THE EFFECT OF NEUROMUSCULAR TRAINING ON FATIGUE RESISTANCE IN FEMALE FOOTBALLERS

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Abstract

ACL injury is predominant in female footballers largely due to a combination of kinetic and neuromuscular risk factors. The majority of ACL injuries in football occur during an unanticipated cutting manoeuvre, and the risk of this injury is heightened during the final 30 minutes of each half of match-play. Due to an increased injury incidence towards the end of match-play, it is possible that fatigue might serve as a risk factor for ACL injury. However, there currently exists limited research examining the effects of fatigue on a variety of kinetic and electromyographic variables in female footballers during an unanticipated cutting manoeuvre. Neuromuscular training programmes have been utilised in injury prevention studies and proven effective in reducing injury incidence by improving certain kinetic and neuromuscular ACL injury risk factors. The overall aim of this thesis is to examine the effectiveness of neuromuscular training on the fatigue resistance of ACL injury risk factors in female footballers.

Study one of this thesis examined the reliability of a combination of kinetic and electromyographic measures in female footballers performing an unanticipated cutting manoeuvre. There were no significant differences in mean values and large to nearly perfect correlations (ICC = 0.49 - 0.96) for all kinetic variables. The majority of kinetic variables displayed a CV of less than 10%, with the exception of loading rates and time to peak force (CV% = 17.33 - 24.51). In comparison to previous research, electromyographic variables displayed a greater range of typical error (CV% = 17.6 - 129.2); however, the majority of electromyographic variables displayed a large, very large or nearly perfect correlation (ICC = 0.26 – 0.91) and no significant differences in the mean score. In line with previous research, standards of reliability, and anticipated changes in response to

acute fatigue, all kinetic and electromyographic variables were deemed acceptable to use in subsequent studies. Kinetic variables showed better reliability than electromyographic variables, which was to be expected due to electromyographic measures being a physiological measure.

Previous research has established that 16 - 18 year old female footballers are at highest risk of ACL injury, and it is most commonly caused during performance of an unanticipated cutting manoeuvre. It has also been established that the majority of injuries in female football are sustained in the last 30 minutes of each half when fatigue is present. Therefore, acute fatigue appears to be an influential risk factor for ACL injury. Study two of this thesis examined the effects of acute fatigue on the electromyographic and kinetic ACL injury risk factors in 16 - 18 year old female footballers, when performing an unanticipated cutting manoeuvre. A modified SAFT90 protocol was used to mimic football match-play. Data showed that during the unanticipated cutting manoeuvre following the SAFT90, participants produced greater GRF (vGRF; *possibly*, apGRF *very likely*), lower GCT (*very likely*), increased background hamstring activation (0 - 30 ms; *very likely*) and increased short-latency feedback activation of the hamstrings (31 - 60 ms; *likely* and *possibly*). Results suggested that following a simulated match-play protocol, female footballers experienced greater force absorption while utilising a safer muscle recruitment strategy. Therefore, injury prevention training should seek to improve a player's aility to tolerate ground reaction forces when experiencing acute fatigue, with a large emphasis on enhancing neuromuscular control within the hamstrings muscle group.

The third study examined the effectiveness of neuromuscular training in developing fatigue resistance of the electromyographic and kinetic variables of female footballers during an unanticipated cutting manoeuvre. The participants from study two were randomly assigned into a control group or experimental group. The control group continued their normal football training, while the experimental group substituted their usual warm-up for the FIFA 11+ two times weekly for eight weeks. Exposure to the eight week intervention training resulted in *likely* improvements in peak apGRF, *very likely* enhancements in feed-forward mechanisms of ST, and *very likely* and *likely* increases in feed-forward H:Q co-activation ratios during pre-activation and 0 - 30 ms respectively. This study demonstrated that an eight week neuromuscular training intervention can have a positive effect on the fatigue resistance of key neuromuscular variables associated with ACL injury risk factors in female footballers.

In its entirety, this thesis has provided insight into the way in which acute fatigue impacts on key ACL injury risk factors during unanticipated cutting. Also, the thesis has demonstrated the benefits of neuromuscular training in minimising the negative effects of acute fatigue on these key risk factors. It has highlighted that acute fatigue can have a negative effect on various kinetic and electromyographic variables, but these detrimental effects can be improved with neuromuscular training. Therefore, it has been identified that kinetic and electromyographic variables in female footballers performing an unanticipated cutting manoeuvre are potentially trainable to resist fatigue, which could possibly decrease the risk of ACL injury.

I declare that the work in this thesis was carried out in accordance with the regulations of the University of Gloucestershire and is original except where indicated by specific reference in the text. No part of the thesis has been submitted as part of any other academic award. The thesis has not been presented to any other education institution in the United Kingdom or overseas.

Any views expressed in the thesis are those of the author and in no way represent those of the University.

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Abbreviations

3D – Three dimensional

ACL – Anterior Cruciate Ligament

Ag – Silver

AgCl – Silver chloride

ANOVA – Analysis of variance

apGRF – Anterior-posterior ground reaction force

ATC – Athletic trainer certified

BF – Biceps femoris

CI – Confidence Interval

CNS – Central nervous system

CMJ – Counter movement jump

CRB – Criminal Records Bureau

CUT – Side cut

CV – Co-efficient of variation

dB – Decibels

deg/s – Degrees per second

EMG – Electromyography

F-MARC – FIFA Medical and Research Centre

FA – Football Association

FAKE – Straight run and fake pass

FIFA – Federation Internationale de Football Association

GB – Great Britain

GM – Gluteus medius

GRF – Ground reaction force

GS – Gluteus minimus

GX – Gluteus maximus

H:Q co-cx – Hamstring:quadriceps co-contraction ratio

HR – Heart rate

Hz – Hertz

ICC – Intraclass Correlation Coefficient

IED – Inter-electrode distance

INT - Intermittent

kg – Kilograms

km - Kilometres

km/h – Kilometres per hour

kΩ - Kiloohms

LCL – Lateral Collateral Ligament

LH – Lateral hamstring

LIST – Loughborough intermittent shuttle test

M – Metres

m/min – Metres per minute

m/s – Metres per second

Max – Maximum

MCL – Medial Collateral Ligament

MG – Medial gastrocnemius

MH – Medial hamstring

Min – Minimum

MLS – Major League Soccer

mm – Millimetres

ms - Milliseconds

MVC – Maximal voluntary contraction

MVIC – Maximal voluntary isometric contraction

n - Number

NCAA – National Collegiate Athletic Association

PASS – Side cut followed by a pass

PCL – Posterior Cruciate Ligament

PDA – Personal digital assistant

PEP – Prevent Injury Enhance Performance

PP – Pre-planned conditions

RESC – Research Ethics Committee

RF – Rectus femoris

RM – Repetition maximum

RMANOVA – Repeated measures analysis of variance

ROM – Range of motion

RPE – Rate of perceived exertion

RSI – Reactive strength index

s – Seconds

S30 – Sidestep cut at 30 degrees

S60 - Sidestep cut at 60 degrees

sEMG – Surface electromyography

SAFT – Soccer Specific Aerobic Field Test

SD – Standard deviation

SEBT – Star excursion balance test

SENIAM - Surface ElectroMyoGraphy for the Non-Invasive Assessment of Muscles

SM - Semimembranosus

SS – Steady state

SSEP – Soccer specific exercise protocol

ST - Semitendinosus

TD – Total Distance

UK – United Kingdom

UN – Unanticipated conditions

US – United States

Vball – Ball velocity

Vfoot – Foot velocity

vGRF – Vertical ground reaction force

VL – Vastus lateralis

VM – Vastus medialis

VO_2max – Maximal volume of oxygen

WUSA – Women’s United Soccer Association

XOV – Crossover cut at 30 degrees

Chapter 1: Introduction

1.1 INTRODUCTION

With football being the world's most popular team sport and the participation in women's football growing rapidly, the risk of injury in female footballers is increasing (FIFA, 2015; The FA Factsheet, 2012). Participation in sport and physical activity has a range of positive effects on an individual's physical health and psychological well-being including; improved cardiovascular health, increased muscular strength and endurance, and decreases in psychological stressors such as; anxiety, depression and tension (Biddle & Asare, 2011; Strong et al., 2005). However, despite these positive effects there is also a negative risk of sustaining an injury. All sports carry the risk of injury and injuries are usually sport-specific. The most common injuries in football are hamstring and quadriceps strains, knee ligament injuries and ankle sprains (Junge & Dvorak, 2007; Price et al., 2004).

The risk of injury in football varies according to sex and age of player. Researchers have identified that male footballers sustain different types of injuries to their female counterparts, with youth female footballers reporting the highest injury rate (Giza et al., 2008; Hagglund et al., 2009; Junge & Dvorak, 2002; 2004; 2007). The most common injuries in males have been identified as hamstring strains and hip and groin injuries, while the most common injuries in females have been identified as knee ligament ruptures (specifically the anterior cruciate ligament [ACL]), ankle sprains and concussions (Hagglund et al., 2009). ACL injuries are predominant in both male and female football and can vary in severity (Junge & Dvorak, 2002; 2004; 2007). However, females are up to eight times more likely to sustain an ACL injury than their male counterparts, with 16 - 18 year old females displaying the highest ACL injury incidence (Hughes, 2006;

Mendiguchia, 2013; Myer et al., 2009). The primary role of the ACL is to act as a restraint to anterior tibial displacement. Research shows that the ACL is injured most commonly during sporting motions such as; landing, cutting and sudden changes of speed, with 70-80% of ACL injuries being non-contact in nature (Cowley, 2006; Landry, 2007; Quatman, 2010; Silvers 2007). In female football, a cutting manoeuvre is the most common mechanism of non-contact ACL injury (Brophy et al., 2010) and with the reactive nature of the game most cutting manoeuvres are performed in an unanticipated manner (Cowley, 2006; Landry, 2007; Silvers 2007). The rotational motions at the knee, hip and ankle combined with deceleration forces during an unanticipated cutting manoeuvre causes' excessive hip adduction and internal rotation, knee abduction, tibial external rotation and anterior translation, and ankle eversion, placing the ACL under stress (Cowley et al., 2006; Quatman, 2010).

1.1.1 Kinetic and Electromyographic Variables

There are many modifiable and non-modifiable risk factors that can contribute to the increased risk of non-contact ACL injury in female footballers. Most research is focused on the modifiable risk factors such as joint positioning, neuromuscular performance and joint loading (Alentorn-Geli, 2009; Cowley, 2006; Landry, 2007; Myer, 2004), which can be addressed through various prevention methods. The modifiable risk factors such as neuromuscular control and biomechanical function are thought to be primary causes accounting for the female predisposition to ACL injury (Braun et al., 2015; Griffin et al., 2000). However, our understanding of the effect of fatigue on the mechanisms that predispose youth females to ACL injuries is unclear.

Kinetics is the branch of mechanics that examines the motion of bodies under the action of forces. Research examining sex-related differences in lower limb injuries has observed that females display greater vertical ground reaction force (vGRF) and knee energy absorption strategies than their male counterparts (Schmitz & Schultz, 2010). In terms of injury mechanism, vGRF and anterior-posterior ground reaction forces (apGRF) are larger during a cutting manoeuvre compared to drop-jump landing, thus a greater risk of injury is observed during a cutting manoeuvre in female footballers (Brophy et al., 2010; Cortes et al., 2011). It has been suggested that greater knee extensor strength can predict greater energy absorption at the knee joint, which in turn places larger amounts of stress on the passive structures of the knee joint (Schmitz & Schultz, 2010). The quadriceps dominance displayed in female footballers could cause greater energy absorption at the knee joint and more stress on the ACL (Ahmad et al., 2006; Alentorn-Geli, 2009; Palmieri-Smith, 2009; Schmitz & Schultz, 2010). The female ACL is more compliant and fails at a lower tensile strain, even after adjusting for age, body anthropometrics, and ligament size, thus the risk of ACL injury could be higher in females due to greater loads absorbed at the knee joint where the ACL is less stiff and fails at a lower level than its male counterpart (Chandrashekar et al., 2006). Also, females display decreased GCT in comparison to their male counterparts (Schmitz & Schultz, 2010). GCT is also greater during a cutting manoeuvre compared to a drop-jump landing, therefore higher forces are absorbed over a shorter period of time increasing force loading rate and subsequent stress on the female ACL during a cutting manoeuvre (Cowley et al., 2006).

Electromyography (EMG) is a measurement method used to record changes in electrical potential of muscle fibres associated with their contraction (Burden, 2008). From an electromyographic perspective, the erect posture of female athletes during decelerating manoeuvres reduces the efficiency of static knee restraints, therefore dynamic stabilisers are important to maintain knee joint stability (Senter and Hame, 2006; Wikstrom et al., 2006). During landing and cutting manoeuvres, the hamstrings and quadriceps work together as dynamic stabilisers to the knee joint (Alentorn-Geli, 2009). With the knee near full extension, the quadriceps contract forcefully, thus causing anterior tibial shear forces that place the ACL under increased stress. Conversely, the hamstrings activate as an antagonist to this movement which decreases the strain on the ACL (Senter and Hame, 2006). Many studies have researched sex differences in Hamstring:Quadricep (H:Q) co-activation ratios and have identified that female footballers activate their quadriceps earlier and to a greater extent than their hamstrings (Ahmad et al., 2006; Alentorn-Geli, 2009; Ebben et al., 2010; Palmieri-Smith, 2009). Researchers have suggested that the H:Q co-activation ratios and quadriceps dominance of females increases the stress on the ACL, which combined heightens their overall risk of injury (Ahmad et al., 2006; Alentorn-Geli, 2009; Palmieri-Smith, 2009). Female athletes not only display a deficit in activation and timing of hamstrings musculature, but also activate their lateral thigh muscles greater than their medial thigh muscles (Hanson et al., 2008; Palmieri-Smith, 2009). Previous research has related this pattern of muscular activation to higher knee abduction loads and valgus stress, therefore placing greater stress on the ACL (Hanson et al., 2008; Palmieri-Smith, 2009).

Although these risk factors have been deemed important in the research, the effect of fatigue on the kinetic and electromyographic variables of youth female footballers performing an unanticipated cutting manoeuvre have not been identified. A limited amount of research has investigated electromyographic and kinetic variables of adult female footballers during an unanticipated cutting manoeuvre, however due to the effects of age and maturation on development of the neuromuscular system, these findings cannot be directly related to youth populations. It is important that 16 - 18 year old female footballers are investigated further due to this age group being most at risk of ACL injury (Hewett et al., 2000; Shea et al., 2004), and such investigations should utilise the most common mechanism of injury in female footballers, i.e. an unanticipated cutting manoeuvre.

1.1.2 Fatigue as a Risk Factor

The effect of fatigue on the risk factors present in youth female footballers remains unclear. Most injuries in female and male footballers occur in the second half of match-play (Hiemstra et al., 2001). Fatigue has been shown to manifest in the last 15 minutes of match-play in male footballers and the last 30 minutes of match-play in female footballers, therefore fatigue has been identified as a key risk factor to injury (Krustup et al., 2003; Mohr et al., 2005). Researchers have observed a negative effect of fatigue on knee injury risk factors such as; reduced electromyographic activation of the hamstrings and quadriceps, and various lower limb mechanical changes in adult male and female footballers (Borotikar et al., 2012; Cone et al., 2012; Cortes et al., 2011; De Abreu Camarda et al., 2012; Lucci et al., 2011; Padua et al., 2006; Smith et al., 2009; Thomas et al., 2010; Wright et al., 2009). It is well documented that adults experience greater fatigability than adolescents and even more so than children (Ratel & Martin, 2015). There is also a proposed withdrawal of fatigue protection during adolescence (Ratel & Martin, 2015), which has been attributed to changes in muscle fibre composition, muscle mass, and relative force production (Ratel & Martin, 2015). Previous research has identified that the effect of fatigue on female ACL injury risk is 2.5 times greater than males, due to decreased muscle force and strength production, increased quadriceps dominance, decreased hamstrings co-activity, increased knee abduction and earlier activation of lateral thigh muscles than medial thigh muscles (Gehring et al., 2009; Jollenbeck et al., 2010).

However, research has yet to examine the effects of a simulated match-play protocol, which mimics the energy demands and fatigue of football match-play, on electromyographic and kinetic variables of footballers (Borotikar et al., 2012; Cone et al., 2012; Cortes et al., 2011; De Abreu Camarda et al., 2012; Lucci et al., 2011; Padua et al., 2006; Smith et al., 2009; Thomas et al., 2010; Wright et al., 2009). Nor has the literature attempted to examine the effects of acute fatigue on kinetics and neuromuscular functioning during unanticipated cutting manoeuvres, which is an integral movement pattern within football and is the most common movement in which ACL injury occurs in female footballers (Brophy et al., 2010; Cowley et al., 2006; Landry et al., 2007; Silvers et al., 2007). With anticipatory effects of cutting such as; lateral trunk flexion, increase knee flexion angles, and larger internal/external knee moments (Besier et al., 2001b; Mornieux et al., 2014; Weinhandl et al., 2014), it is important to understand the electromyographic and kinetic variables displayed by youth female footballers during an unanticipated manoeuvre, and the effects that acute fatigue may have on these variables.

