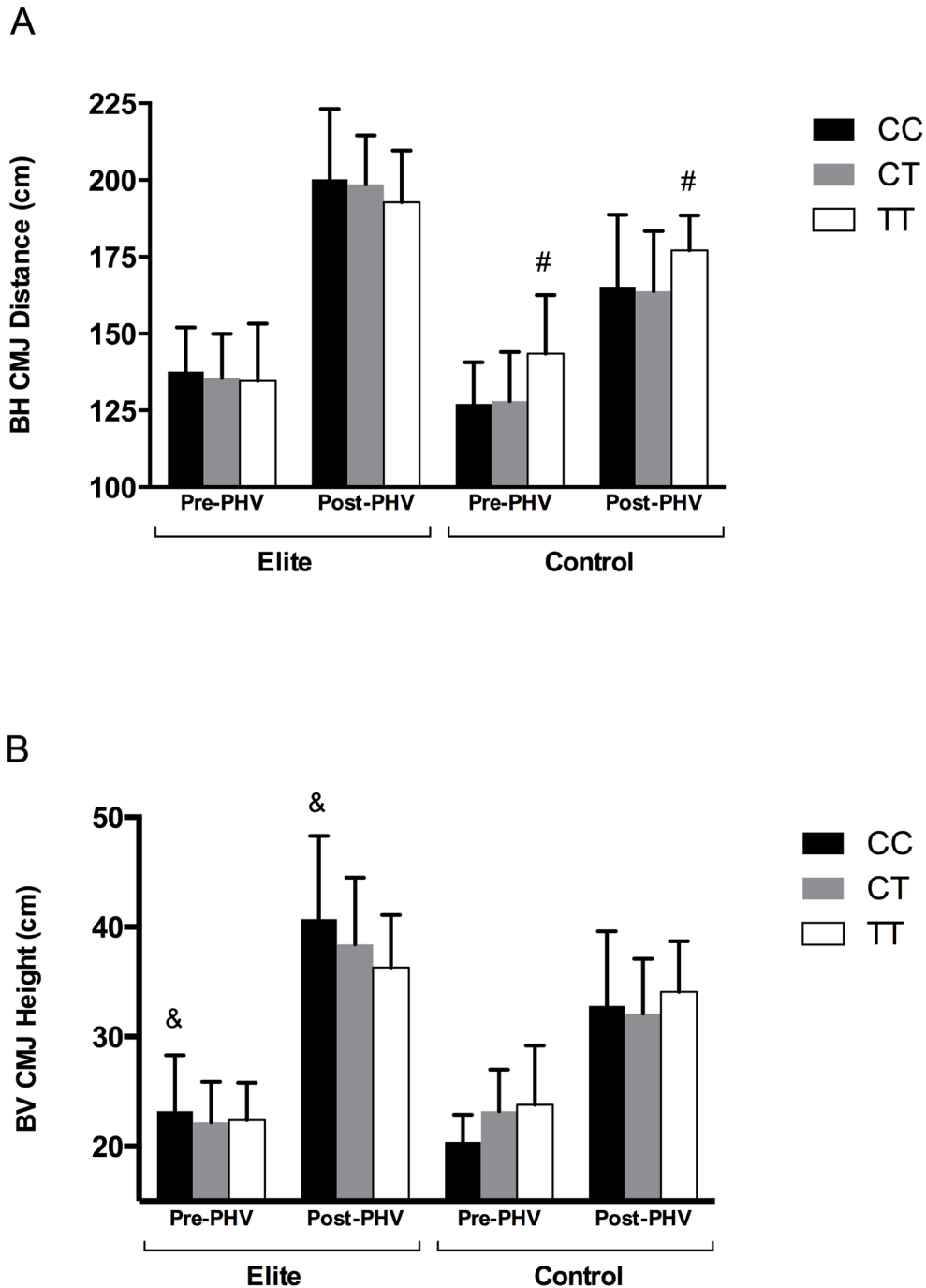
#### *10 m acceleration performance*

There was no main effect for genotype ( $F = 1.154$ ,  $P = 0.317$ ). There was also no two-way interaction between genotype and athlete status ( $F = 1.125$ ,  $P = 0.327$ ), or between genotype and maturation status ( $F = 0.139$ ,  $P = 0.871$ ). There was no three-

way interaction between genotype, athlete status and maturation status ( $F = 0.102$ ,  $P = 0.903$ ).

#### *20 m sprint performance*

There was no main effect for genotype ( $F = 0.419$ ,  $P = 0.658$ ). There were no two-way interactions between genotype and athlete status ( $F = 0.774$ ,  $P = 0.462$ ), or between genotype and maturation status ( $F = 1.002$ ,  $P = 0.369$ ). There was also no three-way interaction between genotype, athlete status and maturation status ( $F = 0.003$ ,  $P = 0.997$ ).



**Figure 8.3.** The association between *COL5A1* C/T (rs12722) genotype and: (A) Bilateral horizontal-forward countermovement jump (BH CMJ) performance, and (B) bilateral vertical countermovement jump (BV CMJ) performance in pre- peak height velocity (PHV) and post-PHV elite soccer players (pre-PHV: n = 94; post-PHV: n = 90) and control participants (pre-PHV: n = 44; post-PHV: n = 54). # Significant difference in BH CMJ performance between control TT and CT genotypes ( $P = 0.004$ ). & Non-significant difference in BV CMJ performance between CC and TT genotypes ( $P = 0.058$ ).



#### 8.3.2.4 COL2A1 C>T (rs2070739)

##### *BH CMJ performance*

There was a main effect for genotype ( $F = 5.195$ ,  $P = 0.024$ ; Fig. 8.4A), with COL2A1 CC homozygotes achieving greater jump distance than T-allele carriers (Fig. 8.4A). There was no two-way interaction between genotype and athlete status ( $F = 0.087$ ,  $P = 0.768$ ), or between genotype and maturation status ( $F = 0.272$ ,  $P = 0.603$ ). There was also no three-way interaction between genotype, athlete status and maturation status ( $F = 0.005$ ,  $P = 0.945$ ).

##### *BV CMJ performance*

There was a non-significant tendency for a main effect of genotype ( $F = 2.873$ ,  $P = 0.091$ ; Fig. 8.4B), with COL2A1 CC homozygotes tending to jump higher than COL2A1 T-allele carriers ( $30.0 \pm 8.9$  vs.  $27.5 \pm 8.0$  cm). There was no two-way interaction between genotype and athlete status ( $F = 1.055$ ,  $P = 0.305$ ), or between genotype and maturation status ( $F = 0.165$ ,  $P = 0.685$ ). There was also no three-way interaction between genotype, athlete status and maturation status ( $F = 0.126$ ,  $P = 0.723$ ).