1.1.3 Prevention of ACL Injuries

Many prevention programmes have been produced and implemented to study their potential protective effects against ACL injury, especially in females (Michaelidis &

Koumantakis, 2014). Specifically in football, the FIFA 11+ has been observed to decrease the risk of injury in male and female footballers (Mendiguchia, 2013; Soligard et al., 2008; Steffen et al., 2013).Some improvements in electromyographic and kinetic variables following exposure to the FIFA 11+ intervention have been identified in male footballers, such as improved H:Q co-activation ratios, increased torque of non-dominant hamstrings (Brito et al., 2010) and decreased vGRF (Hewett et al., 1996; Irmischer et al., 2004; Prapavessis et al., 2003). However, further studies identifying the effect of the FIFA 11+ on a wider range of electromyographic and kinetic variables such as; timing of electromyographic activation, ground reaction force (GRF) loading rates and ground contact time (GCT), specifically in female footballers, is required to identify the mechanisms of ACL injury risk and prevention. In youth female footballers, injury incidence has been observed to decrease following exposure to the FIFA 11+ in which players performed the targeted training two-three times per week, for 6-8 weeks (Soligard et al., 2008). More recent research from Zebis et al. (2016) identified positive effects of an injury prevention programme on the pre-activity of semitendinosus (ST) versus vastus lateralis (VL) in 15 - 16 year old female football and handball players performing an anticipated side cutting manoeuvre. The programme was adapted for the footballers to include kicking activities, rather than throwing activities. The programme increased ST pre-activity in comparison to VL pre-activity in the intervention group, which the opposite was identified in the control group consisting of female football and handball players who continued their normal sport-specific training but did not perform the injury prevention programme. The intervention group were judged to possess a lower risk of ACL injury due to this electromyographic adaptation from training. However, the specific effects of the FIFA 11+ on electromyographic and kinetic variables of youth female footballers performing an unanticipated cutting manoeuvre are still unknown, and it is unclear if any of the beneficial training effects emulating from exposure to the FIFA 11+ can ameliorate modifiable ACL injury risk factors in the presence of acute fatigue.

1.2 RESEARCH QUESTIONS AND OBJECTIVES

The current thesis will investigate further i) the modifiable electromyographic and kinetic ACL injury risk factors present in female footballers during an unanticipated cutting manoeuvre, ii) the effect of fatigue on these risk factors, and iii) the effect of a neuromuscular injury prevention intervention (FIFA 11+) on these modifiable risk factors. Therefore the research questions and objectives are as follows;

1.2.1 Research Questions

1. What is the reliability of kinetic and electromyographic variables during an unanticipated cutting manoeuvre in youth female footballers?
2. What are the effects of acute fatigue on the kinetic and electromyographic variables associated with ACL injury risk during an unanticipated cutting manoeuvre in youth female footballers?
3. To what extent does a neuromuscular injury prevention intervention affect kinetic and electromyographic variables during an unanticipated cutting manoeuvre and in a fatigued state, in youth female footballers?

1.2.2 Research Objectives

a. To determine the reliability of kinetic and electromyographic variables during an unanticipated cutting manoeuvre in youth female footballers

b. To determine the effect of fatigue on the kinetic and electromyographic variables associated with ACL injuries during an unanticipated cutting manoeuvre in youth female footballers
c. To determine the effectiveness of the Federation Internationale de Football Association's (FIFA) 11+ programme in improving the kinetic and electromyographic variables associated with ACL injuries when fatigue is present in youth female footballers performing an unanticipated cutting manoeuvre
d. To suggest appropriate improvements in the effectiveness of such prevention programmes in reducing ACL injury risk in youth female footballers

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Chapter 2: Literature Review

2.1 WOMEN'S FOOTBALL

2.1.1 Participation

Football is recognised as the nation's number one choice of sport. In England, it is the most popular team sport for women; with over 150,000 women playing on a weekly basis (Sport England, 2011). In Europe, 30% of the footballing population are female (UEFA, 2015). However, this popularity of the game has not always existed. The first women's football match was played in 1895, but 26 years following this occasion the English Football Association (FA) banned women from playing on all FA pitches making it difficult for women to have equal rights to participate in the sport. In 1969, the Women's FA was formed, over which, the FA claimed governance in 1993. Since then, the FA has observed steady increases in the amount of females playing football (DCSM, 2012). These females compose a fraction of the 4.1 million female participants who participate in the sport across the globe. The participation in women's football is increasing with 49 licensed centre of excellence female youth teams in England, a Bronze Medal winning Women's World Cup squad, a Team GB Olympic level squad, and an established women's semi-professional league in England, all providing the opportunity of elite level participation in women's football (FIFA, 2015; The FA, 2012).

2.1.2 Injury Risk

Accompanying the rapid growth of participation in women's football is the increased incidence of sports injuries in female footballers (Hewett, 2000; Koutures & Gregory, 2010). Football has a higher injury rate than many other sports (Koutures & Gregory, 2010). In the USA, 80% of football related injuries occur in participants younger than 24 years old, with 44% occurring in those under the age of 15 years (Koutures & Gregory, 2010), clearly indicating that youth footballers are at a high risk of sports injury. Junge and Dvorak (2007) analysed injuries in seven major international women's football tournaments including the 1999 and 2003 FIFA Women's World Cup, the 2002 and 2004 FIFA U19 Women's World Championship, the 2006 FIFA U20 Women's World Championship and the senior women's football competitions in the 2000 and 2004 Olympic Games. The researchers observed that female footballers sustained an average of 67.4 injuries/1000 playing hours or 2.2 injuries/match across the seven major international tournaments. These findings were slightly lower in the most recent FIFA Women's World Cup (2015) with an average of 2.1 injuries/match (FIFA, 2015), it could be suggested that this is because of the increased awareness of injury risk and prevention in sport. However, there is a wide variation in reported incidence as a result of methodical differences including; intensity of exposure, injury definition and classifications, and reporting systems, which could influence the differences in findings between major international tournament data (Koutures & Gregory, 2010). The lower extremity was the most commonly injured body part in all seven major international tournaments studied by Junge & Dvorak (2007), composing 65% of the total injuries reported (n = 248), with 11% of these injuries occurring at the knee. Of all the knee injuries present, 6% were knee ligament injuries (n = 23) with seven ruptures, five of which were non-contact. Females are 6-8 times more likely to rupture their ACL than their male counterparts and 70%-80% of ACL injuries in females are of a non-contact mechanism (Hewett et al., 2000; Hughes, 2006). Further to these studies, research by Braun et al. (2015) have suggested a variety of risk factors for non-contact ACL injuries in female athletes, one of those being a quadriceps dominance strategy when landing and cutting (Braun et al., 2015).

In comparison to men's data by Junge et al. (2004), Junge & Dvorak (2007) identified that women sustain more injuries during major international tournaments than their male counterparts, therefore it is important to identify and prevent the injury risk factors which predispose females to injuries in comparison to their male counterparts (Junge & Dvorak, 2007). In contrast, Giza et al. (2005) analysed injury data across two seasons of the Women's United Soccer Association (WUSA) (2001-2002), and reported an overall injury incidence rate of 1.93 injuries/1000 player hours across the two seasons which was lower than their male counterparts in the Major League Soccer (MLS). Similarly to Junge and Dvorak (2007), the most common location of injury was the knee (31.8%, n = 55) with eight ACL injuries, six of which were non-contact in nature, equating to 0.09 ACL tears/1000 player hours (Giza et al., 2005). These findings are comparable to the Swedish Premier Division producing a higher injury incidence rate in males (4.7 injuries/1000 hours & 28.1 injuries/1000 hours) during training and match-play, respectively, than females (3.8 injuries/1000 hours & 16.1 injuries/1000 hours), and the knee being a common injury site in females (ACL injury rupture rate: 0.15/1000 hours) (Hagglund et al., 2009). As two of the top female football leagues across the globe, the skill levels and physical demands of match-play of the Swedish Premier League and WUSA are similar and could account for the similar injury data collected (Giza et al., 2005; Hagglund et al., 2009). There are limited studies on the incidence rate in amateur football, however recent studies by Mtshali et al. (2015) and Babwah (2014) observed similar injury rates in amateur tournament match-play (61.7 injuries/1000 hours) (Mtshali et al., 2015) to those observed in major international tournaments (67.4 injuries/1000 hours) (Junge & Dvorak, 2007), and higher rates of injury during club seasons (30.8 injuries/1000 hours) (Babwah, 2014) compared with professional club seasons (Giza et al., 2005; Hagglund et al., 2009). The female to male injury rate comparisons observed by Giza et al. (2005) and Hagglund et al. (2009)

contradict the findings of Junge and Dvorak (2007). This difference could be linked to fatigue and recovery. Junge and Dvorak’s (2007) study collated data from international tournament play where match-play is at the highest level with the greatest demands, and rest and recovery periods are short (two to three days). Giza et al. (2005) and Hagglund et al. (2009) data was collected over club seasons in which recovery periods are much longer (five to seven days) and match-play may be a slightly lower level with less physical demand. Therefore, higher injury incidence rates in female footballers during international tournament match-play as compared to club seasons could be due to greater physical demand, fatigue, and limited recovery time (Giza et al., 2005; Hagglund et al., 2009; Junge & Dvorak, 2007). Comparing the literature, it could be speculated that male footballers cope better with limited recovery sustaining fewer injuries during major international tournaments with two to three days’ recovery, and more injuries during club seasons with five to seven days’ recovery, than their female counterparts. However, there is no research identifying sex difference in recovery rates and methodological inconsistencies in injury definition and reporting measures could have caused contrasting findings in the research (FIFA, 2015; Giza et al., 2005; Hagglund et al., 2009; Junge & Dvorak, 2007).

Previous research has identified injury incidence in elite and amateur tournaments and seasons (Giza et al., 2005; Hagglund et al., 2009; Junge & Dvorak, 2007; Mtshali et al., 2015), however it is important to consider the phase of play when injury incidence occurs as this will allow a host of risk factors to be investigated and effective prevention measures to be prescribed. In analysing the time pattern of injury, Junge and Dvorak (2007) observed fewer injuries occurring in the first 15 minutes of each half, as compared to the remaining 30 minutes in each half within the seven major international female football tournaments.

These findings are similar to that of male footballers in the UEFA injury study by Ekstrand et al. (2009). Ekstrand et al. (2009) observed traumatic injuries, contusions, ligament sprains and muscle strains displaying an increasing tendency over time in both the first and second halves of match-play. Studies identifying physical demands of the game have observed player fatigue towards the end of a game, identified by decreases in the amount of high-intensity running and technical performance (Ekstrand et al., 2009). Therefore, it may be speculated that fatigue could be an explanation for these findings and a potential injury risk factor for both male and female footballers.

Time loss data was available for 309 injuries from the Women's Major International Tournaments (Junge & Dvorak, 2007). Of these, 48% (n = 149) caused time lost from match or training, thus preventing the player from participating. Time loss due to injury can affect a female player's mental condition including; a loss of athletic identity, feelings of helplessness and depression, and a decline in physiological condition (Madrigal & Gill, 2014). The long term physical effects of injury such as post-traumatic osteoarthritis are also well documented (Brittney et al., 2014). Therefore, prevention of injuries causing time loss from sport could be pertinent to increasing long term health and well-being of female footballers (Brittney et al., 2014; Madrigal & Gill, 2014).

Between tournaments analysis observed higher injury incidence rates in the U19/U20 tournaments (2.7 injuries/match) than the senior World Cup and Olympic Games tournaments (1.5 injuries/match and 2.2 injuries/match), and most recent senior World Cup tournament (2.1 injuries/match) (FIFA, 2015). These observations could be interpreted as the younger players being more at risk to sustain an injury during a major international tournament (Junge & Dvorak, 2007). Some youth female footballers within a football development academy will have 5-7 day’s rest between competitive matches. However, many youth players will play for a development academy and a local club team with only two to three days recovery between competitive match-play. Therefore, the increased risk of injury in youth female footballers, compared to adult female footballers, is further increased by the limited rest and recovery some youth female footballers, participating in development academy training and matches alongside local club training and matches, experience. Thus, it is important to understand the injury risk and benefits of neuromuscular training in youth female footballers participating at a development academy level with limited recovery periods. Research by Shea et al. (2004) studied the ACL injury rate in male and females aged 5 - 18 years, and observed the highest injury rate occurred in 16 - 18 year old females (ACL injury rate: 0.22 - 0.28), and these ACL injury rates identified were greater than those observed in senior footballers (Giza et al., 2005; Hagglund et al., 2009; Shea et al., 2004). Researchers suggest youth females are at higher risk of injury than female adults due to puberty and maturation (Cowley, 2006), and injury incidence data from youth and senior international tournaments support this (FIFA, 2015; Junge & Dvorak, 2007).

Le Gall et al. (2008) longitudinally analysed injury data of young elite female footballers (15 - 19 years old) across eight seasons. Researchers analysed the difference between age groups and observed a trend that injury incidence reduced with age (Le Gall et al., 2008). Significant differences between the amount of injuries sustained by 15 year olds and 19 year olds were noted, with 15 year olds sustaining significantly more injuries than 19 year olds (Le Gall et al., 2008). Although Le Gall et al. (2008) observed a trend of a higher risk of general injury in the younger youth female footballer (15 years old) compared to the older youth female footballer (19 years old), the highest incidence of ACL injury specifically has been identified in 16 - 18 year old youth female footballers (Hewett et al., 2000; Shea et al., 2004). In comparison to adult elite female footballers, the injury incidence of youth elite female footballers is greater (Giza et al., 2008; Junge & Dvorak, 2007; Le Gall et al., 2008). Researchers observed 92.4% of the youth female footballers (n = 110) sustain at least one injury. Subsequently, an injury incidence rate of 6.4 injuries/1000 player hours was noted with 22.4 injuries/1000 hours of match-play and 4.6 injuries/1000 hours of training. The injury incidence rate/1000 player hour is three times higher in the female youth population in the study by Le Gall et al. (2008), than the female adult population in the WUSA and major league tournaments (Giza et al., 2005; Junge & Dvorak, 2007). The injury incidence observed by Le Gall et al. (2008) is similar to research on injury incidence in Canadian youth and national footballers (Mohib et al., 2014). The difference in injury rate between adult and youth players could be due to the greater fitness, resistance to fatigue, tactical and technical skill level, and efficiency of movement in adult players as compared to their youth counterparts (Ahmad et al., 2006; Ekstrand et al., 2009; Junge & Dvorak, 2007). Methodical differences in terms of the length of study could be a factor causing contrasting findings, as those studies utilising adult female footballers have observed injury incidence over one to two seasons or various tournaments, whereas studies in youth football tend to be longitudinal providing a better overview as injury rates can change season to season (Giza et al., 2005; Junge & Dvorak, 2007; Le Gall et al., 2008; Mohib et al., 2014). Also, youth female footballers may lack injury avoidance skills in comparison to adult female footballers, and could have possibly undertaken too much intense training at an early age (Ahmad et al., 2006). Similar to the findings of Junge & Dvorak (2007), the majority of injuries sustained by the youth players were to the lower extremity (n = 516, 83.4%), with 104 injuries occurring at the knee (Le Gall et al., 2008). The most common injuries sustained by the young elite female footballers were sprains, 25.7% to the knee. Of these sprains, there were 12 ACL ruptures, with 7 occurring on the non-dominant leg (Le Gall et al., 2008). Although youth female footballers are at greater risk of injury, the most common injury sustained remains similar i.e. ligament sprain in the knee. The long term effect of knee joint injury in youth sport is damaging with male and female athletes reporting ongoing symptoms including; pain, poor quality of life and problems with activities of daily living, displaying poorer function and being at greater risk of being overweight/obese three - ten years post-injury, compared with those athletes who did not sustain a knee joint injury as a youth athlete (Whittaker et al., 2015). Therefore, it is important to address the increased risk of knee injury, specifically ACL injury, in female footballers during the higher risk age range of 16 - 18 year olds (Hewett et al., 2000; Shea et al., 2004).

In comparison, older male youth players (17 - 19 years) are more likely to receive an injury than younger male youth players (9 - 16 years) (Price et al., 2004). These findings are opposite to those of youth female footballers, in which studies examining the injury incidence of female 15 - 19 year olds observed greater injury in the younger (15 year old) female players as compared to the older (19 year old) female players (Le Gall et al., 2008). This could be due to the increased competitive nature of males at the age of 17 - 19 years compared to males at the age of 9-16 years, as intensity is linked to injury 17 - 19 year old males have greater physical capacity to play at a higher intensity than their younger counterparts, and effects of fatigue may display greater or earlier in younger male footballers (Ekstrand et al., 2009; Wild et al., 2012). Also, pubertal changes occur later in males which may affect the gender-age difference in injury rates as ACL injuries specifically occur more commonly at the onset of and during puberty (Wild et al., 2012). The injuries sustained in training and match-play were observed as a 50/50 split of the total injuries sustained by male youth footballers unlike the female youth footballers who sustained a greater amount of injuries in match-play compared to training (Price et al., 2004). This could be due to the competitive nature of match-play in comparison to training or greater physical demands in match-play when compared to training, causing a possible fatigue-related decline in performance and increase in injury risk (Ekstrand et al., 2009). Overall injury incidence/1000 player hours was also greater for female youth footballers (6.4/1000 player hours) than male youth footballers (5.6/1000 player hours) (Le Gall et al., 2008; Price et al., 2004). As for injury location, similar to female youth players the lower extremity is the most common site for injury in male youth players with similar proportion of injuries affecting the thigh, ankle, and knee (Koutures & Gregory, 2010; Price et al., 2004). The previous research has shown that youth female footballers are at the highest risk of injury when compared to adult male and female footballers and their youth male counterparts. Therefore, research studying the mechanisms of ACL injury, the effect of acute fatigue on ACL injury, and the prevention of ACL injury in the high-risk youth female footballer population is vital.