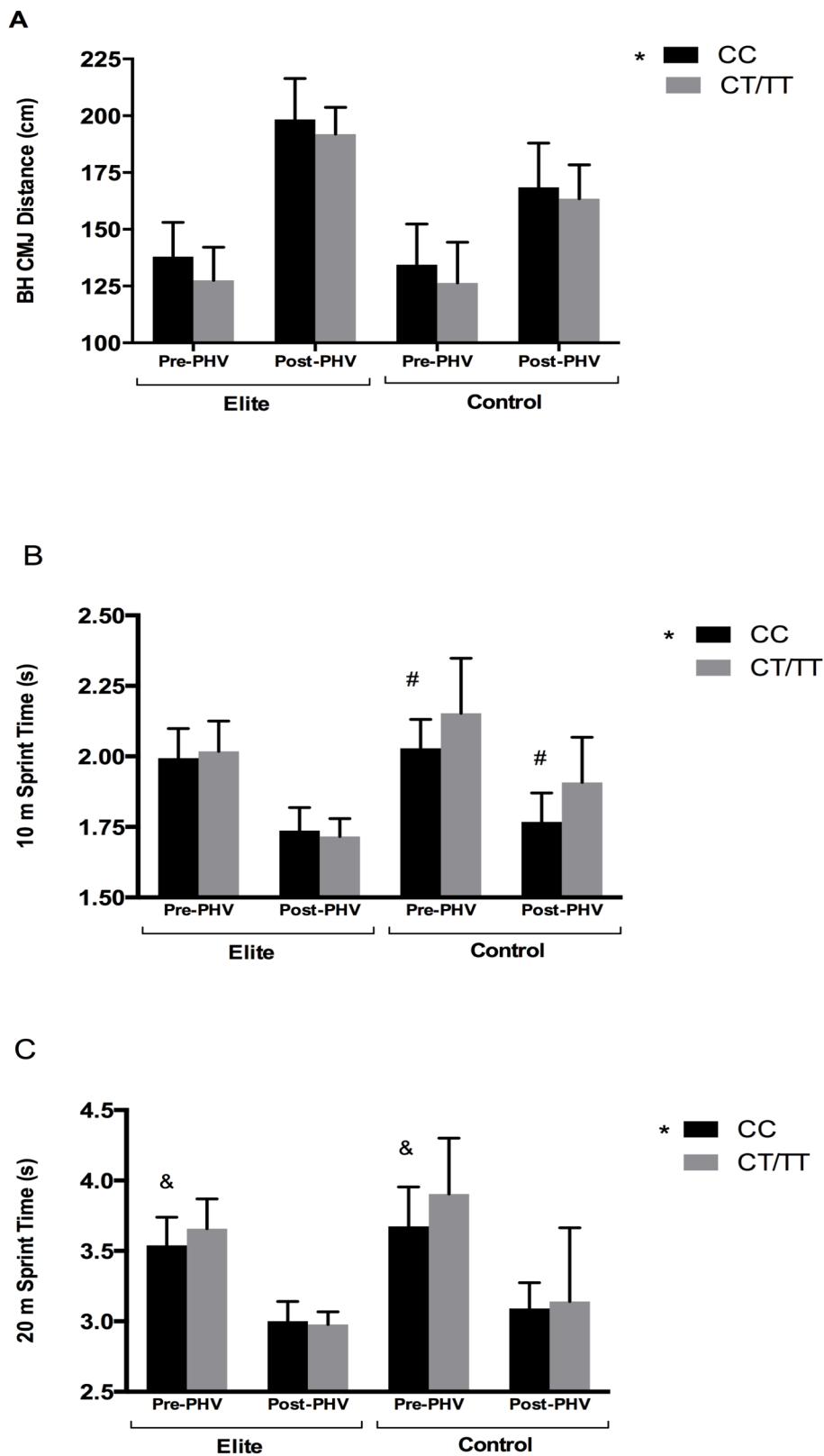
##### *10 m acceleration performance*

There was a main effect of genotype ( $F = 8.581$ ,  $P = 0.004$ ; Fig. 8.4B), with CC homozygotes achieving greater acceleration than T-allele carriers ( $1.881 \pm 0.164$  vs.  $1.950 \pm 0.183$  s). There was also a two-way interaction between genotype and athlete status ( $F = 8.217$ ,  $P = 0.005$ ), with CON COL2A1 CC homozygotes achieving faster 10 m acceleration times compared to CON COL2A1 T-allele carriers ( $P = 0.001$ ; Fig. 8.4B). There was no two-way interaction between COL2A1 genotype and

maturation status ( $F = 0.093$ ,  $P = 0.761$ ), and there was no three-way interaction between genotype, athlete status and maturation status ( $F = 0.458$ ,  $P = 0.499$ ).

#### *20 m sprint performance*

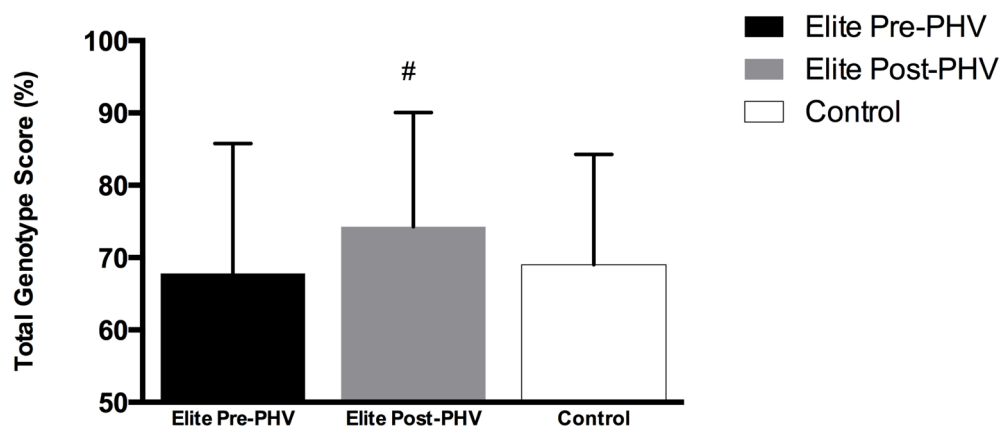
There was a main effect of genotype ( $F = 4.266$ ,  $P = 0.040$ ; Fig. 8.4C), with *COL2A1* CC homozygotes achieving greater sprint performance than T-allele carriers ( $3.316 \pm 0.336$  vs.  $3.449 \pm 0.441$  s). There was also a non-significant tendency for a two-way interaction between genotype and maturation status ( $F = 3.190$ ,  $P = 0.076$ ), with pre-PHV *COL2A1* CC homozygotes tending to be faster than pre-PHV *COL2A1* T-allele carriers ( $F = 7.366$ ,  $P = 0.007$ ; Fig. 8.4C). There was no two-way interaction between genotype and athlete status ( $F = 1.051$ ,  $P = 0.307$ ), and no three-way interaction between genotype, athlete status and maturation status ( $F = 0.048$ ,  $P = 0.827$ ).