2.1.2.1 Summary of Injuries in Women's Football

Those studies that have investigated the sex difference in injury incidence of footballers have come to a common consensus that male footballers have a higher injury incidence rate than female players, with the exception of major international tournaments and youth players, where female injury risk is greater (Giza et al, 2008; Hagglund, 2009; Jacobson &

Tegner, 2006; Le Gall, 2008, Junge & Dvorak 2007; Price et al. 2004; Tegnander, 2008). Therefore, there is a need for injury prevention in the high-risk population of youth female footballers. The majority of studies investigating the injury incidence of female footballers have observed two common trends; i) the knee is a common site for injury, more so than males and, ii) the younger the female footballer, the higher the injury risk (Giza et al, 2008; Hagglund et al., 2009; Jacobson & Tegner, 2006; Le Gall, 2008, Junge & Dvorak 2007; Price et al. 2004; Tegnander, 2008). Therefore, it is pertinent that researchers have an understanding of the mechanisms associated with injury incidence and risks, as well as injury prevention programmes specifically focused on lowering ACL injury risk in youth female footballers.

2.1.3 Mechanism of Injury

Anterior cruciate ligament injuries can be classified as contact or non-contact. A contact injury involves external risk factors i.e. connection with an opposing player or object, whereas a non-contact injury involves internal risk factors i.e. faulty biomechanics during sport-specific manoeuvres (Hewett et al., 2000). ACL injuries in youth female footballers are predominantly non-contact (70%-80%), occur on the non-dominant limb, and most commonly occur during a cutting manoeuvre (Brophy et al., 2010; Cowley et al., 2006; Landry et al., 2007; Silvers et al., 2007). A cutting manoeuvre allows a player to change direction during a game (Brophy et al., 2010). There are two primary techniques utilised to make a directional change; the sidestep cut and crossover cut. Each type of manoeuvre is made up of three phases; deceleration, plant and cut, and takeoff, which can cause excessive knee joint loading placing a physiological strain on the internal structures of the knee by producing a combination of hip adduction and internal rotation, knee abduction, tibial external rotation and anterior translation, and ankle eversion (Quatman, 2010). The most direct loading of the ACL is achieved through anterior tibial shear forces, when the tibia translates anteriorly on the femur, most commonly caused by a forceful landing or deceleration (Quatman, 2010). However, researchers suggest that the ACL injury mechanism is multi-directional and multi-factorial (Quatman, 2010).

2.1.3.1 Deceleration

The primary goal of the deceleration phase of a cutting manoeuvre is to decrease momentum of the player using the largest amount of force production possible in the shortest time. This can lead to large ground reaction forces (GRF's) and increased ground contact time (GCT) to attenuate the large forces (Hewit et al., 2011). At foot strike, the foot plantarflexes rapidly to make full contact with the ground and the player's lower limb is not ahead of their centre of mass, opposing forward momentum. Upon initial contact, the lower extremity flexes at the hip and knee, and ankle dorsiflexion is produced to share the impact forces over as many joints as possible to reduce the stress. As the body is travelling forward to place the swinging limb to the ground, a deceleration force is produced. At this point, the torso is more upright, the ankle dorsiflexes further, and the tibia angles anterior to the vertical axis. When this occurs deceleration force is at its greatest (Hewit et al., 2011). The body pre-activates the quadriceps to generate the deceleration power, which is vital for absorbing eccentric forces during ground contact (Benvenuti et al, 1997; Colby et al., 2000). During the cutting manoeuvre, deceleration creates anteroposterior forces on the knee joint placing stress on the ACL (Andrews et al., 1977).

2.1.3.2 Plant and Cut

The change of direction intended during a cutting manoeuvre is achieved during the plant and cut phase (Andrews et al., 1977). The plant and cut phase occurs from the plant foot controlling the deceleration and the hips and torso rotating towards the intended direction of travel. Acceleration in the changed direction is achieved by the swinging leg then progressing in that direction, further acceleration is provided by the plant leg which then pushes in the new direction. When performing the sidestep cut the player experiences stress on the medial side of the knee, whereas when performing the crossover cut the stress is produced on the lateral side of the knee. In terms of ACL injury and due to the sidestep cut being of common place in football match-play, a medial stress would be of greater concern. During the plant and cut phase of a sidestep cut, the player would plant with the plant foot then swing the leg in the opposing direction of the plant foot to cut in the direction away from the plant foot (Andrews et al., 1977). This manoeuvre causes early internal rotation of the pelvis and torso, hip flexion and external rotation, knee flexion and ankle dorsiflexion (Figure 2.1). During push-off, the knee and hip extend and the ankle plantarflexes fully (Ilmane & LaRue, 2008). Besier et al. (2001) identified an increased risk of knee injury during the cutting manoeuvre when flexion, valgus/varus and internal and external rotation loads acted on the knee, as they do in the sidestep cutting manoeuvre. The greatest magnitude of stress applied to the ACL is determined to be when external flexion loads were accompanied with greater valgus and internal rotation moments (Besier et al., 2001).

2.1.3.3 Take off

The take off phase is similar to running gait. The support phase contains three sub-phases; strike, midsupport and take off. The recovery phase also contains three sub-phases; follow through, forward swing and foot descent. The key difference between the take off phase of cutting and normal running gait is the greater forward lean necessary for the athlete to generate acceleration in a new direction of travel (Andrews et al., 1977).

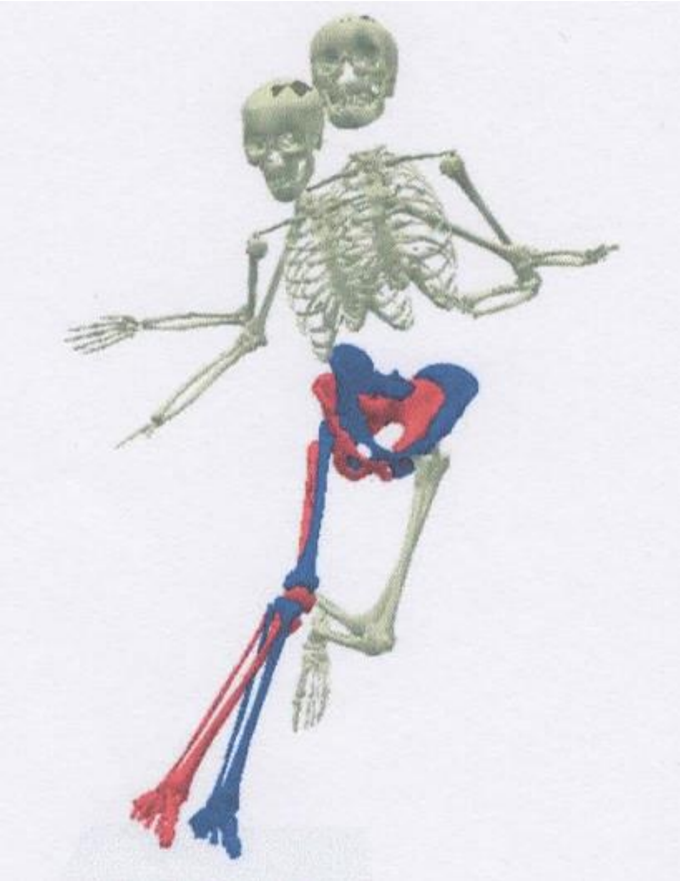

Figure 2.1 Representation of a typical female (red) and male (blue) performing a cutting manoeuvre (From Beaulieu, Lamontagne & Xu, 2009)

2.1.3.4 Anticipated vs. Unanticipated Cutting Manoeuvres

In females, the most common non-contact ACL injury mechanism in football occurs during a cutting manoeuvre, rather than landing (Brophy et al., 2010; Cowley et al., 2006; Walden et al., 2011). In many sports activities, a planned change in direction is rare, therefore it can be assumed that performance of a skill requiring decision making under unanticipated conditions reflects most real-life sports situations (Young & Farrow, 2006). In football specific movements, the cutting motion is usually unanticipated due to the need to react to a multitude of external stimuli such as; a change of ball possession, interception of a pass, or movement of an opponent (Reilly, 2003). Therefore, a cutting manoeuvre that is pre-planned in nature is not a true reflection of the loads applied to the knee joint during a sporting situation. Performance of an unanticipated cutting manoeuvre by female footballers produces sub-optimal electromyographic and biomechanical strategies (Cowley et al., 2006). The initiation of the directional change places a great amount of force through the cutting limb while at the same time a twist is exhibited to change direction, all performed in a reactive nature at a high velocity (Besier, 2001). In order to perform a skill or cutting manoeuvre quickly and with high intensity, players produce higher forces over a shorter period of time, which increases the risk of ACL injury (Cowley et al., 2006).

Previous research has studied the motor control and central nervous system (CNS) response to anticipated and unanticipated manoeuvres (Beaulieu & Xu, 2008; Besier et al., 2001; Bouisset & Zattara, 1987). These researchers identified a feed-forward mechanism present in anticipated manoeuvres, showing that the CNS utilises a pre-planned modification during anticipated manoeuvres that is not present during unanticipated cutting manoeuvres. This has been defined as a learned response (Beaulieu & Xu, 2008; Besier et al., 2001; Bouisset & Zattara, 1987). The anticipatory effects of cutting on the external loads applied to the knee have been studied by Besier et al. (2001). The researchers studied physically active male university students performing ten trials of a straight run, sidestep cut at 30 degrees (S30), sidestep cut at 60 degrees (S60) and a crossover cut at 30 degrees (XOV) under preplanned (PP) and unanticipated (UN) conditions. The researchers observed the participants performing the cutting tasks slower and with greater varus (XOV)/valgus (S30/S60), internal/external rotation moments (S30), and knee flexion angles under the UN conditions as compared to the PP conditions (Besier et al., 2001). The results of the research by Besier et al. (2001) make apparent the potential for an increased risk of noncontact knee ligament injury when performing unanticipated cutting manoeuvres with decreased time to generate modifications or learned responses. The varus/valgus and internal/external moments applied to the knee joint during UN cutting manoeuvres were up to twice the magnitude of those experienced under PP conditions. If muscle activation strategies do not proportionally increase with the large kinematic and kinetic changes, there could be an increased risk of non-contact ACL injury. These anticipatory effects observed by Besier et al. (2001) could increase the load on the ACL. Weinhandl et al. (2014) observed a significant increase in ACL loading of recreationally active females when performing an unanticipated sidestep cutting manoeuvre, in comparison to pre-planned conditions. This increase in loading was primarily due to increase in the sagittal plane i.e. quadriceps:hamstrings co-activation, patella tendon anterior shear, and tibiofemoral joint contact forces. Weinhandl et al. (2014) observed that sagittal plane components contributed greater than the transverse and frontal plane components identified by Besier et al. (2001). Therefore, those electromyographic and biomechanical risk factors that affect the sagittal plane during unanticipated cutting manoeuvres may be more influential in the load on the ACL during an unanticipated cutting manoeuvre. However, Quatman et al. (2010) determined ACL injury was multi-directional, multi-planar and multi-factorial. Further research on the postural adjustments displayed during unanticipated cutting manoeuvres in comparison to preplanned manoeuvres, identified significant increase in lateral trunk flexion as a strategy used to successfully perform the cutting manoeuvre with less time in a reactive situation (Mornieux et al., 2014). Lateral trunk flexion has been associated with increase knee abduction moments, which relates to a valgus collapse and medial to lateral activation patterns of the hamstrings and quadriceps (Jamison, Pan & Chaudhari, 2012; Mornieux et al., 2014; Palmieri-Smith et al., 2009). The anticipatory effects observed in the research provide a rationale for utilising a sport-specific unanticipated cutting manoeuvre in football research to gain a realistic understanding of the electromyographic and kinetic variables of female footballers during match-play, when they are at the highest risk of injury (Besier et al., 2001; Le Gall et al., 2008; Mornieux et al., 2014; Weinhandl et al., 2014).

Previous research has identified anticipatory effects of cutting manoeuvres that reduce the loading on the ACL, in comparison to unanticipated cutting manoeuvres (Besier et al., 2001; Mornieux et al., 2014; Weinhandl et al., 2014). However, the majority of research on injury risk, kinetic and electromyographic variables of female footballers is studied during the performance of an anticipated cutting manoeuvre and have utilised adult participants. Besier et al. (2001) has observed differences in the kinetic variables of male athletes performing pre-planned and unanticipated cutting manoeuvres, showing that there are anticipatory effects of cutting which could be present when a female footballer performs a pre-planned cutting manoeuvre, and absent if performing a reactive unanticipated cutting manoeuvre during football match-play. As well as this, previous research has identified learned responses to produce feed-forward mechanisms during anticipated manoeuvres that are not present in unanticipated manoeuvres, and are better developed in adult athletes, than youth athletes (Beaulieu & Xu, 2008; Besier et al., 2001; Bouisset & Zattara, 1987). A combination of these factors, specifically those operating in the sagittal plane, increase the load on the ACL during unanticipated manoeuvres compared to preplanned manoeuvres (Weinhandl et al., 2014). Therefore, the kinetic and electromyographic variables of youth female footballers performing an unanticipated cutting manoeuvre, comparable to football match-play, is yet to be elucidated. In order to prevent a high risk participant group (16 - 18 year old female footballers) from sustaining an ACL injury (Shea et al., 2004), it is important to understand the kinetic and electromyographic variables employed by these players during game realistic scenarios, such as the unanticipated cutting manoeuvre, and how game specific fatigue experienced in the final 30 minutes of each half may effect this risk (Junge & Dvorak, 2007). By identifying these characteristics, researchers can develop prevention programmes to address the specific electromyographic and kinetic predispositions to ACL injury in youth female players during football match-play.

2.1.4 Injury Risk Factors

There are many factors thought to contribute to the female predisposition to ACL injury. These factors have been categorised as biomechanical, neuromuscular, anatomical and hormonal (Cowley et al., 2006; Hewett et al., 2008; Landry et al., 2007; Myer et al., 2004; Posthumus et al., 2011). The hormonal and anatomical predispositions present in females are non-modifiable risk factors. However, the biomechanical and neuromuscular deficits predisposing females to ACL injury are potentially modifiable risk factors that can be addressed through the use of prevention programmes (Myer, 2004). However, firstly the kinetic and electromyographic variables present in youth female footballers performing an unanticipated cutting manoeuvre must be identified.

2.1.4.1 Electromyographic Variables of Female Footballers

The hamstrings and quadriceps musculature are key dynamic stabilisers of the knee. The two muscle groups work together in synchronicity to stabilise the knee joint and prevent ligamentous injury (Alentorn-Geli, 2009). However, the way in which the hamstrings and quadriceps work together across the sexes is significantly different to an extent that the H:Q co-activation ratios of females may predispose them to ACL injury (Alentorn-Geli, 2009). A study by Simonsen et al. (2000) investigated the co-activation of the hamstring muscle group of 16 sedentary male participants during maximal quadriceps contraction. The researchers observed that antagonistic co-activation of the hamstrings was greater in the lateral hamstrings as compared to the medial hamstring, and overall the hamstring co-activation was 15 - 35% of the agonist contraction. The researchers concluded that there was a considerable amount of antagonistic hamstring co-activation during slow isokinetic knee extension. With the hamstrings working as an antagonist to the quadriceps, co-activation ratios can be key in decreasing the load on the ACL. With considerable amount of co-activation of the hamstring musculature during isokinetic knee extension tasks, the co-activation strategies of sedentary males minimise ACL injury risk (Simonsen et al., 2000). A study by Zazulak et al. (2005) investigated the sex differences in EMG activity of the gluteal and quadriceps muscles during a single leg landing. The researchers compared division I collegiate athletes (13 female, 9 male) performing single leg landings from two differing heights (30.5 cm and 45.8 cm). The researchers observed greater quadriceps activation demonstrated by females, as compared to males. Contrary to research on male athletes (Simonsen et al., 2000) and similar to findings of Zazulak et al. (2005), previous research has observed females to have quadriceps dominant tendencies in both strength and muscle firing patterns (Hewett et al., 2000; Zazulak et al., 2005). Young female athletes have been observed to have significantly lower hamstring to quadriceps strength and activation ratios, with non-dominant hamstrings displaying significantly weaker (40%), less and slower activation than the dominant leg (Hewett et al., 2000). Increased quadriceps activation and strength combined with slow and weak hamstring activation may increase anterior tibial shear force and therefore according to Quatman (2010) will predispose females to greater risk of ACL injury. Therefore, prevention programmes should be designed to address the poor level of hamstring co-activity present in young female athletes to minimise the risk of ACL injury. Previous research utilise sample sizes of less than 20 female participants and drop-jump landing manoeuvres, which does not truly reflect the risk female footballers face during an unanticipated cutting manoeuvre performed regularly in match-play (Brophy et al., 2010).

Medial to lateral activation patterns of the hamstrings and quadriceps muscles have also been suggested to contribute to knee injury risk. In a study by Palmieri-Smith et al. (2009) studying the sex differences in electromyographic activation of the quadriceps and hamstrings muscles during a dynamic forward hopping manoeuvre, the researchers observed risky medial to lateral activation patterns in females (n = 11) compared to their male (n = 10) counterparts. However, the sample size was small and might not accurately reflect the greater population. In the study (Palmieri-Smith et al., 2009), the female participants demonstrated less activation of their vastus medialis in comparison to vastus lateralis (0.567 mV ± 0.058 mV and 0.692 mV ± 0.164 mV), and less activation in the medial hamstrings than in the lateral hamstrings (0.175 mV ± 0.037 mV and 0.247 mV ±

0.080 mV). This lower medial-to-lateral H:Q co-activation ratio accounted for a significant portion of the variance in the peak external knee abduction moment in females. The greater peak external knee abduction moment observed in females could produce a valgus collapse, which shows an inability of the muscles to control GRF (Ford et al., 2003; Palmieri-Smith et al., 2009). The medial to lateral activation patterns produced by females place greater strain on the ACL and increases the risk of ACL injury, compared to their male counterparts. Palmieri-Smith et al. (2009) utilised a forward hopping manoeuvre which is not a common manoeuvre for ACL injury in football, therefore the electromyographic variables observed in the study by Palmieri-Smith et al. (2009) cannot be directly linked to ACL injury mechanisms in female footballers. A cutting manoeuvre is a multi-directional movement and the most common non-contact mechanism for ACL injury in female footballers, whereas a forward hopping manoeuvre is a linear movement. Thus, differences in electromyographic variables of females performing these two movements would be expected. As well as this, females have been observed to employ a lateral trunk flexion strategy to successfully perform unanticipated cutting manoeuvres which increases knee abduction loads (Mornieux et al., 2014). Therefore, the findings of Palmieri-Smith et al. (2009) observed during a pre-planned forward hopping manoeuvre could be exaggerated during the performance of an unanticipated cutting manoeuvre. Medial thigh muscle activation is crucial in providing resistance to knee abduction loads, minimising valgus laxity, and accommodating the lateral trunk flexion strategy that females display during an unanticipated cutting manoeuvre (Mornieux et al., 2014; Zhang & Wang, 2001). The amount of valgus observed during a sporting movement suggests poor muscular control of the GRF. As a result, ligaments tend to absorb the additional force. This overreliance on the ligaments to absorb force and control motion may create a greater risk factor for ACL injury (Ford et al, 2003). Therefore, it is important that prevention programmes aimed at decreasing the risk of ACL injury in youth female footballers address the medial-to-lateral activation patterns of the quadriceps and hamstrings, specifically increasing the medial quadriceps and medial hamstrings activation in comparison to the lateral quadriceps and lateral hamstrings.

Muscle synchrony and timing of hamstring and quadriceps activation has also been observed to contribute to increased ACL injury risk. A study by Krosshaug et al. (2007) investigated the mechanisms of ACL injury in basketball players (17 male, 22 female), with analysts assessing the playing situation, player behaviour and joint kinematics of 39 videos of injury situations. The researchers observed the estimated time of ACL injury ranged from 17 to 50 ms after initial ground contact. Therefore, the timing of muscular activation is particularly important when studying hamstrings and quadriceps activation as potential ACL injury risk factors, as it would be important for an athlete to activate their hamstrings with enough antagonistic force to protect the ACL within 17 to 50 ms of ground contact (Krosshaug et al., 2007). A study by Cowling and Steele (2000) examined the gender differences (7 males, 11 females) in lower limb muscle synchrony during single-leg landings and observed male participants display delayed onset activation of SM relative to initial contact and the timing of the peak tibiofemoral anterior shear forces. The male participants, although delayed, displayed better synchrony between peak hamstring activation and peak tibiofemoral shear forces than females, enabling the hamstrings of male participants to act as more effective synergists to the ACL, when compared to females (Cowling and Steele, 2000; Quatman, 2010). Therefore the timing of hamstring activation of male participants provided more protection to the ACL than the less synchronous peak hamstring activity and peak tibiofemoral shear displayed by females. Interpreting the findings of these two studies, it could be suggested that SM activity of male participants occurred within 17 - 50 ms of initial contact; however Cowling & Steele (2000) identified peak SM activation occurring 98 ms after initial contact coinciding with peak tibiofemoral anterior shear forces, which was after the time of ACL injury observed by Krosshaug et al. (2007). This delayed onset in comparison to the time of ACL injury defined by Krosshaug et al. (2007) could be due to injury mechanism. Less than one third of the injuries analysed by Krosshaug et al. (2007) were single leg landings (n = 10), whereas Cowling & Steele (2000) were utilising only single leg landings. Therefore, it could be speculated that during a single leg landing the time of ACL injury may be later after initial contact coinciding with the delayed onset of SM activation of males relative to initial contact and the timing of the peak tibiofemoral anterior shear forces (Cowling & Steele, 2000).

The sex differences in H:Q co-activation ratio, medial-to-lateral quadriceps and hamstrings activation patterns, and the timing of hamstrings and quadriceps activation develops throughout adolescence and justifies why injury prevention programmes must be introduced as early as possible (Ahmad et al., 2006; Mendiguchia, 2013; Myer et al., 2009). Adolescent awkwardness and the increased risk of ACL injury in youth females, specifically 16 - 18 year olds, compared with adult female footballers, provides reason to identify and address the deficits youth female footballers display during high risk dynamic tasks, particularly an unanticipated cutting manoeuvre (Hewett et al., 2000; Le Gall et al., 2008). As well as this, the effectiveness of prevention programmes in minimising predispositions to ACL injury and reducing ACL injury risk in the high-risk participant group of 16 - 18 year old youth female footballers performing a common injury manoeuvre is yet to be elucidated. Owing to a distinct lack of research utilising an unanticipated cutting manoeuvre, it remains unclear as to the electromyographic variables displayed by youth female footballers during such a high risk manoeuvre. Additionally, it is unknown if prevention programmes improve the electromyographic variables of youth female footballers performing an unanticipated cutting manoeuvre as previous research has not utilised such a manoeuvre with an intervention programme.

2.1.4.1.1 Methods for Measuring Electromyographic Variables

Electromyography (EMG) is the study of the electrical signals of a muscle. Muscles produce electrical activity during the performance of each muscle action, the changes in the electrical potential caused by this activity is measured by EMG (Eston & Reilly, 2001). The major aim of using EMG is to analyse the function, activation and co-ordination of muscles under different movements (Jonsson, 1978). Surface electromyography (sEMG) is a method that measures the electrical activity of a muscle or muscle group as it does work (Cram, 1998). It can measure muscle timing (onset and offset) and amplitude which can provide information about the neuromuscular control mechanisms of the body (Cram, 1998). Muscle is an excitable tissue, it responds to neural stimulation known as depolarisation and repolarisation waves, which create action potentials (Eston & Reilly, 2001; Konrad, 2005). The voltage output detected by EMG systems is the result of the formation of action potentials within the muscle. The fundamental structure of the muscle with greatest importance for neuromuscular control is the motor unit. A motor unit is composed of one motor nerve fibre and all the muscle fibres it innervates (Eston & Reilly, 2001; Konrad, 2005). The number of muscle fibres innervated by a motor nerve fibre varies depending on the level of control required by that muscle. For example, the ocular muscles of the eye have a small number of muscle fibres per motor unit (~300 fibres per unit) because they produce fine movements, whereas large muscles in the leg (that are used primarily for gross movements) comprise a large number of muscle fibres per motor unit (~2000 fibres per unit). For a motor unit to contract, it is an all or nothing phenomena; all of the muscle fibres in the motor unit must activate in synchronicity to produce a muscle contraction (Konrad, 2005).

Considering the role of the quadriceps and hamstrings musculature in maintaining joint stability at the knee, there has been considerable research investigating electromyographic response characteristics of the two muscle groups and their association with ACL injury. A number of researchers have employed sEMG to evaluate activation patterns at the knee during feed-forward and feedback phases of contraction (Ahmad et al., 2006; De Abreu Camarda et al., 2012; Fedie et al., 2010; Mendiguchia. 2013; Myer et al., 2009; Landry et al., 2007). However, most of these models have evaluated this relationship from a post-injury, rehabilitative reference point rather than a pre-injury or preventative one. The factors influencing sEMG assessment of muscle function can be separated into intrinsic and extrinsic factors (Eston & Reilly, 2001). Intrinsic factors are physiological, anatomical and biochemical characteristics of a muscle which may have an effect on sEMG recording. The intrinsic factors consist of; number of active motor units during muscle action, muscle fibre type and diameter, blood flow within the muscle, depth and location of the active fibres within the muscle relative to the electrode position, motor unit twitch, firing characteristics of the motor unit, and the amount of subcutaneous tissue between the electrode and the muscle. These factors influence sEMG recording by changing the amplitude and frequency content of the signal, through spatial filtering and alterations in conduction velocity (Eston & Reilly, 2001). Limitations in current knowledge, methods, and technology means that intrinsic factors affecting sEMG recordings cannot be controlled. The extrinsic factors are centred on electrode configuration. The extrinsic factors consist of; electrode shape and size, inter-electrode distance, electrode placement (location), and skin preparation (Eston & Reilly, 2001). These extrinsic factors can be controlled by the researcher to minimise their effects on sEMG recordings. There are some guidelines suggested by SENIAM that many previous researchers have utilised (Ahmad et al., 2006; De Abreu Camarda et al., 2012; Eston & Reilly, 2001; Fedie et al., 2010; Mendiguchia, 2013; Myer et al., 2009; Landry et al., 2007; SENIAM).

Due to their non-invasiveness where possible, surface electrodes are utilised rather than in-dwelling electrodes. In a review by Hermens et al. (2000), the researchers noticed that Ag/AgCl electrodes are most commonly used as surface electrodes following recommendations by SENIAM. Electrode shape can be described as the shape of the conductive area on the electrode. In the literature review of Hermens et al. (2000), the most commonly used shape and size of electrode was a 10 mm diameter circular electrode. This commonality follows the principles and recommendations of SENIAM, recommending bi-polar Ag/AgCl 10 mm diameter circular electrodes (Hermens et al., 2000). The inter-electrode distance (IED) is defined as the distance between the centres of the conductive areas of electrodes. The effect of IED on sEMG recording characteristics is considered one of the most relevant properties (Hermens et al., 2000). IED can affect the cross talk and pick up area of the sEMG recording (Hermens et al., 2000). The most commonly used IED in the literature review of Hermens et al. (2000) was 20 mm, as recommended by SENIAM.

The recording of electrical activity of a muscle using sEMG is highly dependent on the electrode placement. Thus, when studying multiple subjects on multiple occasions consistency of electrode placement is key (Hermens et al., 2000). When determining the correct placement of electrodes, international guidelines recommending electrode placement over the centre of the muscle belly/most prominent part of the muscle belly, set out by SENIAM are highly recommended (Hermens et al., 2000). This recommendation is utilised widespread as the most commonly used guidelines for sEMG electrode placement (Eston & Reilly, 2001; Hermens et al., 2000; Konrad, 2005). The middle of the muscle belly can be found utilising the individual muscle guidelines provided by SENIAM (Appendix 2.1). As well as the positioning of the electrodes, there is also the aspect of electrode orientation to consider. The majority of previous research follows the SENIAM recommendation of aligning the electrode in the direction of the muscle fibres (Hermens et al., 2000). Movement of surface electrodes during dynamic tasks is inevitable, which in turn disturbs the electrode and skin equilibrium (Gleeson, 2001). Electrode gels or pre-gelled electrodes minimise this change by moving the electrode away from the skin so that movement of the skin does not affect the electrode (Gleeson, 2001). Reduction of impedance between skin and electrode is important for accurate sEMG recordings and to minimise induced currents from external sources (Eston & Reilly, 2001).There are many different skin preparation techniques utilised to reduce impedance including; shaving, rubbing/abrasion and cleaning of the skin with alcohol, sandpaper or glasspaper (Hermens et al., 2000; Konrad, 2005). The most commonly used method of skin preparation is cleaning the skin with alcohol and shaving hair if necessary. SENIAM guidelines recommend that the skin surface be shaved of any hair and dead skin cells at the location of electrode placement. After shaving, the skin should be cleaned with alcohol and allowed to dry before the electrodes are positioned (SENIAM).

Due to the previously discussed intrinsic and extrinsic factors that may affect sEMG, it is important to normalise the sEMG system before testing (Ball & Scurr, 2008). sEMG normalisation is particularly important when comparing multiple tasks, and several participants across numerous days, as it rescales the millivolts to percent of a standardised reference value obtained through a normalisation task or equation. A reliable sEMG normalisation procedure aims to improve absolute reliability and provides an expression of relative muscle activation (Ball & Scurr, 2008). Previous studies have used a range of isometric, isokinetic, and dynamic muscle actions as normalisation methods (Burden et al., 2004; De Luca, 2007). Despite the majority of research showing poor reliability both between and within participants and between sessions, maximal isometric muscle contractions are the most widely used method of sEMG normalisation, and are recommended by SENIAM (Ball & Scurr, 2008; Bamman et al., 1997; Heinonen et al., 1994).

Previous researchers have studied the reliability of absolute sEMG values from various tasks including; isometric, isokinetic and dynamic tasks (Ball & Scurr, 2008). Ball & Scurr (2008) studied normalisation procedures for the triceps surae. Isometric data was found to be reliable as a normalisation method for triceps surae, but muscle dependent, with some muscles showing greater reliability than others, and isokinetic data did not display reliability. Therefore, isokinetic methods are not recommended for the normalisation of sEMG values of triceps surae. However, dynamic tasks, such as a squat and 20m sprint, have been demonstrated to be acceptable and reliable methods for sEMG normalisation of the triceps surae (Ball & Scurr, 2008). Therefore, in research utilising dynamic tasks for testing, a dynamic sEMG normalisation task is a reliable method to create a relative value for reference (Ball & Scurr, 2008). Bolgla & Uhl (2005) studied normalisation methods for the gluteus medius muscle using maximal voluntary isometric contraction (MVIC) and a dynamic hip abduction task. The researchers observed that MVIC normalisation methods provide greater intra-class correlation coefficients (ICCs), lower standard error measurements (SEMS), and lower intrasubject coefficient of variation (CV) than dynamic tasks, inferring high measurement reliability (Bolgla & Uhl, 2005). However, a limitation of MVIC is that some participants may not be able to perform MVIC due to muscle inhibition or pain, and previous research has observed that maximal muscle activation is not possible through voluntary muscle actions and healthy adults only achieve maximal voluntary muscle activation in approximately 25% of trials (Gandevia et al., 1998).

It is recognised that optimal normalisation methods are muscle and task dependent. Dynamic alternatives to isometric methods where the muscle action is similar to that of the task are advised. Dynamic methods based on a % expression of mean and peak values do not depend on maximal contraction and previous research has shown that these methods may provide better representation of muscle activity, delivering a better reference value. Oliver & Smith (2010) utilised a dynamic method of sEMG normalisation by expressing muscle activation during the latency phases as a % of activity during ground contact time. This approach has been reported to address the measurement issues when comparing the sEMG response of children and adults (Frost et al., 1997; Oliver & Smith, 2010). This method of sEMG normalisation provides the researcher with an opportunity to obtain a reference value for maximal activation during the same dynamic task being tested. Using this method reduces problems associated with selecting a reference muscle action and requires no additional testing when using high velocity muscle actions like the unanticipated cutting manoeuvre (Ball & Scurr, 2013). However, the implication of various normalisation methods being used throughout previous research is the difficulty in directly comparing electromyographic variables of specific populations across the research.

2.1.4.1.2 EMG Analysis

Many studies have utilised sEMG to measure muscle activity and co-activation ratios (Kellis et al., 2011; Lloyd et al., 2012; Oliver et al., 2014; Russell et al., 2007). In sports research, some scientists are highly interested in the feed-forward (preparatory) and feedback (reactive) mechanisms. Some studies vary in the way in which the data is analysed for this purpose. Various studies have utilised a standard 100 ms pre-contact to analyse feed-forward mechanisms (Kellis et al., 2011; Lloyd et al., 2012; McBride et al., 2008; Oliver et al., 2014; Russell et al., 2007) of the thigh musculature during dynamic tasks. However, various different feedback phases have been utilised when analysing muscular activation following ground contact.

Kellis et al. (2011) divided the feedback mechanisms into initial loading response (first 50ms of contact) and late loading response (50 – 200 ms after initial contact). Russell et al. (2007) measured knee joint muscle activation and co-contraction ratios, rather than co-activation ratios. Co-contraction ratios refer to the simultaneous contraction of a pair of muscles; agonist and antagonist (Alter, 2004), whereas co-activation refers to the co-ordinated activation of muscles (Christer, 2011). Russell et al., (2007) analysed two separate feedback mechanism phases; initial contact to 100 ms and 100 ms after initial contact to maximum knee flexion (Russell et al., 2007). The first phase is double the initial loading response studied by Kellis et al. (2011) the second phase is dependent on the amount of time a participant takes to present maximal knee flexion during the manoeuvre. McBride et al. (2008) utilised three separate phases for each manoeuvre; pre-activity, eccentric phase and concentric phase. Similarly, studies by Oliver & Smith (2010), Oliver et al. (2014), and Lloyd et al. (2012) studying neuromuscular control of the lower limb during two-footed hopping separated feedback muscle activity into phases. These phases represented different latency reflexes during feed-forward and feedback muscle activity. The study defined pre-activation (feed-forward mechanisms) as 100 ms pre-contact and utilised four phases to describe the feedback mechanisms; reflex time phase (0 - 30 ms, background muscle activity), short latency spinal reflex (31 - 60 ms), supraspinal intermediate latency reflex (61 - 90 ms), and long latency reflex (91 - 120 ms) (Lloyd et al., 2012; Oliver & Smith, 2010; Oliver et al., 2014). The latency phase approach represents reflexive EMG responses identified by Lee & Tatton (1982); with the EMG response consisting of an early component with a latency of 30 - 35 ms, a long-latency component beginning 55 - 65 ms after onset, and a further reflexive component with a latency of 90 - 100 ms (Lee & Tatton, 1982). These reflexive phases have been developed and utilised by various researchers utilising sEMG measurements during a series of stretch shortening contractions and now represent reflex time phase (0 - 30 ms, background muscle activity), short latency spinal reflex (31 - 60 ms), supraspinal intermediate latency reflex (61 - 90 ms), and long latency reflex (91 - 120 ms) (Horita et al., 1996; Lazaridis et al., 2010; Lloyd et al., 2012; Oliver & Smith, 2010). The implication of previous research utilising various different time frames is the inability to directly relate or compare findings as there is no standardisation of timings of EMG analysis.