**Figure 8.4.** The association between *COL2A1* C/T (rs2070739) genotype and: (A) Bilateral horizontal-forward countermovement jump (BHCMJ), (B) 10 m sprint and (C) 20 m sprint performance in pre- peak height velocity (PHV) and post-PHV elite soccer players (pre-PHV: n = 94; post-PHV: n = 90) and control participants (pre-PHV: n = 44; post-PHV: n = 54). \* Significant main effect of *COL2A1* CC and CT/TT genotypes ( $P < 0.050$ ). # Significant difference CC and TT genotypes ( $P < 0.050$ ).

### 8.3.3 Total Genotype Score Comparisons

There was a main effect of participant group ( $F = 3.735$ ,  $P = 0.025$ ). Post-hoc analyses revealed the TGS was higher in post-PHV ESP compared to pre-PHV ESP ( $P = 0.025$ ; Fig. 5). There was no significant difference in TGS between pre-PHV ESP and CON ( $P = 1.000$ ; Fig. 8.5), or post-PHV ESP and CON ( $P = 0.157$ ; Fig. 8.5).



**Figure 8.5.** Differences in total genotype score (TGS) between pre-peak height velocity (PHV) elite soccer players (elite Pre-PHV;  $n = 94$ ), and post-PHV elite soccer players (elite Post-PHV;  $n = 90$ ), and control participants ( $n = 114$ ).

# Significant difference between pre-PHV elite and post-PHV elite players ( $P = 0.024$ ).

## 8.4 DISCUSSION

The first aim of our study was to investigate whether the *ACTN3* R577X *COL5A1* C>T (rs12722), *COL2A1* C>T (rs2070739) and *BDNF* G>A (rs6265) SNPs were individually, and in combination, associated with elite soccer playing status at different stages of maturation. The second aim was to establish whether these SNPs were associated with acceleration, sprint, BH CMJ and BV CMJ performance in ESP and CON participants at different stages of maturation. The main findings were that

the *ACTN3* R- and *BDNF* G-allele frequencies, and *BDNF* GG genotype frequencies, were higher in post-PHV ESP compared to pre-PHV ESP. In comparison to *COL2A1* T-allele carriers, individuals with the *COL2A1* CC genotype were associated with greater BH CMJ and faster 20 m sprint performance in all participants, thus suggesting that this SNP plays a role in enhancing soccer performance at all stages of maturation regardless of athlete status. However, while the *BDNF* G>A SNP was associated with 20 m sprint performance in pre-PHV ESP only, the *ACTN3* R577X SNP had a tendency to influence BV CMJ in post-PHV participants only.

We previously documented in Chapter Seven that muscular power may only be important in elite youth soccer after PHV. Muscle power output has been shown to be largely determined by muscle volume and fibre type composition (Cormie, McGuigan and Newton, 2011, Pearson et al., 2006). Homozygosity for the *ACTN3* X-allele of the *ACTN3* R577X SNP results in  $\alpha$ -actinin-3 deficiency and the compensatory upregulation of the closely related isoform,  $\alpha$ -actinin-2 (Beggs et al., 1992, North and Beggs, 1996). Alpha-actinin-2 regulates calcineurin signalling in skeletal muscle and induces activation of the slow myogenic program, causing a shift in fast twitch muscle fibre characteristics towards a more slow twitch, oxidative phenotype (Delling et al., 2000, Seto et al., 2013), thus enhancing fatigue resistance and endurance performance (Jiang et al., 2010, Pimenta et al., 2013). The frequency of *ACTN3* XX genotype in our study had a tendency to be more common in pre-PHV ESP compared to CON (30.9% vs. 17.5%, respectively), thus suggesting that pre-PHV elite youth soccer players may have been selected based on a greater endurance capacity, rather than explosive power and speed capabilities. In accordance with these findings, we have also shown for the first time, that the *ACTN3* R-allele was more common in post-PHV ESP compared to pre-PHV ESP. As the *ACTN3* R-allele has previously been positively associated with increased muscle volume (Erskine et al., 2014), the proportion of fast twitch fibres (Ahmetov et al.,

2011, Vincent et al., 2007), and greater speed and power performance in Brazilian professional senior soccer players (Pimenta et al., 2013), our findings suggest that, in contrast to pre-PHV elite youth soccer, post-PHV elite youth soccer may be characterised by a genetic profile that favours strength and power, rather than endurance capabilities.

Our analysis of the *BDNF* G>A (rs6265) SNP further illustrates that different genetic profiles may characterise pre- vs. post-PHV elite youth soccer. We found that *BDNF* GG genotype and *BDNF* G-allele were more common in post-PHV compared to pre-PHV ESP. Based on the role of BDNF in regulating neurogenesis and synaptic plasticity (McAllister, Katz and Lo, 1999), the greater frequency of *BDNF* GG genotype and the *BDNF* G-allele, in post-PHV compared to pre-PHV ESP, suggests that ESP retained or selected in an elite soccer development programme after PHV may have greater neuromuscular activation, motor unit synchronisation and inter-muscular co-ordination capabilities. Such advantageous neural adaptations may enable ESP to generate more power during sport-specific actions compared to CON (Cormie, McGuigan and Newton, 2011). However, in order to identify the specific role of a genetic variant on athletic performance, the relationship between the SNP and physical capacity needs to be investigated.

Establishing genotype-phenotype associations can help to predict future performance capabilities. In all ESP and CON, individuals with the *COL2A1* CC genotype demonstrated greater BH CMJ and 20 m sprint performance in comparison to *COL2A1* T-allele carriers. As there was no association between the *COL2A1* C>T SNP and BV CMJ performance, these findings suggest that the *COL2A1* CC genotype may enhance the ability to perform maximal actions only in the horizontal-forward direction. We previously demonstrated in Chapter Six that the main physiological determinant of horizontal-forward CMJ performance in elite and non-elite youth soccer players was patellar tendon elasticity. Moreover, it has previously

been documented that a more extensible vastus lateralis aponeurosis was associated with faster 100 m sprint performance in elite level sprinters (Kubo et al., 2000b, Stafilidis and Arampatzis, 2007). Subsequently, it could be hypothesised that the *COL2A1* CC genotype increases the concentration of collagen type II (Donoso et al., 2003, Tarpey et al., 2013) located at the tendon-bone interface (Adamczyk et al., 2008, Buckley et al., 2013, Waggett et al., 1998) and therefore enhances horizontal explosive performance by increasing patella tendon elasticity. A more elastic patellar tendon is believed to have a greater capacity to store and release elastic energy, thus enhancing power output during stretch shortening cycle actions orientated in the horizontal-forward direction (please see Chapter Six) (Kubo et al., 2000b, Stafilidis and Arampatzis, 2007). However, it should be noted that there was a non-significant tendency for the *COL2A1* C>T SNP to be associated with 20 m sprint performance in pre-PHV ESP and CON only. A larger cohort may therefore be required to establish how maturation affects the role of the *COL2A1* C>T SNP on 20 m sprint performance.

The surge in systemic hormone concentration (particularly testosterone and growth hormones) during maturation (Forbes et al., 2009, Round et al., 1999) stimulates many biological changes in the human body (Malina, Bouchard and Bar-Or, 2004). Some genes may therefore influence power and speed performance differentially depending on maturation status. In pre-PHV ESP and CON only, the *BDNF* GG genotype was associated with faster 20 m sprint performance compared to *BDNF* A-allele carriers. It could therefore be postulated that 20 m sprint performance prior to PHV is underpinned by neural factors (Egan et al., 2003, McAllister, Katz and Lo, 1999). This hypothesis would agree with research showing that speed performance prior to the onset of maturation is underpinned by inter-muscular and intra-muscular co-ordination capabilities (Venturelli, Bishop and Pettene, 2008, Viru et al., 1999). However, the lack of an association between the

*BDNF* GG genotype, and 20 m sprint performance in post-PHV individuals may be due to other physiological determinants of sprint performance developed during maturation (Rumpf et al., 2013). These include increased muscle volume (Jones and Round, 2008, Malina, Bouchard and Bar-Or, 2004), selective hypertrophy of fast twitch fibres (Lexell et al., 1992, Metaxas et al., 2014), increments in motor unit recruitment (Dotan et al., 2012, O'Brien et al., 2010a), and stiffening of the tendon-aponeurosis structures (O'Brien et al., 2010b). These factors could reduce the overall contribution that the *BDNF* G>A SNP has on 20 m sprint ability.

In contrast to the *BDNF* G>A SNP, the *ACTN3* R577X SNP may only affect vertical power performance after PHV. Indeed, only post-PHV ESP and CON *ACTN3* RR homozygotes demonstrated a tendency for greater BV CMJ performance compared to *ACTN3* RX genotypes. As vertical jump performance has previously been associated with quadriceps femoris muscle volume (please see Chapter Five) (O'Brien et al., 2009b), and males exhibit a significant increase in lean muscle mass (Malina, 1969) concomitant with the surge in testosterone and growth hormone during puberty (Forbes et al., 2009, Round et al., 1999), the *ACTN3* R577X SNP may influence muscle growth during maturation. In agreement with this theory, previous research reported untrained male adult *ACTN3* RR homozygotes presented greater QF muscle volume, strength and power compared to XX (Erskine et al., 2014).

In Chapters Four and Five we documented that ESP presented different neuromuscular-tendon characteristics compared to NSP. Our current study shows that some SNPs were associated with horizontal explosive performance capabilities in CON, but not ESP, which could potentially be because explosive performance is underpinned by different neuromuscular-tendon properties in ESP compared with CON. Post-PHV CON with the *BDNF* GG genotype achieved greater BH CMJ performance compared to post-PHV CON *BDNF* A-allele carriers. These findings



suggest that post-PHV CON with enhanced neuromuscular characteristics may perform better in the BH CMJ than those with reduced heritability for neural adaptation. The lack of an association with *BDNF* G>A SNP and BH CMJ performance in ESP may be because the main physiological determinant of horizontal-forward CMJ performance in ESP is patellar tendon elasticity (please see Chapter Five). Therefore, while a genetic predisposition to favourable neuromuscular characteristics may be advantageous, this does not have a significant impact on horizontal-forward CMJ performance in the ESP population (please see Chapter Five). Similarly, CON with the *COL2A1* CC genotype demonstrated greater 10 m acceleration compared to *COL2A1* T-allele carriers. These findings may illustrate the importance of the presence of collagen type II at the tendon bone interface (Adamczyk et al., 2008, Buckley et al., 2013) for optimising acceleration performance in CON, but not ESP (Kubo et al., 2000b, Stafilidis and Arampatzis, 2007). Early acceleration relies on contractile force capabilities (Mero, 1988), and the maximum force-generating capacity of the muscle is directly related to the physiological cross sectional area (PCSA) (Close, 1972, Degens, Hoofd and Binkhorst, 1995). Subsequently, as ESP have previously been shown to have quadriceps femoris muscles with greater PCSA than NSP (please see Chapter Five), 10 m acceleration performance in ESP may be determined to a greater extent by muscle size, rather than the *COL2A1* C>T SNP and its potential influence on tendon properties. Tendon extensibility was strongly correlated with UH CMJ performance in ESP and NSP (please see Chapter Six). Previous research has documented that *COL5A1* TT genotype has no effect (Foster et al., 2014), or is associated with less extensible vastus lateralis tendon-aponeurosis structures (Kirk et al., 2016, Kubo, Yata and Tsunoda, 2013). However, we show that CON with the *COL5A1* TT genotype achieved greater BH CMJ performance compared to *COL5A1* CC homozygotes. Subsequently, our results perhaps disagree with previous findings (Kubo, Yata and

Tsunoda, 2013) and suggest that the *COL5A1* TT genotype may increase the mechanical energy the tendon can store, thus allowing a more elastic tendon to enhance stretch-shortening cycle capacity during horizontal-forward CMJs (please see Chapter Six). However, it is unknown why the *COL5A1* C>T SNP is only associated with BH CMJ in CON and more research is required to establish the influence of this SNP on tendon properties and horizontal-forward CMJ performance in elite athlete populations and CON. Nevertheless, we show the importance of including both CON and elite participants when investigating the role of various SNPs in determining athlete status and power/speed performance.

Our study documents that the *ACTN3* R577X, *BDNF* G>A, *COL5A1* C>T and *COL2A1* C>T SNPs have all been individually associated with power performance in ESP players and/or CON. However, muscular power phenotypes are thought to be polygenic in nature (Ahmetov et al., 2013) and over 20 gene variants have been linked to strength and power performance (Ahmetov and Rogozkin, 2009, Hughes et al., 2011). The present study showed that the total genotype score (TGS) for the four genes investigated here was significantly greater in post-PHV compared to pre-PHV ESP. However, there was no difference in TGS between ESP and CON. These findings suggest that post-PHV elite youth soccer requires a different polygenic profile compared to pre-PHV elite youth soccer. This may be a challenge for any future talent identification programme involving genetic testing, as genotypes that are advantageous for pre-PHV elite youth soccer, may not predispose a player for successful performance post-PHV. This could be a reason for the considerable drop-out rates in elite youth soccer players during the pubertal period (Deprez et al., 2015, Figueiredo et al., 2009). Hence, the findings from our study could be used to inform and improve talent identification and soccer genetic screening procedures.