2.1.4.1.3 Electromyographic Variables of Female Footballers during Unanticipated Cutting

Muscle activation during an unanticipated cutting manoeuvre can be separated into two components; feed-forward or preparatory muscle activation, and feedback or reactive muscle activation (Oliver & Smith, 2010). Feed-forward muscle activation can stiffen the joint before the load, whereas reactive muscle activation stabilises the joint during loading (Oliver & Smith, 2010). Landry et al. (2007) measured electromyographic response, kinematics and kinetics of the lower limb during an unanticipated cutting manoeuvre, and analysed the feedback muscle activation utilising sEMG analysis. Guided by a three-light system, 42 elite adolescent footballers (21 female, 21 male) performed a 35 - 60 degree unanticipated cutting manoeuvre at a speed of 3.5 m/s. Electrodes collecting muscle activation data during the stance phase of the unanticipated cutting manoeuvre were placed over the medial gastrocnemius (MG), lateral gastrocnemius (LG), medial hamstrings (MH), lateral hamstrings (LH), vastus medialis (VM), vastus lateralis (VL), and rectus femoris (RF) (Landry et al., 2007). In agreement with previous studies, the researchers identified that the activity of the quadriceps muscles was greater in females than males, whereas the activity of the hamstring muscles was reduced in females compared to males performing the unanticipated cutting manoeuvre (Landry et al., 2007, Sigward & Powers, 2006). Therefore, females had a smaller H:Q co-activation ratio during unanticipated cutting manoeuvres, when compared to their male counterparts. Similarly, in a study by Hanson et al. (2008), female footballers displayed smaller H:Q co-activation ratios than male footballers during pre-planned sidestep cutting manoeuvres. Therefore, the muscle co-activation strategies of female footballers performing a pre-planned and unanticipated cutting manoeuvre places greater strain on the ACL, when compared to male footballers. This places female footballers at greater risk of a non-contact ACL injury than their male counterparts. The difference in methodology of these two studies did not seem to affect the sex differences observed in hamstring and quadriceps activation; however both studies instructed their participants to perform the cutting manoeuvres at speeds less than recommended in previous research (4 m/s) to obtain meaningful knee loading mechanisms without the risk of task failure (Hanson et al., 2008; Landry et al., 2007; Vanrenterghem et al., 2012). Therefore, a greater deficit of H:Q co-activation ratios in females could be identified when the cutting manoeuvre is performed at a higher speed which replicates meaningful knee loading. However, to date no studies have utilised the recommended speed (4 m/s) for meaningful knee loading during a cutting task to investigate the electromyographic and kinetic variables of youth female footballers performing an unanticipated cutting manoeuvre (Vanrenterghem et al., 2012).

Hanson et al. (2008) also analysed the medial and lateral activation patterns of male and female footballers. The researchers observed significantly greater VL activation in females compared to males during preparatory and loading phases of the pre-planned running sidestep cut. Immediately after foot contact with the ground, female footballers demonstrated 40% more VL activation than males. Non-contact ACL injuries are reported to occur immediately after foot contact with the ground, most often during tasks requiring a change of direction or deceleration (Krosshaug et al., 2007). Hanson et al. (2008) defined the loading phase as the first 50% of stance during sidestep cutting manoeuvres, which encompasses the time phase when non-contact ACL injuries most often occur. Greater VL activity during the loading phase can be related to greater anterior tibial shear forces causing direct loading of the ACL (Quatman, 2010), when females are undergoing rapid deceleration and directional changes. Also, greater lateral quadriceps activation in comparison to medial quadriceps activation can cause higher knee abduction loads producing a valgus collapse and strain on the ACL (Palmieri-Smith et al., 2009). Therefore, adolescent female footballers display medial to lateral activation patterns during pre-planned cutting manoeuvres that may increase the risk of ACL injury. Hanson et al. (2008) compared the electromyographic variables of female and male footballers during the preparatory and loading phase of a running sidestep cut and box-jump sidestep cut. The researchers observed significantly greater activation of all muscles and significantly smaller H:Q co-activation ratio with the pre-planned running sidestep cut that is commonly performed in football match-play, as compared to the box-jump sidestep cut. These findings highlight the importance to study sport-specific movements when investigating performance or injury risk.

A study by Ebben at al. (2010) evaluated the gender differences in the magnitude and timing of hamstring and quadriceps activation during a pre-planned drop jump and a pre-planned sprint and 45 degree cut. Utilising sEMG analysis of VM, RF, VL, lateral hamstrings and medial hamstrings, the researchers observed male participants demonstrated greater lateral and medial hamstring activation than females during the post-contact phase of the cut. Female participants demonstrated greater and longer VM and RF muscle activation than males during the post-contact phase of the cut. The H:Q co-activation ratio during the post-contact phase of the cut was greater in male participants compared with female participants, producing a greater predisposition to ACL injury in female participants compared with male participants. Ebben et al (2010) observed no gender differences in the timing of activation of the individual muscles during the pre-planned cutting manoeuvre. However, when calculating the timing ratio between the hamstrings and quadriceps muscles, the researchers observed an earlier activation of the hamstrings in females during the pre-contact phase of the cut. This finding supports the results of other studies that have demonstrated delayed onset of SM in male athletes when compared with female athletes (Cowling & Steele, 2000). This is suggested to be a protective mechanism displayed by male footballers allowing maximal hamstring activation to correspond with the timing of anterior tibial shear (Cowling, 2001). Therefore, male footballers display a more protective timing of muscle activation, and the timing of muscle activation in female footballers during cutting motions may predispose them to ACL injury.

There are limited studies utilising unanticipated cutting manoeuvres and the anticipatory effects of cutting on muscular activation is unclear. Those studies that utilised a pre-planned cutting manoeuvre at a slower speed than recommended for meaningful knee loading (4 m/s) have observed sub-optimal muscular activation strategies in females when compared to males. These strategies included; smaller H:Q co-activation ratios, poor timing of hamstrings activation, and increasing medial to lateral activation patterns of the hamstrings and quadriceps (Ebben et al., 2010; Hanson et al., 2008; Vanrenterghem et al., 2012). Similar findings have been observed in the limited research utilising unanticipated cutting manoeuvres (Landry et al., 2007). However, the previous literature (Ebben et al., 2010; Hanson et al., 2008; Landry et al., 2007) utilised adult female footballers and the electromyographic variables of youth female footballers performing these manoeuvres is yet to be identified. Thus, it is important for future research to identify the electromyographic variables of the high-risk participants, 16 - 18 year old females, during the most common manoeuvre causing ACL injury in female football, an unanticipated cutting manoeuvre (Hewett et al., 2000; Shea et al., 2004). From these future research directions, researchers can develop and implement accurate and sport-specific prevention strategies to address electromyographic predispositions to ACL injury in youth female footballers performing unanticipated cutting manoeuvres. Some prevention programmes are already utilised but to date their effectiveness in addressing electromyographic predispositions to ACL injury in youth female footballers performing an unanticipated cutting manoeuvre is yet to be identified.

2.1.4.2 Kinetic Variables of Female Footballers

An array of kinetic variables can contribute to the female predisposition to ACL injury. Non-contact mechanisms of injury associated with landing and cutting are implicated in many lower extremity injuries. Previous researchers have observed greater loading rate, greater GRF, and reduced time to peak GRF, increases the risk of lower extremity injury (McNitt, 1991). Therefore, it is important to understand the kinetic variables of youth female footballers performing an unanticipated cutting manoeuvre.

Schmitz & Schultz (2010) & Harrison et al. (2011) determined similar sex differences in vGRF during jump landing manoeuvres. Schmitz and Schultz studied college aged students, whereas Harrison studied high school athletes. The researchers observed greater vGRF in females, compared to males. This finding shows a lower ability of females to control the valgus forces at the knee (Harrison et al., 2011; Schmitz & Schultz, 2010). Harrison et al. (2011) also observed greater vGRF loading rates in females compared to males, and Schmitz and Schultz observed greater normalised energy absorption at the knee, greater knee work absorption, and weaker knee flexor and extensor strength in females compared to males. From these findings it could be concluded that females demonstrate knee joint strategies during the stretch shortening cycle (SSC) of a drop jump landing that is characterised by greater energy absorption, higher forces and loading rates, and ligament/tendon loading (Harrison et al., 2011; Schmitz & Schultz, 2010). This will place female athletes at risk of ACL injury due to an inability to attenuate forces and control the valgus motion at the knee. Previous research identifies that sex differences in adults are present during youth stages of development and the need for early injury prevention programme intervention in youth athletes (Ahmad et al., 2006; Mendiguchia, 2013; Myer et al., 2009). The studies by Harrison et al (2011) and Schmitz & Schultz (2010) obtained similar gender differences in two different manoeuvres, identifying that whether a female is performing a single or double leg manoeuvre the kinetic variables produced during each of these manoeuvres put the female at more risk than the male performing the same manoeuvres (Harrison et al., 2011; Schmitz & Schultz, 2010). Repetitive high impact forces that are not effectively attenuated during single and double leg landings may increase the risk of injury to lower extremity structures, such as the ACL (Zhang et al., 1998). Researchers have identified increased knee joint energy absorption strategies in females during increasingly challenging tasks, it could be argued that an unanticipated cutting manoeuvre is more challenging than a double footed landing due to the decision making skills, speed of movement and multidirectional nature of the unanticipated cutting manoeuvre. Therefore, it could be speculated that the knee joint energy absorption strategies would be even greater during an unanticipated cutting manoeuvre compared with previous research utilising drop-jump landings (Schmitz & Shultz, 2010).

In contrast, Smith et al. (2009) observed no gender differences in vGRF during a double foot drop landing. These findings conflict those of Schmitz & Schultz (2010) & Harrison et al. (2011) who identified greater vGRF in females than males during double drop-jump landing and single foot hopping. The difference in findings between these studies could be due to sample size and population, as well as methodical differences. Methodically, Smith et al. (2009) utilised a slightly higher platform (50 cm) than Schmitz & Schultz (2011) (45cm), and placed two inches of synthetic turf padding onto the platform to soften the landing and reduce the risk of injury to their participants. This could be a justification for the absence of any gender differences in the study of Smith et al. (2009). Smith et al. (2009) also utilised 14 female and 12 male volunteers who were described as healthy and active, whereas the research of Schmitz & Schultz (2010) (n = 81) and Harrison et al. (2011) (n = 109) utilised a larger sample size that could provide better representation of the general population. Also, the sample population utilised by Smith et al. (2009) represented, on average, the oldest population of all three studies (Harrison et al., 2011; Schmitz & Schultz, 2010; Smith et al., 2009). Swartz et al. (2005) observed developmental differences in peak vGRF, time to peak vGRF and impulse. The researchers studied the force variables exhibited by adults (19 - 29 years) and children (7 - 11 years) during vertical landings. The researchers observed a developmental difference between children and adults with children landing with a strategy producing greater peak vGRF, greater impulse and shorter time to peak vGRF, than adults. These findings suggest children may be at a higher risk of knee injury, which coincides with injury incidence rates in youth athletes compared to adult athletes (Giza et al, 2008; Hagglund et al., 2009; Jacobson & Tegner, 2006; Le Gall, 2008, Junge & Dvorak 2007; Price et al. 2004; Tegnander, 2008). The researchers only investigated pre-pubescent and post-pubescent participants and did not investigate gender differences, but this trend in changes of vGRF with age could have affected the gender difference findings of previous research (Harrison et al., 2011; Schmitz & Schultz, 2010; Smith et al., 2009). The age range in the current study (16 - 18 years) was not investigated by Swartz et al (2005) when investigating developmental differences. It could be suggested that youth female footballers aged 16 - 18 years would display higher peak vGRF and impulse, and shorter time to peak vGRF than adults, but not as much so as children (Swartz et al., 2005). Previous research does not portray an understanding of the kinetic variables of 16 - 18 year old youth female footballers performing dynamic tasks, there is currently limited research on this participation group who are at highest risk of ACL injury (Shea et al., 2004). Therefore, the kinetic variables of this high risk participant population performing an unanticipated cutting manoeuvre remain to be elucidated. Without identifying the kinetic variables of 16 - 18 year old female footballers performing an unanticipated cutting manoeuvre, the effect of acute fatigue and the effectiveness of currently used prevention programmes, such as the FIFA 11+, on these variables cannot be investigated.

2.1.4.2.1 Methods for Measuring Kinetic Variables

Kinetic variables are commonly analysed using force-time data from force plates or platforms (Cortes et al., 2011; Harrison et al., 2011; Schmitz & Schultz, 2010; Smith et al., 2009). Despite a variety of methods being available to measure force, it has been suggested that measuring force directly or calculated from GRF-time data recorded using a force platform is the most accurate way to assess these outcome measures (Hori et al., 2006). The majority of research on injury and performance parameters utilise laboratory force platforms which are often heavy, highly sensitive and mounted in the ground to limit irrelevant vibrations affecting the outcome measurement. Research utilising portable force platforms is less common, generally due to the inability to sub-mount the portable force platform into the ground and participants altering mechanics to compensate for this (Walsh et al., 2006). Walsh et al. (2006) identified the reliability and validation of portable force platforms for measuring and analysing dynamic jumping and landing tasks. Utilising a

Pearson's correlation co-efficient, the researchers determined that a portable force platform produces similar results for peak landing force, peak take-off force, and time to maximum force as a laboratory sub-mounted force platform showing that any compensatory mechanisms that may be present when using a portable force platform are insignificant in the measurements of peak force and time to peak force (Walsh et al., 2006). As well as the type of force platform being used, portable or laboratory, the rate at which the force signal is sampled, sampling frequency, is another contributing factor to reliability of force-time data. A portable force platform usually has a lower capacity of sampling frequency, than the laboratory sub-mounted force platform. Hori et al. (2009) identified the differences between reliability of force, power and velocity data analysed at seven different sampling frequencies (500, 400, 250, 200, 100, 50 and 25 Hz) when performing countermovement jumps. The researchers observed high reliability across the range of sampling frequencies for the majority of outcome measures with very large (> 0.7) and nearly perfect (> 0.9) ICC's and strong positive correlations (> 0.9) between outcome measures collected at 500 Hz and all other sampling frequencies. However, the researchers observed that when sampling frequency was less than 200 Hz, percentage differences in outcome measures to reference values at 500 Hz were greater than 2%. Therefore, a sampling frequency of 200 Hz or higher is recommended in the collection of force-time data (Hori et al., 2009). Previous research has observed reliability of force-time data during dynamic tasks, but research is limited and many tasks are of a pre-planned nature (Alenezi et al., 2014; Ferber et al., 2002). These pre-planned dynamic studies have utilised sub-mounted laboratory force platforms and frequencies ranging from 960 Hz to 1200 Hz. The research by Walsh et al. (2006) and Hori et al. (2009) would suggest that the difference in sampling frequencies and force platform (portable vs. laboratory) would produce similar results, thus suggesting that force-time data collected during pre-planned dynamic tasks is reliable.

However, the increased task demands and greater degrees of freedom in unanticipated manoeuvres compared to pre-planned manoeuvres creates difficulty in directly applying the reliability of pre-planned dynamic tasks to unanticipated tasks (Todorov & Jordan, 2002). Therefore the reliability of force-time data measured during an unanticipated manoeuvre is yet to be elucidated, and in order to determine the effect of fatigue or intervention on the kinetic variables produced during unanticipated cutting manoeuvres, the reliability of these measures must be determined first.

2.1.4.2.2 Kinetic Variables of Female Footballers during Unanticipated Cutting

During a cutting manoeuvre there are numerous GRF's including; horizontal, lateral and vertical forces. Cortes et al. (2011) observed greater vGRF displayed in female footballers during cutting manoeuvres as compared to drop-jump manoeuvres. The researchers studied 19 female collegiate footballers performing a drop-jump task and two unanticipated manoeuvres; sidestep cutting and a pivot task. The female footballers displayed significantly greater vGRF ($F_{2,36} = 6.525$, $p < 0.001$) with the unanticipated sidestep cutting manoeuvre as compared to the pivot or drop-jump manoeuvres, increasing the risk of injury during sidestep cutting compared with the pivot or drop-jump manoeuvres. However, time to peak vGRF of female footballers was greater during the sidestep cutting manoeuvres, as compared to the pivot or drop-jump tasks. Therefore, female footballers have more time during an unanticipated sidestep cutting manoeuvre to pre-activate their hamstrings and quadriceps to absorb the greater vGRF experienced, and minimise knee injury risk. During initial contact, Cortes et al. (2011) observed that female footballers displayed the greatest posterior GRF with unanticipated sidestep cutting. Researchers have suggested a high correlation between posterior GRF and proximal anterior tibia shear force

(Sell et al., 2007; Yu et al., 2006). Consequently, a higher posterior GRF during initial contact of an unanticipated sidestep cutting manoeuvre could place greater strain on the ACL and increase the risk of injury in female footballers. The study by Cortes et al. (2011) is one of few studies to utilise an unanticipated cutting manoeuvre, however the approach speed utilised by Cortes et al. (2011) (3.5 m/s) was less than the recommended approach speed (4 m/s) for meaningful knee loading, and minimisation of task failure (Vanrenterghem et al., 2012). Further to this, the effect of acute fatigue on performance of this manoeuvre was not identified.