## 8.5 CONCLUSION

We demonstrate for the first time that *ACTN3* R- and *BDNF* G-allele frequencies, and *BDNF* GG genotype frequencies, are more common in post-PHV ESP compared to pre-PHV ESP, thus suggesting that the polygenic profile characterising pre-PHV elite youth soccer performance is different from that of post-PHV elite youth soccer. One reason for this may be that certain gene variants have a greater impact on speed and power performance at specific stages of maturation. While *COL2A1* CC genotype was associated with greater BH CMJ and 20 m speed performance at all stages of maturation, the *BDNF* GG genotype was only associated with 20 m sprint ability prior to PHV. In contrast, the *ACTN3* RR SNP was only associated with vertical jump performance after the PHV. Talent identification strategies in soccer should consider genetic profiling pre-PHV players to enhance the ability to predict the player's long-term soccer performance, speed and power potential. Our novel data suggests that elite soccer clubs should consider genetically screening all youth ESP for *COL2A1* C>T, *BDNF* G>A, and *ACTN3* R577X SNPs. Results could be used to predict future speed and power potential, and could inform selection criteria and possibly the detail of specific speed/power training intervention strategies.

**CHAPTER NINE**  
**SYNTHESIS OF FINDINGS**

## **9.0 SYNTHESIS**

The purpose of this chapter is to provide a conceptual interpretation of the current findings in relation to the original aims and objectives of the thesis. This chapter will also aim to provide practical recommendations, which could be applied in elite soccer academies to improve muscular power-associated talent identification and development protocols. We also recommend future lines of research that may improve the current understanding of the physiological and genetic determinants of soccer-associated muscular power performance. The limitations and advantages of conducting research with ESP, both in the field and in the laboratory, will also be discussed.

The following section aims to discuss the key outcomes of the present thesis in relation to the current body of knowledge on soccer-associated power. The outcomes of this thesis, and how they could influence novel soccer talent identification and development strategies at elite soccer clubs, are discussed. The limitations of this work are also discussed.

## **9.2 GENERAL DISCUSSION**

The ability to generate maximal muscular power is considered the most important neuromuscular function in sports performance (Cormie, McGuigan and Newton, 2011). Empirical evidence supported by previous research has documented that a greater ability to produce muscular power typically results in superior athletic performance (Kraemer and Newton, 2000, Sleivert and Taingahue, 2004, Young et al., 2005). A key aim of strength and conditioning practitioners is therefore to prescribe training intervention programmes that will optimise maximal power production during sports performance (Haff and Nimphius, 2012). In order to provide optimal power development programmes tailored to the needs of the individual

athlete, practitioners need to assess the athlete's maximal power capabilities and have a knowledge of the physiological mechanisms underpinning these specific qualities (Haff and Nimphius, 2012). Maximal power is a specific quality which should be assessed according to the specific demands of the sport (Maulder and Cronin, 2005). Subsequently, to optimise the detail of sport-specific maximal power assessment protocols, there needs to be an understanding of the specific movements elicited during the sport, which require the production of maximal power.

Within the context of soccer, maximal power is achieved during actions whereby the player accelerates their body mass with the intention of generating the greatest possible velocity at take-off (Cormie, McGuigan and Newton, 2011). By showing that explosive horizontal accelerations of short duration ( $< 1.5$  s), and from different starting speeds, are the most dominant powerful action in elite youth soccer match-play, our findings suggest that applied practitioners should equally prioritise the assessment and development of short duration horizontal acceleration capabilities from both static and dynamic starts. As initiating accelerations from different speeds require the player to produce horizontal impulse from different types of inertia, and from various body positions and joint angles (Wild et al., 2011), our data also suggests that soccer-associated maximal power assessment protocols should be performed in the horizontal-forward and mediolateral directions, in the form of both acyclic (i.e. countermovement jumps) and cyclic unilateral assessments (i.e. drop jumps or multiple jumps). We also recommend that when performing pitch-based acceleration development drills, soccer practitioners should consider prescribing competitive drills which require the player to perform an equal proportion of explosive leading and initial acceleration actions. Whilst considerably less sprint actions were performed in comparison to accelerations, our data suggests that ESP are required to perform ~eight sprint actions during match-play. This data should therefore be considered in ESP player assessment and speed enhancement

protocols. Also, as sprinting has been shown to be a common action whereby hamstrings injuries are sustained in ESP (Woods et al., 2004), our findings documenting the frequency of sprint actions during a game could inform load management and injury reduction strategies. The vertical jump demands of elite soccer match-play seem to vary between games or player position (range between: 2-18 vertical jumps per game) and therefore, we suggest that vertical jump assessment and development protocols should be specific to the individual player's powerful action profile. Whilst more extensive research is required to confirm these findings, our data suggests that the development and assessment of horizontal (in the horizontal-forward and mediolateral directions), rather than vertical power capabilities, should be prioritised in elite soccer.

In accordance with our findings in Chapter Three, our data in Chapter Four showed no difference in BV CMJ performance between ESP and NSP thus suggesting that the BV CMJ should not be used to assess specific muscular power capabilities in ESP. We therefore challenge guidelines from the Premier League which imply that all English Soccer Academies are currently required to employ the BV CMJ as a performance assessment for measuring maximal power (Premier League, 2011). Rather, our data shows that unilateral CMJ abilities in different directions (horizontal-forward, medial and vertical) are greater in ESP compared to NSP and therefore, can be considered indicators of elite soccer playing status. We also show in Chapter Four that unilateral CMJs in different directions require specific muscle activation profiles and assess separate power qualities, which allows us to recommend that all of these unilateral assessments warrant inclusion as separate tests in novel soccer muscular power assessment protocols for U18 and U21 professional ESP. Moreover, as the UH CMJ required more hamstring activation in comparison to UM and UV, training interventions for improving UH CMJ performance should focus specifically on the hamstring muscle group in comparison to other

CMJs. Finally, our data suggests that, when practitioners are monitoring and developing unilateral direction-specific jump performance in soccer players, the key variable that the practitioner should aim to assess and improve is peak power in the direction of the jump.

Whilst performance variables are useful for the applied practitioner when evaluating certain physical capabilities, they do not reveal the physiological mechanistic factors that underpin power performance. To allow soccer talent identification strategies to include physiological parameters, in Chapter Five we aimed to identify the specific neuromuscular factors that characterised elite soccer playing status and more specifically, that underpinned unilateral jump performance in different directions. Knowledge of the underlying physiological determinants of muscular power could play a crucial role in helping the practitioner understand how to target specific adaptations when attempting to develop a component of muscular power. Our data suggests it is imperative that muscular power development programmes prescribed to ESP should consider the neuromuscular factors that underpin performance in each direction (Table 9.1). We suggest that when aiming to improve UV and UM CMJ performance, the player should aim to increase QF muscle size, VL pennation angle and VL neural activation during the upward phase of the jump. However, training interventions that may induce these desirable adaptations, such as heavy strength training of the knee extensor muscle group, could have a negative impact upon UH CMJ performance capability. For example, an in-season period of heavy strength training involving the knee extensor muscle group in ESP has previously been shown to increase VL  $\theta_p$  in ESP by a large practical magnitude (Enright et al., 2015). Whilst unilateral jump performance in different directions was not evaluated in this study (Enright et al., 2015), our findings may suggest that this intervention programme could have enhanced UV and UM CMJ performance, but negatively impacted upon UH CMJ performance. Our data would therefore suggest



that the detail of strength and conditioning intervention programmes is important for the optimising the enhancement muscular power in ESP. We provide valuable information on the specific neuromuscular factors which underpin explosive unilateral direction-specific CMJ capabilities in U18 and U21 soccer players.