Similarly Cowley et al. (2006) investigated the effect of task (unanticipated cutting vs. landing), sport (football vs. basketball) and side (dominant vs. non-dominant) on peak vGRF, stance time and knee valgus angles of young female athletes. The female high school athletes (15 basketball, 15 football) performed drop vertical jumps and unanticipated cutting manoeuvres. The high school female footballers displayed greater peak vGRF and decreased stance time (GCT) during the unanticipated cutting manoeuvre when compared to the drop vertical jump, similar to the collegiate female footballers in the study by Cortes et al. (2011). However, in contrast, the female basketball players participating in the study by Cowley et al. (2006) displayed greater peak vGRF and decreased stance time during the drop vertical jump compared with the unanticipated cutting manoeuvre. Overall, participants demonstrated differences in GRF’s and stance times during two movements associated with non-contact ACL injuries. The research provides observations that kinetic variables are sport-specific and injury risk increases with sport-specific movements. Therefore, neuromuscular training for youth female footballers specifically targeting injury risk factors present during unanticipated cutting manoeuvres could be beneficial in decreasing injury risk (Cowley et al., 2006). Methodically, the unanticipated cutting manoeuvre utilised by Cowley et al. (2006) did not utilise a running approach, instead participants jumped from a height and performed the cutting motion upon landing. Therefore, knee loading mechanisms and kinetic variables would be different to the study utilising a running approach, as commonly performed in football when losing possession or faking an opponent (Brophy et al., 2010), particularly when studying the effect of acute fatigue due to changes in step length and cadence altering lower limb mechanics (Gerlach et al., 2005; Verbitsky et al., 1998). Future research should take into account the effects of sport-specific movements on injury risk. A range of kinetic variables of youth female footballers performing football specific movements such as an unanticipated cutting manoeuvre remains to be identified.

Previous research has identified risky kinetic variables produced by collegiate aged female footballers during unanticipated cutting manoeuvres, more so than drop-jump landings. Therefore, it is important to study sport-specific movements in assessing ACL injury risk factors. However, previous research has not utilised a youth population to study the kinetic variables employed during an unanticipated cutting manoeuvre. Thus, the kinetic variables of youth female footballers during an unanticipated cutting manoeuvre, especially those at highest risk (16 - 18 year old females) remain to be identified. Research in this area would contribute to the development of prevention programmes to address the biomechanical predispositions to ACL injury present during unanticipated cutting manoeuvres.

2.1.4.3 Summary of Knee Injury Risk Factors

Previous research has identified sub-optimal electromyographic and kinetic variables of female footballers performing unanticipated cutting manoeuvres, which may place them at risk of ACL injury. Previous research has observed a greater injury risk in females compared to males, and children compared to adults including; greater vGRF, GRF loading rates, quadriceps dominant tendencies and delayed co-activation of the hamstrings musculature during dynamic tasks (Cortes et al., 2011; Cowley et al., 2006; Ebben et al., 2010; Hanson et al., 2008; Landry et al., 2007; Schmitz & Schultz, 2010; Swartz et al., 2005). Further research has identified the greatest predispositions to ACL injury are present during an unanticipated cutting manoeuvre compared to drop-jump landings and pre-planned cutting manoeuvres (Cowley et al., 2006; Cortes et al., 2011; Landry et al., 2007). However, the characteristics of the high risk population of 16 - 18 year old youth female athletes performing such manoeuvres are yet to be elucidated. Although a vast amount of research has been undertaken in the area of ACL injury risk factors, the research specific to the youth female football population is somewhat limited. Therefore, it is important that future research identifies the electromyographic and kinetic variables of youth female footballers performing an unanticipated cutting manoeuvre to address injury risk and prevention. Considering many injuries occur in the final moments of the game, when players are fatigued, and the most common mechanism of injury is an unanticipated cutting manoeuvre, it is important to investigate the effect of fatigue on ACL injury risk factors during an unanticipated cutting manoeuvre in youth female footballers.

2.2 FATIGUE

Owing to the majority of injuries occurring in the final moments of a football match, it seems fatigue plays an important role in the injury risk present in female footballers with significantly more injuries occurring in the last 30 minutes of each half of football match-play than the first 15 minutes of each half (Hiemstra et al., 2001; Junge & Dvorak, 2007). Researchers have observed detrimental effects of fatigue on lower limb kinetic and electromyographic variables in female footballers including; decreased and delayed muscular activation and increased anterior tibial translation from pre to post-fatigue, which could predispose them to an increased risk of ACL injury (Benjaminse et al., 2008; Chagela et al., 2012; Cortes et al., 2011; Gear et al., 2011; Patrek et al., 2011; Schmitz et al., 2015, Smith et al., 2009). However, these fatigue studies are limited by small sample sizes and non-specific fatiguing protocols for youth female footballers. They do not utilise an unanticipated cutting manoeuvre which is considered an integral movement pattern within the sport and is the most common movement from which ACL injury mechanisms are exacerbated in female footballers (Brophy et al., 2010; Cowley et al., 2006; Landry et al., 2007; Silvers et al., 2007). Therefore, the role of fatigue in knee injury risk of youth female footballers warrants further exploration.

2.2.1 Types of Fatigue

Physical fatigue can be defined as any exercise-induced inhibition in the ability to generate muscle force or power (Gandevia, 2001), or the inability of the body to maintain the required or expected power output (Edwards, 1983). Fatigue can further be defined as central fatigue; mental fatigue that develops during prolonged exercise, and is attributed to impaired function of the central nervous system, or peripheral fatigue; a transient inability in the muscles capacity to exercise due to a number of factors including; muscle glycogen depletion and blood lactate levels (Hunter et al., 2004). There are two common types of fatigue; acute and chronic. Acute fatigue is experienced immediately following exercise or strenuous activity and can be readily modified by rest and/or task moderation. Continuous exertion whilst fatigued can lead to chronic fatigue. Recovery from chronic fatigue is of greater complexity (Hunter et al., 2004).

In football match-play, acute fatigue is experienced by players in three phases. The phases in which fatigue occurs include; temporary fatigue after short term intense periods, the initial phase of the second half, and at the end of the match (Mohr et al., 2005). According to Mohr et al. (2005), each fatigue phase has different underlying physiological mechanisms. Temporary fatigue can be related to homeostasis ions with an accumulation of interstitial potassium within the muscle, fatigue at the initial phase of the second half can be related to decreased muscle temperature from the half time recovery period inhibiting a players ability to perform high intensity exercise, and at the end of the match due to muscle fibre glycogen depletion (Mohr et al., 2005).

Temporary fatigue in football has been observed by few researchers and this could be due to the difficulty of measuring this type of fatigue. Mohr et al. (2005) studied top-class male professional players in competitive games at international level. Utilising time motion analysis, the researchers noted that the amount of high intensity running performed by any player five minutes following the most intense five minute interval recorded was less than the average of the entire game (Mohr et al., 2005). These findings have been replicated in top class women's football (Krustrup et al, 2003). Other researchers have used a repeated sprint test immediately after an intense bout within a match and at the end of each half. These researchers found that players sprint performance was significantly reduced immediately following an intense bout of match-play, whereas at the end of the first half the ability to perform repeated sprints was recovered (Krustrup et al., 2003). Therefore, performance recovery from temporary fatigue can occur within the same half of match-play within bouts of lower intensity. Together, these results suggest that footballers experience temporary fatigue during match-play.

Fatigue in the initial phase of the second half has been related to decreased muscle temperature from the half time interval, typically a 15 minute rest interval for players. Several studies have observed a pattern of decreased work rate and high intensity exercise in the first five minutes of the second half of a match, as compared to the first five minutes of the first half of a match. In the following ten minutes of each half, no differences were noted. Researchers have observed these findings in male and female footballers, as well as match officials (Krustrup & Bangsbo, 2001; Krustrup et al., 2002; Mohr et al., 2003).

The final phase of fatigue in football match-play is observed at the end of a match. Many researchers have observed a decline in high intensity exercise towards the end of a match. In male footballers, researchers have observed this decline in the last 15 minutes of the game (Mohr et al., 2005). However, in female footballers, researchers have observed this decline in the last 30 minutes of the game (Krustrup et al., 2002). Physiologically, researchers have found that muscle glycogen stores are depleted towards the end of a game which could account for the decrease in high intensity exercise, and peripheral fatigue. Therefore, male footballers could have an increased resistance to fatigue, greater muscle glycogen stores and greater muscle glycogen use efficiency, as compared to females (Krustrup et al., 2002; Mohr et al., 2005). However, research on the sex differences of skeletal muscle fatigue provides a conflicting view. Hicks et al. (2001) has documented a female advantage in fatigue resistance, particularly within those protocols that incorporate submaximal contractions. Three common themes support this viewpoint including; muscle mass; females generate lower force when performing the same relative work, substrate utilisation; males have a greater glycolytic capacity and greater reliance on glycolytic pathways than females, and muscle morphology; greater numbers of fatigable type II fibres have been identified in the vastus lateralis of males compared with females (Hicks et al., 2001). Therefore, rather than females displaying less resistance to the same level of fatigue than their male counterparts in a football match, it could be suggested that females are at more risk of injury with less fatigue than males. Thus, a lower level of fatigue could have a more detrimental effect on injury risk in female footballers, and male footballers cope with fatigue better in terms of injury risk.

As well as physiological fatigue, footballers experience psychological fatigue during match-play (Boksem et al., 2005; Lorist et al., 2005; Sanders, 1998; Williams, 2000). A football match requires players to perform with sustained concentration, decision making and perceptual skills, combined with external pressure from opponents and coaches. Football match-play is versatile and constantly changing (Williams, 2000). Various studies have observed mental fatigue in players that although has not affected the ability of a player to perform highly over-learned, automatic skills, it does cause deterioration of tasks that require voluntary allocation of attention (Boksem et al., 2005; Lorist et al., 2005; Sanders, 1998). There are many factors that can affect mental fatigue including; external stressors, travel, and match outcome. Further research is needed on how each of these factors may affect mental fatigue and post-match recovery from mental fatigue. In terms of youth female footballers performing an unanticipated cutting manoeuvre, the reactive task requires voluntary allocation of attention and reaction which can deteriorate with fatigue (Boksem et al., 2005; Lorist et al., 2005; Sanders, 1998), and potentially increase the risk of ACL injury. It is clear that football match-play can produce physiological and psychological fatigue in male and female footballers. However, research on the effects of such fatigue on ACL injury risk is limited.

2.2.2 Fatigue in Youth Athletes

The differences in fatigability from central and peripheral perspectives between children (females up to age of 11 years, males up to the age of 13 years), adolescents (females 12 - 18 years, males 14 - 18 years), and adults (18+ years) have been studied and researchers have identified greater central and peripheral neuromuscular fatigability of adults compared to adolescents, and adolescents compared to children (Ratel & Martin, 2015). Children and adolescents have specific and differing physiological responses to exercise, which reflect the existence of protective mechanisms to fatigue in children, which decline throughout adolescence. Therefore, greater fatigability and slower recovery is observed in adolescents compared to children. The mechanisms of these differences in fatigue can be explained through various factors; muscle mass and fibre type composition, energy metabolism, musculotendinous stiffness, voluntary activation and antagonist co-activation (Ratel & Martin, 2015).

A greater muscle mass and a larger percentage of Type II fibres in adolescents allow a bigger absolute power production in adolescents compared to children, which in turn can induce more neuromuscular fatigue in adolescents (Ratel & Martin, 2015). Adolescents producing more power and force during repeated high intensity exercise will experience higher vascular occlusion which will decrease blood flow and cause a build-up of muscle by-products limiting supply of crucial nutrients and oxygen to the muscles. Vascular occlusion has not only been used to understand the differences in fatigability between adolescents and children, but also between male and females (Ratel & Martin, 2015). As well as vascular occlusion producing more muscle by-product, the energy metabolism changes during puberty have been related to higher muscle by-product level in adolescents through a lower oxidative metabolism compared to pre-pubertal children (Berg & Keul, 1988). This muscle by-product build-up alongside the possibility of greater muscle damage occurring with larger forces and a greater muscle mass engagement could determine greater fatigability in adolescent athletes compared to children. Many fatigue protocols utilise repeated maximal contractions which fatigue Type II muscle fibres (Kellis et al., 2011; Shenoy et al., 2010). As individuals age and mature, pubertal changes occur with the muscle fibre type composition with Type I fibres transforming into Type II fibres in adolescence creating a greater percentage of Type II fibres in adolescents when compared to children, and furthermore so in adults (Du Plessis et al., 1985; Glenmark et al., 1994; Lexell et al., 1992). During maximal contractions and high intensity exercise, Type II fibres are recruited, fatigued and consequently damaged. As a higher percentage of Type II fibres exist in adolescence, this could account for a greater fatigability in adolescence. Since greater force and power production is developed during adolescence through the higher recruitment of Type II muscle fibres, it has been suggested that adolescents have higher musculotendinous stiffness positively related to maximal force (Chen et al., 2014).

Children are considered to have a low musculotendinous stiffness which could limit the amount of stretch on muscle fibres during eccentric contractions. This limited stretch would reduce the occurrence of muscle damage and lower the fatigability of the muscles. However, this mechanism of fatigability requires further research (Ratel & Martin, 2015).

During childhood, the ability to maximally produce force is limited due to an inability to activate motor units and an undeveloped, immature cortico-spinal pathway. This low voluntary activation will contribute to the lower force production observed in children (Ratel & Martin, 2015). Henneman's size principle states that individuals with lower voluntary activation recruit larger proportions of Type I fibres than individuals with a similar muscle composition, but higher activation (Henneman et al., 1965). Type I fibres are more resistant to fatigue and muscle damage due to their aerobic capacity and ability to produce small, repetitive contractions in comparison to Type II fibres. Therefore, adolescents with greater force production and higher voluntary activation will recruit higher levels of Type II fibres which will in turn produce greater fatigability. Also, centrally adults produce a higher co-activation of the antagonist muscle compared to children, which is consistent with greater force production in adults and could explain higher levels of fatigability (Ratel & Martin, 2015).

2.2.3 Sex Differences in Fatigue

It has been discussed that females are at greater risk of ACL injury than their male counterparts. The influence of fatigue on this risk can cause further differences between sexes (Jollenbeck et al., 2010). In male footballers, researchers have observed a decline in performance and high intensity running in the last 15 minutes of the game (Mohr et al., 2005). However, in female footballers, researchers have observed this decline in the last 30 minutes of the game (Krustrup et al., 2002). In relation to male footballers, female footballers seem to experience fatigue earlier and quicker, but research on the sex differences of the effect of fatigue on ACL injury risk is limited. Previous research has observed greater negative effects of fatigue on ACL injury risk in females, compared to males (Gehring et al., 2009; Jollenbeck et al., 2010). Jollenbeck et al. (2010) investigated the effect of fatigue on male and female U17 footballers utilising a drop jump landing and an isokinetic dynamometry fatigue protocol. The researchers observed that both sexes displayed a significant reduction of quadriceps force post-fatigue. However, male footballers displayed significantly higher forces for all muscles under all conditions with greater overall levels of strength. The lower level of quadriceps force could produce slower deceleration, which was observed in a study by Gehring et al. (2009) (Benvenuti et al., 1997; Colby et al., 2000). Gehring et al. (2009) determined the effect of fatigue on adult male and females utilising a drop jump landing and a submaximal muscular fatigue protocol using a leg press machine. The researchers observed females displayed increased maximum knee abduction angles, activation of lateral thigh muscles later than medial thigh muscles, 33% increased knee velocity during the first 50 ms of ground contact, and slower deceleration. The activation of lateral thigh muscles later than medial thigh muscles could be directly related to the increase in knee abduction angles and subsequently causes a valgus stress at the knee (Palmeiri-Smith et al., 2009). Males were observed to display increased knee flexion angles during drop landing post-fatigue, which would have decreased their vGRF. The vGRF during dynamic task is an inability of the muscles to control a valgus force (Ford et al., 2003), the difference in findings for male and female footballers post-fatigue would indicate a greater risk of ACL injury due to the decrease in vGRF observed in males, and the medial to lateral activation patterns of fatigued females. Both sexes displayed decreased gastrocnemius and lateral hamstring muscle pre-activation levels post-fatigue, resulting in an increased H:Q co-activation ratio post-fatigue (Gehring et al., 2009). A decrease in lateral hamstring muscle pre-activation levels post-fatigue would expose male and females to increased valgus stress at the knee, which can increase the strain on the ACL (Palmieri-Smith et al., 2009). Due to the time of ACL injury occurring in the immediate feedback mechanisms (17 - 50 ms), ACL injury occurs too quickly for reactive electromyographic activity and pre-activity plays a vital role in dynamic stabilisation of the joint during a electromyographic cutting manoeuvre (Krosshaug et al., 2007). Jollenbeck et al. (2010) concluded that 75% of youth females display an increased risk of ACL injury as compared to 32% of youth males (2.5 fold) under fatigued conditions (Jollenbeck et al., 2010). However, Jollenbeck et al. (2010) and Gehring et al. (2009) studied drop-jump landings, and the effect of acute fatigue on ACL injury risk of female footballers performing a high risk manoeuvre in football, such as an unanticipated cutting manoeuvre, is limited. Due to the lateral trunk flexion coping strategy females utilise in reactive cutting manoeuvres, increased knee abduction loads could be expected, and the effects of fatigue on the medial:lateral thigh muscle activation observed by Gehring et al. (2009) could be greater in an unanticipated cutting manoeuvre and increase the risk of ACL injury. These similar findings in adult and youth participants in terms of sex difference shows that females are at a greater risk of injury when fatigued compared to males. The risk of ACL injury in female footballers, youth and adult, is greater than males in a non-fatigued state, and even more so with fatigue (Jollenbeck et al., 2010).

Iguchi et al. (2014) is one of few researchers that have studied the effect of sex and fatigue on unanticipated cutting manoeuvres. The researchers observed significant increase in the impulses of GRF during the first 50 ms of initial contact in collegiate female athletes, compared to collegiate male athletes. Higher impulses of GRF are likely to predispose a female athlete to a greater risk of ACL injury than their male counterparts, as this would increase tibiofemoral joint compression which combined with a posteriorly sloped tibia causes posterior displacement of the femur on the tibia and additional stress on the ACL (Quatman, 2010). Therefore, when performing an unanticipated cutting manoeuvre, a fatigued female athlete is at greater risk of ACL injury compared to a fatigued male athlete (Iguchi et al., 2014). Youth female footballers represent a high-risk participant group for ACL injury. Therefore, it could be speculated that a youth female footballer experiencing football match-play fatigue displays the greatest risk of ACL injury. Thus it is important for researchers to understand the effect of fatigue on the kinetic and electromyographic variables of youth female footballers performing a high-risk manoeuvre, specifically an unanticipated cutting manoeuvre, to enable the development and implementation of prevention programmes addressing the detrimental effects caused by fatigue.

2.2.4 Effect of Fatigue on Electromyographic and Kinetic variables

2.2.4.1 The Effect of Fatigue on Electromyographic Variables of Female Footballers

Muscle fatigue can be caused by various mechanisms of fatigue and have an effect on the electromyographic strategies of female footballers, particularly the players H:Q co-activation ratios (Wright et al., 2009). Wright et al. (2009) observed increases in hamstrings activation during concentric quadriceps action post-fatigue protocol and a decrease in quadriceps activation with eccentric hamstrings activation post-fatigue. Wright et al. (2009) had a small sample size of only 8 recreational male footballers and utilised the isokinetic dynamometer in their fatigue protocol. However, clear observations were made that fatigue had an effect on H:Q co-activation levels which could affect injury risk, rehabilitation and injury prevention (Wright et al., 2009). A study by Oliver et al. (2014) examined the changes in neuromuscular control of leg stiffness in youth male soccer players after a 42 minute football specific exercise. Ten youth male footballers performed two-legged hopping at a self-selected frequency on a force plate, immediately before and after a 42 minute soccer specific intermittent exercise test. The researchers analysed the data in four phases; 0 - 30 ms (background activity), 31 – 60 ms (short latency reflexes), 61 – 90 ms (medium latency reflexes), and 91 – 120 ms (long latency reflexes). The researchers observed no significant change in leg stiffness, peak GRF, and CoM displacement pre and post-fatigue, however leg stiffness was mediated by modulating CoM displacement which was strongly related to changes in feed-forward and feedback activity of lower limb extensor muscles. Changes in feed-forward and feedback activity of lower limb muscles can affect the risk of ACL injury with feed-forward mechanisms being crucial to landing preparation and stiffness, and feedback mechanisms reacting to external and internal forces (Oliver et al., 2014). Both previous studies investigated small sample sizes of male footballers, and both observed electromyographic changes with fatigue. Due to the small sample sizes the findings of previous research may not represent the general population of male footballers and the effects of fatigue on electromyographic variables of female footballers is limited. Although similar differences were observed by Wright et al. (2009) and Oliver et al. (2014), there were differences in methodology and age of participants, with Oliver et al. (2014) utilising youth male footballers performing two-legged hopping, and Wright et al. (2009) utilising adult male recreational players and utilised isokinetic dynamometry. Therefore, the testing protocols and age of participants did not change the effect of fatigue. There is limited research studying fatigue related changes in electromyographic variables of female footballers, specifically studies that utilise football specific fatigue protocols. Fatigue increases the risk of ACL injury in female U17 footballers by three times greater than male U17 footballers (Jollenbeck et al., 2010). As well as this, it has been observed that adolescent athletes (females aged 12 - 18 years, males aged 14 - 18 years) experience greater neuromuscular fatigue than children (females up to the age of 11 years, males up to the age of 13 years), which could place them at higher risk of ACL injury (Ratel & Martin, 2015).

Kellis et al. (2011) studied the effect of isokinetic fatigue on muscle co-activation of the hamstrings and quadriceps of female adult middle distance runner's pre and post-impact phase of running. The participants displayed increased VM recruitment and a more quadriceps dominant strategy with fatigue. These observations would place female athletes at greater risk of ACL injury in a fatigued state compared to non-fatigue, as the quadriceps dominant athlete will experience greater anterior tibial shear which would directly load the ACL (Quatman, 2010). However, previous research has identified a decline in the ability to maintain force or power during high intensity repeated exercise from childhood to adolescence, and from adolescence to adulthood due to peripheral and central changes that occur through puberty (Ratel & Martin, 2015). The fatiguing protocol of Kellis et al. (2011) requires maximal isokinetic contractions which would fatigue Type II muscle fibres. From childhood to adolescence, and from adolescence to adulthood, Type I fibres transform into Type II fibres, therefore adolescents and adults have a greater percentage of Type II fibres which could explain the greater electromyographic fatigability in adults compared to adolescents, and adolescents compared to children. Therefore, the youth female footballers in the current study may maintain electromyographic variables with fatigue better than the adult female middle distance runner's (Ratel & Martin, 2015). The effect of acute fatigue on electromyographic variables of youth females is yet to be elucidated. Risk of knee injury was also observed to increase with fatigue in a study by Gehring et al. (2008), who observed reduced pre-activation of the medial and lateral hamstrings with fatigue in both males and females. The hamstrings act as an antagonist to stress placed on the ACL, and ACL injury occurs too quickly for electromyographic feedback mechanisms (Krosshaug et al., 2007). Therefore, a reduction in the preparatory mechanisms could increase the risk of ACL injury. Research suggests that acute fatigue has a negative effect on H:Q co-activation ratio of adult athletes, which may increase the risk of ACL injury. However, the effects of acute fatigue on H:Q co-activation ratios of youth female footballers is yet to be investigated.

Neuromuscular fatigue research on youth females is limited. However, De Ste Croix et al. (2015) have identified significant football specific fatigue related changes in electromechanical delay (EMD) of youth female footballers, utilising prone eccentric hamstring actions on an isokinetic dynamometer at 60°, 120° and 180° before and after a football specific fatigue protocol (SAFT90). The researchers observed significant increases in EMD post-fatigue, which were greater in U13 female footballers, compared to U15 and U17 female footballers. The significant increase in EMD of youth female footballers experiencing football specific fatigue could compromise neuromuscular control of the knee, and increase the risk of ACL injury of youth female footballers experiencing temporary fatigue within football match-play. Females tend to display longer latency phases which place them at a greater risk of ACL injury than males. Significant increases with fatigue would increase this risk due to the importance of immediate feedback mechanisms in reducing the stress on the ACL during the time of ACL injury (17 – 50 ms) (Krosshaug et al., 2007). Limited studies have utilised a football specific fatigue protocol to investigate the electromyographic variables of youth female footballers experiencing football related fatigue, the study by De Ste Croix et al. (2015) was the first to investigate the effect of football specific fatigue on the electromyographic variables, specifically EMD, of youth female footballers. The SAFT90 replicates the running profiles of elite male footballers; however it does not include any ball work, jumping, or cutting which is commonly performed in a football match and places greater energy demands on the player. Therefore, it is possible that the protocol does not fully meet the energy demands of football match-play and the full extent to which EMD is affected by football match-play is not identified. As well as this, the study by De Ste Croix et al. (2015) utilised isokinetic dynamometry instead of a functional dynamic task which female footballers commonly perform, therefore the application to football match-play is limited. The extent to which football match-play fatigue affects the electromyographic variables of youth female footballers remains to be elucidated.

2.2.4.2 The Effect of Fatigue on Kinetic Variables of Female Footballers

Research by Smith et al. (2009) and Gerlach et al. (2005) as discussed previously have observed beneficial effects of maximal voluntary contractions and an exhaustive treadmill protocol on peak vGRF and vGRF loading rates. However, the relevance of these findings to female youth footballers is limited as the study populations were adults, the action being analysed was not a “high risk” manoeuvre in football i.e. cutting, and the fatigue protocols that were utilised in these studies do not replicate the demands of football match-play, thus could be a poor indicator of football match-play fatigue. Fatigue has a more negative effect on youth athletes compared to adult athletes; therefore it is important to understand the fatigue related changes of kinetic variables observed in youth female footballers. A more recent study by Boham et al. (2013) examined the GRF occurring to the knee during non-fatigued and fatigued conditions utilising a jump, land and cut in an unanticipated direction task and an intermittent fatigue protocol consisting of a T-test agility, 300 yard shuttle, and repeated sprint ability test. Once the participants performed all three fatiguing protocols, they then repeatedly performed the repeated T-test agility until HR was above 90% of the participants HR_{max} or the participant had an RPE of 17+ (Borg scale). The researchers observed different results for each direction of cut (right, left, central) throughout the landing and push-off phases. When participants were cutting left, the dominant leg exhibited landing forces occurring medially and anteriorly, and a 10% increase in vGRF during the landing and push-off phases with fatigue. When the participants ran centrally, the landing forces of the dominant limb increased 22% in the Y direction when fatigued, and the push-off forces of the non-dominant limb increased 31% in the Z direction when fatigued. When participants performed the right directional cut, fatigue had a significant impact on the landing force in the Y direction with 23% greater force, and fatigue increased force in the X direction (medially) by 106%, on the dominant leg. Boham et al. (2013) concluded that fatigue had a significant effect on the GRF applied to the knee during landing and push-off of an unanticipated cutting task. The greater GRF would increase the load on the knee, thus increasing risk of ACL injury. The study by Boham et al. (2013) shows that fatigue can affect the GRF on dominant and non-dominant limbs during unanticipated cutting manoeuvres. Unlike, Smith et al. (2009) and Gerlach et al. (2005), Boham et al. (2013) observed an increase in GRF during the landing and push-off phases of a cutting manoeuvre. These studies display the differences the effect of fatigue can have on differing manoeuvres as the research by Boham et al. (2013) utilised an unanticipated cutting manoeuvre, whereas Smith et al. (2009) and Gerlach et al. (2005) utilised pre-planned jump landing manoeuvres. As well as this, the anticipatory effects of dynamic tasks could have accounted for the differences in findings between Bohm et al. (2013), and previous research (Gerlach et al., 2005; Smith et al., 2009). Fatigue can cause deterioration in mental condition, although it may not affect the ability to perform highly over-learned, automatic skills, it can cause deterioration of tasks that require voluntary allocation of attention (Boksem et al., 2005; Lorist et al., 2005; Sanders, 1998). A reactive manoeuvre such as the unanticipated cutting manoeuvre utilised by Boham et al. (2013) may be more effected by fatigue related changes in mental condition than a pre-planned jump landing task in previous research (Gerlach et al., 2005; Smith et al., 2009), because an unanticipated cutting maneouvre requires greater degrees of freedom, decision making and perceptual skills, and voluntary allocation of attention and reaction that can deteriorate with fatigue (Boksam et al., 2005; Lorist et al., 2005; Sanders, 1998). As well as this, Boham et al. (2013) utilised a fatigue protocol that involved various changes of direction and cutting motions similar to the testing protocol. This could have caused greater fatigue of the movement, in comparison to Smith et al. (2009) who used maximal voluntary contractions, and Gerlach et al. (2005) who used an exhaustive treadmill protocol, neither of which replicated the dynamic task used in the testing protocol. Although Boham et al. (2013) utilised an unanticipated cutting manoeuvre, the fatigue protocols used by previous research do not mimic the energy and skill demands of football match-play. Therefore, the findings of previous research (Boham et al., 2013; Gerlach et al., 2005; Smith et al., 2009) cannot be directly applied to the fatigue experienced in football, and the electromyographic and kinetic changes that may be experienced with football specific fatigue. Similarly, there is limited research on the fatigue related changes of kinetic and electromyographic variables of youth female athletes. The effect of football specific fatigue on youth female footballers performing common “high risk” manoeuvres such as an unanticipated cutting manoeuvre is yet to be identified. Therefore, the fatigue mechanisms of ACL injury in the last 30 minutes of each half of a football match, when injuries commonly occur and fatigue is experienced by female footballers, remains to be identified.

2.2.5 Cutting and Fatigue

Previous research has determined that the most common mechanism of ACL injury in youth female footballers is an unanticipated cutting manoeuvre (Cowley et al., 2006; Landry et al., 2007; Silvers et al., 2007). Researchers have also observed a pattern of injury during times at which a female footballer experiences fatigue, thus fatigue as a risk factor (Hiemstra et al., 2001; Junge & Dvorak, 2007). However, there is only a small amount of research investigating the effect of fatigue on a cutting manoeuvre and even less with a study population of youth female footballers.

A study by Shenoy et al. (2010), examined the effect of quadriceps fatigue on the sEMG activity of the gluteal muscles during a box drop cutting manoeuvre. The study participant population consisted of 20 recreational athletes and 20 professional athletes. The participants performed multiple trials of a box drop cutting manoeuvre before and after a squatting fatigue protocol. The researchers observed decreased vastus medialis (VM) activity post-fatigue protocol in professional and recreational athletes, gluteus minimus (GS) activity also decreased post-fatigue protocol in recreational athletes, but increased in professional athletes. The activity of the gluteus medius (GM) and gluteus maximus (GX) also increased post-fatigue protocol in both recreational and professional athletes. A significant negative correlation was noted between VM and GM and a significant positive correlation was noted between GX and GS average sEMG activity. Female athletes displayed smaller change in GX activity post-fatigue protocol. The researchers concluded that neuromuscular fatigue could increase the risk of injury, especially in female athletes (Shenoy et al., 2010). Although the researchers did not use a football specific fatigue protocol, the decreased vastus medialis activity observed by Shenoy et al. (2010) could lead to greater knee abduction loads and a valgus collapse of the knee, which would indicate the inability of the muscles to control GRF (Ford et al., 2003). This would increase the risk of ACL injury in female footballers, whom without fatigue experience less activation of medial thigh muscles in comparison to lateral thigh muscles. Prevention programmes must address the medial to lateral activation pattern of female athletes in a non-fatigue and fatigued state.

Sanna and O’Connor (2008) and Lucci et al. (2011) examined the fatigue related changes of the lower limb mechanics of collegiate female footballers during a sidestep cutting manoeuvre. Sanna & O’Connor (2008) observed the effects of a 20 M progressive shuttle run and counter movement jumps on the anticipatory effects of cutting in females, whereas Lucci et al. (2011) studied an unanticipated manoeuvre and utilised the FAST-FP and SLO-FP. Both researchers observed detrimental effects of fatigue on knee internal rotation ROM with fatigue. Although Sanna & O’Connor (2008) concluded no other lower limb mechanical changes with fatigue, Lucci et al. (2011) also observed detrimental effects of fatigue on knee and hip flexion. These detrimental effects could lead to increased GRF and decreased force production of the quadriceps and hamstrings muscles (Lucci et al., 2011; Nigg, 1985; Sanna & O’Connor, 2008). Further research utilising the unanticipated cutting manoeuvre has observed similar findings of detrimental fatigue related changes on lower limb mechanics of collegiate female footballers performing unanticipated cutting manoeuvres. Weiss & Dickin (2013) utilised a Yo-Yo Intermittent Running Test to fatigue collegiate female football and field hockey players, followed by treadmill running and vertical jumps to maintain fatigue before re-testing the participants. Cortes et al. (2013) utilised a functional agility short-term fatigue protocol to induce fatigue-related changes in collegiate female footballers and also found similar results. These studies demonstrate i) female footballers experience detrimental effects of fatigue on the lower limb mechanics displayed when performing an unanticipated cutting manoeuvre, ii) differing fatigue protocols produce similar effects on lower limb mechanics of female footballers and therefore the mechanism in which fatigue is experienced is slightly irrelevant in the findings of these studies. However, none of these studies utilised a protocol mimicking the fatigue experienced during football match-play, therefore the extent to which football match-play fatigue may affect the kinetic and electromyographic variables of female footballers is yet to be elucidated and may differ from previous research utilising generic fatigue protocols.

There are differences in the research findings of the effect of fatigue on lower limb mechanics between Sanna and O’Connor (2008), Lucci et al. (2011), Cortes et al. (2013) and Weiss & Dickin (2013), which highlight the anticipatory effects of cutting and the importance of studying reactive sport-specific manoeuvres in order to directly apply research findings to game/injury situations (Besier et al., 2001b). Sanna and O’Connor (2008) utilised a cutting protocol which was pre-planned, whereas Lucci et al. (2011), Cortes et al. (2013) and Weiss & Dickin (2013) utilised an unanticipated cutting manoeuvre replicating many reactive sports activities. Those studies that utilised the sport-specific unanticipated cutting manoeuvre observed significant detrimental effects of fatigue on lower limb mechanics which could lead to decreased force production of the dynamic stabilisers of the knee and increased vGRF (Lucci et al., 2011; Cortes et al., 2013; Weiss & Dickin, 2013), whereas Sanna & O'Connor (2008) utilised a pre-planned manoeuvre and observed little lower limb mechanical changes with fatigue. It could be suggested that the anticipatory effects of cutting manoeuvres could have an effect on acute fatigue related changes in lower limb mechanics. The anticipatory effects of cutting on non-fatigued females have been observed and include greater lateral trunk flexion and increased knee flexion angles, but the effects of fatigue on the anticipatory effects of cutting have not been investigated. Therefore, when studying youth female footballers, anticipatory effects of a cutting manoeuvre could alter the fatigue related changes to a participants' lower limb mechanics and subsequently provide contrasting results (Besier et al., 2001; Cortes et al., 2013; Lucci et al., 2011; Sanna and O'Connor, 2008; Shenoy, 2010; Weiss & Dickin, 2013). Due to the uncontrolled and reactive environment of football, an unanticipated cutting manoeuvre is much more applicable to football match-play and should be considered an integral movement pattern in research (Brophy et al., 2010). Although there is limited research available, detrimental effects of fatigue on ACL injury risk factors during cutting manoeuvres in female footballers and athletes have been observed. However, some research is contrasting and only a few knee injury risk factors have been investigated (Lucci et al., 2011; Sanna & O'Connor; 2008; Shenoy, 2010). The effect of fatigue on unanticipated manoeuvres is limited, as well as studies utilising youth female footballers and football specific fatigue protocols. Due to the majority of injuries occurring in the final moments of a game when players are fatigued, it is important to understand the effect of acute fatigue on ACL injury risk in high risk participants performing commonly injuring manoeuvres. Therefore, the effect of football specific fatigue on ACL injury risk in female footballers performing an unanticipated cutting manoeuvre requires further exploration.