Unilateral CMJs in different directions induce stretch shortening cycle (SSC) actions in the muscle-tendon complex and performance may therefore also be influenced by the viscoelastic properties of the patellar tendon (Bojsen-Møller et al., 2005, Kubo et al., 2007). Our findings in Chapter Six suggested that a more elastic patellar tendon acts as power amplifier in a catapult-like motion during UH and UM CMJs, but does not influence vertical jumping capabilities (Table 9.1). We have postulated that this may be due to a quasi-isometric contraction of the knee extensor muscle group during CMJs requiring less knee flexion [i.e. horizontal-forward vs. vertical CMJs (Fukashiro et al., 2005)], which may induce greater patellar tendon lengthening (Reeves and Narici, 2003). The quasi-isometric contraction may therefore allow the tendon to store more potential energy and recoil at greater speeds, thus enhancing muscular power output. This data provides further information to support our novel findings that unilateral jump performance in different directions is underpinned by direction-specific physiological factors. As tendon properties change in response to resistance training (Reeves, Maganaris and Narici, 2003, Seynnes et al., 2009), our findings should also be considered when prescribing training for the development of maximal power in elite soccer players. Heavy resistance training of the knee extensor muscle group has previously been shown to increase the stiffness of the patellar tendon (Reeves, Maganaris and Narici, 2003, Seynnes et al., 2009). Such adaptations may therefore have a negative impact on unilateral horizontal-forward and medial power capabilities in ESP. However, this has yet to be investigated and could be of interest in future research projects. Nevertheless, our findings from Chapter Six provide a strong rationale for including

**Table 9.1.** Neuromuscular factors and tendon properties significantly correlated with performance variables during unilateral countermovement jumps (CMJs) in different directions in elite (n = 23 for neuromuscular variables, n = 16 for tendon properties) and/or non-elite (n = 20 for neuromuscular variables, n = 13 for tendon properties) players.

<b>Muscle variable</b>	<b>UV</b>	<b>UH</b>	<b>UM</b>
QF $V_m$ (cm <sup>3</sup> )	+ve		+ve
Relative QF $V_m$ (cm <sup>3</sup> /cm)	+ve		+ve
QF PSCA (cm <sup>2</sup> )	+ve		+ve
VL Muscle thickness (mm <sup>2</sup> )	+ve		
VL $\theta_p$ (°)	+ve <sup>&amp;</sup>	-ve <sup>&amp;</sup>	+ve <sup>&amp;</sup>
VL $L_f$ (mm)			
Relative VL $L_f$ (mm/cm)		+ve <sup>@</sup>	
Peak VL EMG (% iMVC)	+ve <sup>&amp;</sup>		+ve
Peak BF EMG (% iMVC)			
PT Mean CSA, mm <sup>2</sup>		+ve	+ve
Resting Tendon Length, mm	-ve <sup>&amp;</sup>		
PT Stiffness, N/mm		-ve	-ve
PT Elongation, mm		+ve	+ve
PT Strain, %		+ve	+ve
PT Stress, MPa		-ve	-ve
PT Young's Modulus, GPa		-ve	-ve <sup>@</sup>

Key: UV, unilateral vertical countermovement jump; UH, unilateral horizontal-forward countermovement jump; UM, unilateral medial countermovement jump; +ve, significant positive correlation; -ve, significant negative correlation; QF, quadriceps femoris muscle group;  $V_m$ , muscle volume; PSCA, physiological cross-sectional area; VL, vastus lateralis muscle;  $\theta_p$ , angle of pennation;  $L_f$ , fascicle length; EMG, electromyographic activity; iMVC, isometric maximal voluntary contraction; PT, patellar tendon; BF, biceps femoris muscle; CSA, cross sectional area; <sup>&</sup>, denotes correlation was only significant when analysing the cohort of elite youth soccer players; <sup>@</sup>, denotes correlation was only significant when analysing the cohort of non-elite youth soccer players.

the assessment of patellar tendon properties in soccer physiological talent identification protocols in U18 and U21 professional ESP.

Whilst the development of professional soccer players is of major importance in elite soccer academies, a key goal is to recognize and promote talented soccer players at an early age. If this process is done successfully, it can provide major financial gains for the club. Major changes in the muscle-tendon unit occur during maturation and therefore, the physiological variables that underpin muscular power may be specific to the stage of maturation. As our data in Chapters Four, Five and Six may only be applicable to U18 and U21 professional ESP, we aimed to investigate the relative importance of muscular power for determining EPL elite soccer playing status at different stages of maturation. By comparing power and speed performance capabilities in ESP and CON matched for maturation status, we concluded that acceleration and sprint assessments, rather than jump assessments, should be included in pre-PHV soccer talent identification protocols. However, when comparing the magnitude of practical difference between ESP and CON, our data would suggest that when prescribing the detail of talent identification criteria for mid-PHV and post-PHV maturation groups, elite soccer clubs should prioritise horizontal-forward CMJ performance over BV CMJ, acceleration and sprint capabilities.

Our next aim was to investigate if a genetic association existed with acceleration, speed and power in ESP. The results from this study (please Chapter Seven) had the potential to inform whether genetic profiling could be included in soccer talent identification protocols. Our data, showing that *BDNF* GG genotype was only associated with 20 m sprint ability in pre-PHV participants suggests that a genetic predisposition to superior neuromuscular activation and/or greater inter- and intra-muscular coordination might influence 20 m sprint speed in pre-PHV boys. The surge in systemic hormone concentrations (particularly testosterone and growth hormone) during maturation (Forbes et al., 2009, Round et al., 1999) stimulates a

significant increase in lean muscle mass in males (Forbes et al., 2009, Malina, 1969, Round et al., 1999). We also show a tendency for post-PHV *ACTN3* RR homozygotes to demonstrate greater BV CMJ performance compared to *ACTN3* RX genotypes. As we previously showed that vertical jump performance is associated with quadriceps femoris muscle volume (please see Chapter Four) (O'Brien et al., 2009b), and untrained adult male *ACTN3* RR homozygotes have greater QF muscle volume, strength and power compared to XX homozygotes (Erskine et al., 2014), our data suggest that the *ACTN3* R577X SNP potentially influences vertical jump performance in post-PHV individuals through its influence on muscle growth during puberty. Irrespective of maturation status, individuals with the *COL2A1* CC genotype demonstrated greater BH CMJ and 20 m sprint performance in comparison to *COL2A1* T-allele carriers. These findings suggest that the *COL2A1* CC genotype may enhance the ability to perform powerful actions in the horizontal-forward direction. It is possible that *COL2A1* CC genotype enhances horizontal explosive performance by increasing patellar tendon elasticity [possibly by stimulating a greater concentration of collagen type II (Donoso et al., 2003, Tarpey et al., 2013) at the tendon-bone interface (Adamczyk et al., 2008, Buckley et al., 2013, Waggett et al., 1998)]. We are the first to investigate the association between muscular power and gene polymorphisms that have been (*COL5A1* rs12722), or might be (*COL2A1* rs2070739), associated with tendon properties. Our novel findings concerning the *ACTN3* rs1815739, *BDNF* rs6265, and *COL2A1* rs2070739 SNPs suggest these SNPs may be incorporated into a genetic profiling component of talent identification of elite youth soccer players.

As the genetic profile for pre- and post-PHV ESP was different for *ACTN3* R577X (rs1815739) and *BDNF* G>A (rs6265) SNPs, this could indicate weaknesses in the current talent identification and selection processes for pre-PHV ESP. In theory, if players are to be selected and successfully nurtured through an elite soccer

development programme, there should be no difference between the genetic profiles presented by pre- and post-PHV ESP. The reason for the difference in the genetic profile between pre- and post-PHV players may be due to a possible high drop-out rate, and the subsequent recruitment of new ESP to an elite development programme around maturation (Deprez et al., 2015). Our findings would therefore support previous data showing that maturation is a confounding factor in the talent identification process (Pearson, Naughton and Torode, 2006, Vandendriessche et al., 2012). Subsequently, by genetically profiling pre-PHV ESP, elite soccer clubs may be able to predict maximal power performance potential and make a more informed decision during the selection process. Although research in soccer genetics is in its infancy, and many more studies are needed before we can predict future performance levels of young individuals, our cross-sectional association study supports previous research (Ahmetov and Fedotovskaya, 2012, Eynon et al., 2013), namely that muscular power has genetic component. Although we have identified genetic associations with athlete status and/or performance in three of the four SNPs we investigated, we acknowledge that many more SNPs may influence the ability to produce speed and power in elite youth soccer players.

### **9.3 CONCLUSIONS**

The overarching aim of this thesis was to investigate the importance of muscular power in elite youth soccer. The main objectives were to provide performance testing, physiological assessment and genetic screening guidelines for elite soccer talent identification protocols at different stages of maturation. By analysing powerful actions performed during competitive soccer games, and subsequently devising and validating a specific assessment of soccer power, we recommended the inclusion of unilateral jump assessments in different directions, rather than the BV CMJ, when assessing elite professional youth soccer players. From our subsequent analysis of

the physiological determinants of unilateral power performance in the laboratory, we identified that unilateral CMJ performance in different directions was underpinned by direction-specific neuromuscular-tendon properties in professional youth ESP (Table 9.1). These data showed that unilateral CMJ capabilities in different directions should be assessed and developed independently in U18 and U21 professional ESP. We then illustrated that soccer talent identification criteria regarding muscular power should be specific to maturation status. While acceleration and sprint performance assessments should be included in talent identification protocols at all stages of maturation, vertical and horizontal-forward power are only important at mid- and post-PHV. Our data also indicated that horizontal-forward power capabilities should be prioritised in talent identification and selection protocols for mid- and post-PHV ESP. Our final study showed that current talent identification and selection processes for pre-PHV ESP could be sub-optimal, as these players presented with a different genetic profile compared with post-PHV ESP. We showed that muscular power in ESP has a genetic component and recommended that soccer genetic profiling should include the *COL2A1* C>T (rs2070739), *BDNF* G>A (rs6265) and *ACTN3* R577X (rs1815739) SNPs. To conclude, we have investigated the importance of muscular power in elite youth soccer from the pitch (e.g. determining the type and number of powerful actions during elite youth match-play), to the whole muscle-tendon complex (e.g. determining the physiological underpinnings of soccer-associated power in the laboratory), to the gene (e.g. identifying associations between candidate gene polymorphisms in the laboratory and soccer performance in the field). We believe that our specific recommendations (based on the findings within this thesis) will enhance the selection process in elite youth soccer, and provide valuable information for practitioners when optimising muscular power development programmes to individual players.

#### **9.4 PROJECT LIMITATIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH**

We have provided novel information relating to talent identification in elite youth soccer players at different stages of maturation. In achieving these aims, we have identified some limitations and formulated recommendations for future research in this area. The following section aims to discuss the limitations and recommendations for future research in relation to each specific chapter of our thesis.

##### *Suggestions arising from Chapter Three:*

The physical demands of elite soccer match-play have previously been reported to be related to player position (Di Salvo et al., 2010). Hence, future work should use our SSPA coding system and methods but include a larger sample size that would allow an analysis of the powerful action profile of various soccer player positions. We only analysed players from one English Premier League club academy and future research should aim to analyse players from a variety of clubs to gain a more accurate representation of the powerful activity of elite youth soccer match-play.

##### *Suggestions arising from Chapter Four:*

In chapter Four, we compared elite youth professional soccer and non-elite player performance to validate unilateral jump assessments in different directions as a measure of soccer associated power. Future studies should aim to validate unilateral jump assessments in different directions as a measure of soccer associated power by comparing performance in different practice levels (i.e. non-elite, sub-elite, elite youth soccer players). Such a comparison would provide a more accurate insight into whether unilateral jump assessments in different directions be used to characterise elite soccer playing status.

*Suggestions arising from Chapter Five and Six:*

In chapters Five and Six, we compared neuromuscular-tendon properties between elite youth professional soccer players and non-elite players to identify which physiological factors may be indicators of elite soccer playing status. However, we only investigated neuromuscular-tendon properties of the knee extensor muscle-tendon complex. Hence, future studies should investigate the role of the hip extensors and knee flexors in determining soccer playing status and soccer-associated muscular power performance.

*Suggestions arising from Chapter Seven:*

In Chapter Seven, we investigated the importance of power and speed performance at different stages of maturation by comparing maturity matched ESP and CON. Due to difficulties in familiarising such a large cohort of ESP and CON with unilateral jump assessments in different directions, we compared only BV CMJ and BH CMJ, i.e. relatively simple tasks requiring minimal learning. However, our findings in Chapter Three and Four would suggest that bilateral vertical CMJs are not as soccer-specific as unilateral CMJs and, therefore, we recommend that future studies compare unilateral CMJ performance in different directions between ESP and CON at different stages of maturation.

*Suggestions arising from Chapter Eight:*

In chapter Eight, we reported that the genetic profile of post-PHV ESP was different to pre-PHV ESP, and we made subsequent recommendations for elite youth soccer talent identification. However, our data was only representative of the players assigned to one club and, therefore, only indicative of one club's recruitment and talent identification philosophies. Hence, using data from a range of elite club academies would provide a more accurate representation of the talent identification



procedures in English Premier League soccer academies. The work of this chapter demonstrated that the *ACTN3* R577X (rs1815739), *BDNF* G>A (rs6265), and *COL2A1* C>T (rs2070739) SNPs were associated with power and speed performance. As muscular power has been reported to be a polygenic trait (Ruiz et al., 2010), future studies should aim to include more SNPs, which would help improve genetic profiling procedures and enhance the selection process of ESP, particularly at pre-PHV.

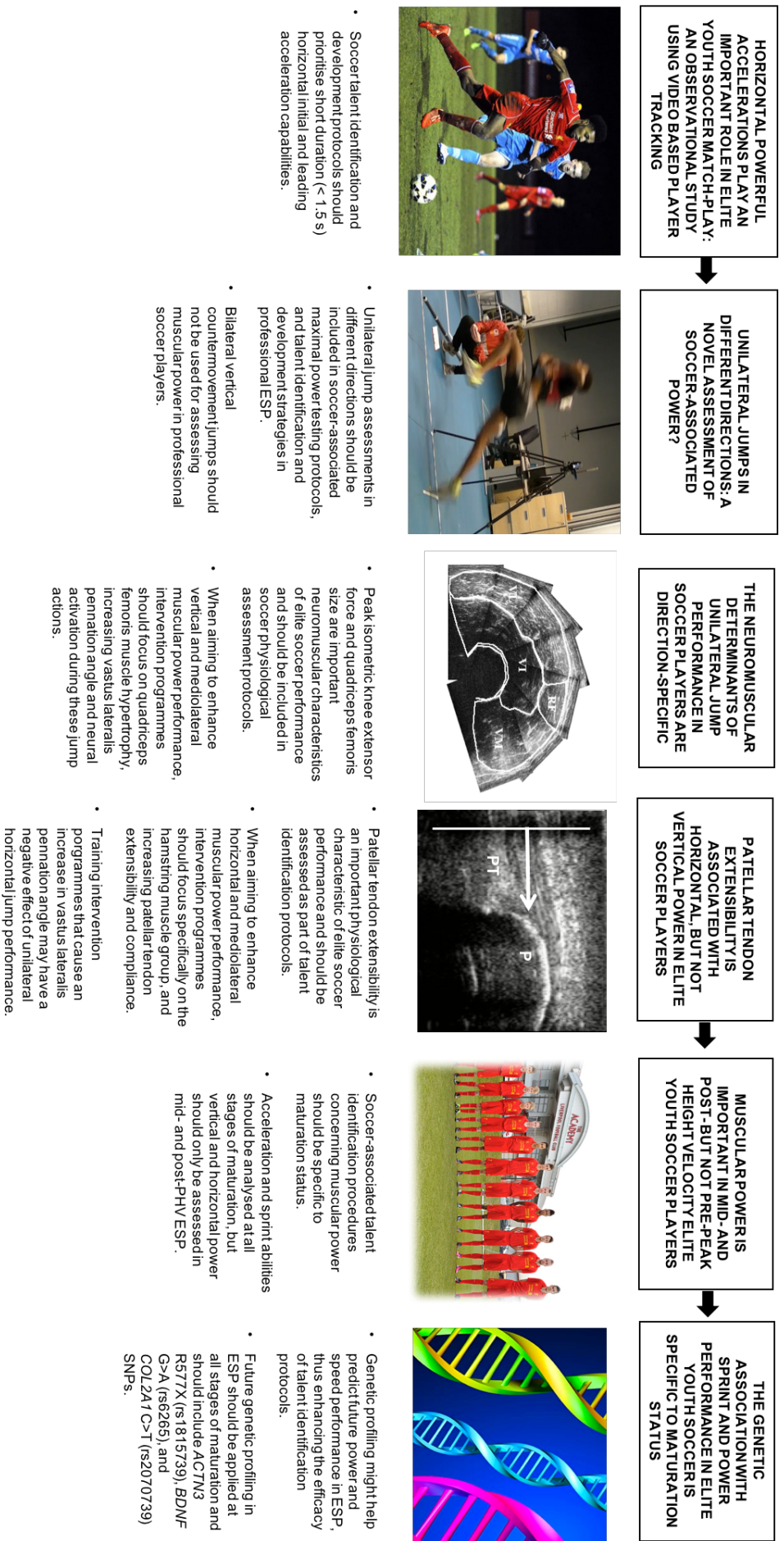
### **8.5 PRACTICAL RECOMMENDATIONS FROM THE PRESENT THESIS**

For this thesis to help improve soccer talent identification and development practice, it is important that practitioners can gain valuable information that can have an impact in the applied setting. Below is a summary of key practical recommendations that have been identified through completion of the present thesis (these recommendations are also illustrated in Figure 8.1 relative to the specific studies):

1. Soccer talent identification and development protocols should prioritise short duration (< 1.5 s) horizontal initial and leading acceleration capabilities.
2. Unilateral jump assessments in different directions should be included in soccer-associated maximal power testing protocols, and talent identification and development strategies in professional ESP.
3. Bilateral vertical countermovement jumps should not be used for assessing muscular power in professional soccer players.
4. Peak isometric knee extensor maximal isometric force, quadriceps femoris muscle size and patellar tendon extensibility may be important physiological characteristics for determining elite soccer playing status and should be assessed as part of talent identification protocols.

5. When aiming to enhance vertical and medial muscular power performance, intervention programmes could focus on knee extensor muscle hypertrophy and neural activation.
6. When aiming to enhance horizontal-forward muscular power performance, intervention programmes should focus specifically on the hamstring muscle group, and increasing patellar tendon extensibility and compliance. Increasing vastus lateralis pennation angle may have a negative impact on horizontal-forward muscular power capabilities.
7. Soccer-associated talent identification procedures concerning muscular power should be specific to maturation status. Acceleration and sprint abilities should be analysed at all stages of maturation, but vertical and horizontal-forward power should only be assessed in mid- and post-PHV ESP.
8. Genetic profiling might help predict future power and speed performance in ESP, thus enhancing the efficacy of talent identification protocols. Future genetic profiling in ESP should be applied at all stages of maturation and should include ACTN3 R577X (rs1815739), BDNF G>A (rs6265), and COL2A1 C>T (rs2070739) SNPs

# THE PHYSIOLOGICAL AND GENETIC FACTORS UNDERPINNING POWERFUL ACTIONS IN ELITE YOUTH SOCCER



**Figure 9.1.** A diagram illustrating a summary of key practical recommendations that have been identified through completion of the present thesis relative to the studies in each Chapter.

## **CHAPTER TEN**

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