2.3 PREVENTION

A systematic review of the effects of knee injury prevention programmes on ACL injury in female athletes found 12 knee injury prevention programmes, with nine of these programmes tested on female footballers (Michaelidis & Koumantakis, 2014) (Table 2.1). Of the nine prevention programmes performed by footballers, seven of them were multi-component, one utilised only balance training (SODERMAN) and one was plyometric based (KLIP). Of the nine programmes, only three prevention programmes were observed to reduce the rate of ACL injuries in female footballers, the PEP, HPT, and the WALDEN. All of these programmes were multi-component and incorporated football-specific drills (Michaelidis & Koumantakis, 2014).

Table 2.1 Prevention programmes tested on female footballers

Reference	Comparison groups	Prevention programme	Training volume and overall compliance	Hours of exposure	Non-contact ACL injury (& injury rate)	Total ACL injuries (& injury rate)	Between-group significance
Heidt et al. (2000)	I: n=42 C: n=258	FATP MC: Cardiovascular conditioning, plyometrics, strengthening, agility, sport-specific drills, flexibility	75 min/session 3 d/wk TOTAL: 7 wks	7896 48504		1 (0.13) 8 (0.16)	p=>0.05 NS
Soderman, Werner, Engstrom, and Alfredson (2000)	I: n=62 C: n=78	SODERMAN Balance-Proprioception Training	10-15 min/session for 30 sessions, then 3d/wk rest of the season TOTAL: 6 months Compliance: 31.3%	8246 9262		4 (0.49) 1 (0.11)	p=>0.05 NS
Mandelbaum et al. (2005)	I: n=1885 C: n=3818	PEP MC: warm-up, stretching, strengthening, plyometrics, agility	20 min/session two - three times/wk TOTAL: 12 wks per season (3 seasons)	135,720 274,896	6 (0.04) 67 (0.24)		p=<0.0001
Steffen, Myklebust, Olsen, Holme, and Bahr (2008)	I: n=1073 C: n=947	FIFA 11 MC: core stability, balance, plyometrics, eccentric hamstring strengthening	15 min/session for 15 sessions then 1d/wk rest of the season TOTAL: 7.5 months Compliance: 10/7%	66,423 65,725	3 (0.05) 2 (0.03)	4 (0.06) 5 (0.08)	p=0.73 NS
Gilchrist et al. (2008)	I: n=583 C: n=852	PEP MC: warm-up, stretching, strengthening, plyometrics, agility	20 min/session 3 times/wk TOTAL: 4-5 months	35,220 52,919	2 (0.06) 10 (0.18)	7 (0.20) 18 (0.34)	Non-contact ACL: p=0.066 NS ACL injuries: p = 0.198 NS p=0.025
Kiani, Hellquist, Ahlqvist, Gedeborg, Michaelsson, and Byberg (2010)	I: n=777 C: n=729	HPT MC: warm-up, muscle activation, balance, strength, core stability	20-25 mins/session 2d/w for 2 months pre-season, 1d/wk in season TOTAL: 9 months Compliance: 70.4%	66,981 66,505	0 5 (0.08)		
Walden, Atroshi, Magnusson, Wagner, and Hagglund (2012)	I: n=2479 C: n=2085	WALDEN MC: core stability, strength, balance, jump-landing technique, knee alignment feedback	15 min/session 2 d/wk TOTAL: 7 months Compliance: 26.3%	149,214 129,084	5 (0.03) 8 (0.06)	7 (0.05) 14 (0.11)	Non-contact ACL (compliant): p=0.049 ACL injuries: p=0.02
Hewett et al. (1999)	Mixed population study- I: n=97 C: n=193	SPORTSMETRICS MC: flexibility, plyometrics, weight training, technique analysis and feedback	60-90 min/session 3 alternating d/wk TOTAL: 6 wks Compliance: 45.2%	9034 18,034	0 2 (0.11)	0 2 (0.11)	Non-contact ACL: p=0.32 NS
Pfeiffer et al. (2006)	I: n=855 C: n=¼942	KLIP Plyometrics, agility training	20 min/session 2d/wk TOTAL: 4-5 months Compliance: 23 session/athlete	11,826 18,714	0 1 (0.05)		p=0.43 NS

Analysing the prevention programmes reviewed, Michaelidis & Koumantakis (2014) concluded that a successful and well-rounded prevention programme for a female footballer should contain multiple components of training, including; plyometrics, dynamic stabilisation, strength training of the trunk, upper and lower body, and sport-specific agility training. Key to the successful delivery of a knee injury prevention programme is education and feedback on correct techniques. The researchers also observed that the prevention programmes that significantly reduced knee injury in female footballers were 15 - 20 minutes in duration and replaced participants' usual warm up routines two - three times per week (Michaelidis & Koumantakis, 2014). In the review by Michaelidis & Koumantakis (2014), the FIFA 11 was observed to be insignificant in reducing knee injury. Since the original FIFA 11 was produced, the FIFA Medical and Research Centre (F-MARC) have developed the improved FIFA 11+.

Further to the review by Michaelidis & Koumantakis (2014), Weber et al. (2016) conducted a review of prevention training on youth and adolescent athletes specifically. The researchers observed that prevention programmes produce beneficial effects in injury reduction for youth and adolescent athletes, particularly prevention programmes targeted towards female athletes and containing jumping or plyometric exercises were observed to be especially beneficial in decreasing injury risk. Michealidis & Koumantakis (2014) observed that prevention programmes were most effective when utilising multiple components of training, whereas Weber et al. (2016) place particular importance on those programmes that utilise plyometric exercises. The difference in findings between these studies could be due to participant age; Michaelidis & Koumantakis (2014) reviewed studies using a range of age groups, whereas Weber et al. (2016) utilised only youth or adolescent athletes.

2.3.1 FIFA 11+

The FIFA 11+ is a complete warm-up programme implemented as a mode of prevention to reduce injury rates of male and female footballers aged 14 years and older (FIFA) (Appendix 2.2). In 2006, the FIFA 11+ prevention programme was developed from FIFA's "The 11" by an international group of experts with the support of F-MARC. F-MARC has tried to implement the FIFA 11+ nationwide in many countries by providing free access to information sheets on the FIFA 11+ programme at http://f-marc.com/11plus/home/.

The FIFA 11+ programme is designed to be performed twice weekly at the beginning of training sessions in substitute for a team's standard warm-up. The programme takes approximately 20 minutes to complete. It has three parts totaling 15 exercises that are required to be performed in specific sequence as set out in the FIFA 11+ Manual. Part one consists of running exercises at a slow speed, active stretching, and controlled partner contacts. Part two consists of six sets of exercises focusing on core strength, plyometrics, agility and balance. All of the exercises in part two have three levels of difficulty, all players must start on the easiest level of difficulty for each exercise and when they can perform an exercise at ease with correct technique they may increase the difficulty of the exercise. Part three of the programme consists of running exercises at a moderate to high speed with the inclusion of planting and cutting motions. For all exercises, correct performance is emphasised. Recent research by Steffen et al. (2013) suggests adherence of adolescent female footballers to injury prevention programmes is greater when facilitated by appropriately skilled coaches. Therefore, a coach or medical staff personnel should supervise the programme and correct the player's technique if necessary (F-MARC website).

In a study utilising the FIFA 11+, researchers observed a significantly lower risk of overall injury in the intervention group as compared to a control group who followed their traditional warm-up (Soligard et al., 2008). The participants (1055 youth female footballers, age: 13 - 17 yrs) performed the FIFA 11+ twice weekly throughout one regular football season. Exposure and injury data was collected by team medical staff and coaches. As well as, a significantly lower risk of overall injury in the intervention group compared with the control group, the researchers observed a reduction in the risk of match injuries, training injuries, knee injuries and acute injuries from 26% to 38%. Also, significantly fewer players from the intervention group sustained two or more injuries when compared to the control group. Overall, the research showed that the FIFA 11+ was effective in reducing the risk of injury in youth female footballers. The researchers suggested programmes aimed at increasing strength, awareness and neuromuscular control should be introduced at an early age, as soon as children start playing organised football (before establishing basic motion patterns) (Mendiguchia, 2013; Soligard et al., 2008). Various studies have observed beneficial effects of the FIFA 11+ on injury risk in youth female and male footballers, however the effects on adult footballers is contradicting. Grooms et al. (2013) observed 72% reductions in relative risk of lower extremity injury in collegiate male footballers; however research by Hammes et al. (2015) observed no difference in overall injury rate between intervention and control groups of male veteran footballers.

The difference in findings could be due to age as the FIFA 11+ was designed for youth footballers (aged 13 - 17 years old) who have higher levels of Type I muscle fibres, small muscle mass, and a higher resistance to fatigue (Ratel & Martin, 2015). Therefore, collegiate male footballers are only slightly older than the intended age bracket (18 - 25 years old) (Grooms et al., 2013), whereas the veteran footballers in the study by Hammes et al. (2015) had a mean age of 45 years old. As well as this, the male veteran footballers performed a low overall frequency of training sessions for a protective effect of the programme (Hammes et al., 2015).

Further studies examining the effectiveness of the FIFA 11+ have also assessed the effect of different delivery methods on injury risk and performance measures. Steffen et al. (2013) studied 13 - 18 year old youth female footballers across 31 different teams. The researchers divided the participants into a control group, who were given access to online FIFA 11+ resources, and an intervention group in which the coaches attended a coaching workshop for the FIFA 11+. All coaches were asked to carry out the FIFA 11+ with their team two-three times weekly in substitute for their team's usual warm-up. Players performed pre and post-intervention performance testing consisting of; single-leg eyes-closed balance on an Airex Balance Pad, the Star Excursion Balance Test (SEBT), the Single-leg triple hop, and the jump-over-a-bar test (total number of two-leg jumps in 15 s) (Steffen et al., 2013). From the exposure and adherence data, the researchers observed players performing an average of 1.9 FIFA 11+ sessions per week. For all groups, significant post-season improvements were found for all SEBT directions. In the intervention group, an enhanced triple–hop performance, single leg balance, jumps-over-a-bar, and anterior direction of the SEBT was noted more so than the control group. When dividing the participants into adherence groups; high, medium, and low, the researchers observed better functional balance and 72% reduced injury risk for players who highly adhered to the prescribed exercises during the season compared with those with fewer adherences. Therefore, it is important to gauge the adherence to any intervention to ensure that any non-significant findings are a measurement of the intervention effectiveness and not due to participant adherence levels. The researchers also observed that education of coaches using an extensive workshop, followed by supervised delivery by these coaches resulted in significantly higher team adherence than unsupervised delivery of the FIFA 11+, and consequently significant improvements in performance and lower risk of injury. Therefore, the FIFA 11+ programme is effective in reducing injury risk and improving performance measures in youth female footballers who adhere to the programme with high adherence (Steffen et al., 2013).

The effects of adherence to the FIFA 11+ on injury risk observed by Steffen et al. (2013) are further supported by previous research investigating the effect of the FIFA 11+ on youth female footballers (Soligard et al., 2010; Steffen et al., 2008). Steffen et al. (2008) did not see a reduction of injury rate in youth female footballers performing the FIFA 11+, however it is suggested this contradicting finding is due to low adherence by the teams in the intervention group. Only 14 of the 58 teams in the intervention group completed more than 20 sessions during the first three months, and each player performed 15 training sessions on average (Steffen et al, 2008). Whereas, Soligard et al. (2010) observed differences in injury risk between low, intermediate and high adherence groups of footballers performing the FIFA 11+. Soligard et al. (2010) observed a 35% lower risk of all injuries in players with high adherence compared to players with intermediate adherence. It was suggested that coaches had a significant influence on this finding as those coaches who had previously utilised injury prevention training coached teams with a 46% lower risk of injury (Soligard et al., 2010). Therefore, adherence of coaches and players to the FIFA 11+ programme can influence training effects and researchers should ensure measures are in place to aid and track adherence. Various studies have investigated how to predict and aid adherence of players and coaches to the FIFA 11+. McKay et al. (2016) used the Health Action Process Approach (HAPA) to predict adherence to the FIFA 11+ programme in elite youth female footballers (McKay et al., 2016). The reserachers observed that the HAPA model could strongly predict the coach's intentions to uptake the FIFA 11+, but could not be used to predict player intentions. McKay et al. (2016) reported that risk perceptions, outcome expectancies, and task self-efficacy accounted for 92.7% of uptake intention variance. Therefore, it could be suggested that utilising methods to increase a coaches perception of risk and ensuring understanding and appreciation of the FIFA 11+ outcomes could increase coach adherence to the FIFA 11+ programme. Lindblom et al. (2012) and Steffen et al. (2008) criticise the FIFA 11+ in terms of the lack of motivational incentive for athletes to repeatedly perform the same exercises throughout the season, and suggesting this could be a reason for low adherence. However, previous research with high adherence would contradict this claim (Van Beijsterveldt et al., 2011; Soligard et al., 2008; Steffen et al., 2013). Furthermore, they suggest the intensity of the exercise in the FIFA 11+ would not be enough to produce improvements in strength and speed. However, Bizzini et al. (2013) observed statistically significant increases in 20m sprint, agility t-test, counter movement jump, squat jump, and SEBT performed by male amateur footballers (age: 25.5 years) after performing the FIFA 11+ two - three times a week. Although, the FIFA 11+ has been identified to reduce injury risk, research on the mechanisms by which the prevention programme works and the injury risk factors it addresses is limited.

2.3.2 Effectiveness to Reduce Kinetic and Electromyographic Variables Associated with ACL Injury

2.3.2.1 The Effectiveness of the FIFA 11+ in Reducing Electromyographic Variables Associated with ACL Injury

Neuromuscular prevention training can address co-contraction ratios and strength imbalances (Britoa et al., 2010; Soligard et al., 2008). Prevention programmes like the FIFA "11+" can reduce the risk of injuries by altering electromyographic properties (Soligard et al., 2008). Britoa et al. (2010) researched the effect of "The 11+" on muscle strength balances and co-activation ratios. Within this study, 18 sub elite male footballers performed "The 11+" three times weekly for ten weeks. Pre and post testing measures employed isokinetic dynamometry with a knee ROM of 0 - 90 degrees to test muscle strength, peak torque, and H:Q co-activation ratio. Concentric strength was tested at speeds of 60 deg/s and 180 deg/s, while eccentric strength was tested at a speed of 30 deg/s. In comparing pre and post-testing results, the researchers identified a significant increase in peak torque of the non-dominant hamstrings and H:Q co-activation ratio significantly improved post intervention. These results provide observations that "The 11+" could help to improve electromyographic variables and reduce lower extremity injury in youth male footballers (Britoa et al., 2010). However, females were not included in this research and from previous research it is evident that the H:Q co-activation ratio and hamstring strength of females is much weaker than males (Ebben et al., 2010; Hanson et al., 2008). Therefore, females would have a greater neuromuscular deficit to overcome. As well as this, previous research utilised isokinetic dynamometry, so the effect of the FIFA 11+ on the electromyographic variables of youth female footballers performing dynamic tasks such as the unanticipated cutting manoeuvre is yet to be elucidated. As the FIFA 11+ programme is generic, it does not allow for individualisation, therefore it is difficult to quantify if athletes of different baseline strength measures have similar loadings and training responses to the programme (Britoa et al., 2010). There is no research studying the effects of the FIFA 11+ on time to peak activation of the quadriceps and hamstrings muscle groups or the medial:lateral activation patterns of the hamstrings and quadriceps groups. The effectiveness of the FIFA 11+ on the electromyographic variables of youth female footballers during an unanticipated cutting manoeuvre requires further exploration.

2.3.2.2 The Effectiveness of the FIFA 11+ in Reducing Kinetic Variables Associated with ACL Injury

In a systematic review by Padua & DiStefano (2009), six studies researching the effect of prevention programmes on vGRF were analysed. The results of these studies were inconsistent with three studies observing no significant change in vGRF post-intervention, and three studies observing significant reductions in vGRF post-intervention (Chappell and Limpisvasti, 2008; Herman at al., 2008; Hewett et al., 1996; Irmischa et al., 2004; Lephart et al., 2005; Prapavessis et al., 2003). The three studies that observed no change in vGRF utilised basic strength training, plyometric training, isolated strength training, and integrated training programmes (Chappell and Limpisvasti, 2008; Herman at al., 2008; Lephart et al., 2005). Significant changes in vGRF were noted by Hewett et al. (1996), Prapavessis et al. (2003), and Irmischer et al. (2004), in these studies the participants performed their intervention under direct supervision, contrasting to those studies observing no significant changes in vGRF. Hewett et al. (1996) incorporated a supervised six week integrated training programme with verbal instruction and feedback specifically regarding the jump performance of the participants. Prapavessis et al. (2003) and Irmischer et al. (2004) utilised a similar intervention to Hewett et al. (1996) consisting of a 4-phase jump-training program with plyometric exercises performed two times per week over a 9-week training period under direct supervision. Each study that demonstrated significant decreases in vGRF post-intervention incorporated performance under direct supervision offering verbal and auditory feedback. In contrast, those studies indicating no change in vGRF did not incorporate regular verbal or auditory feedback and performance under direct supervision. As such, ACL injury prevention programs that incorporate performance under direct supervision offering verbal and auditory feedback and cues are able to demonstrate large reductions in vGRF (*range;* 18% – 38%) (Padua & DiStefano, 2009). Therefore, supervision of knee injury prevention programmes could be key in improving kinetic variables and decreasing ACL injury risk in youth female footballers. There is no research studying the effect of the FIFA 11+ on loading rates, time to peak forces, or GCT, or the effect of the FIFA 11+ on kinetic variables produced by youth female footballers performing an unanticipated cutting manoeuvre. The effectiveness of the FIFA 11+ on the kinetic variables of youth female footballers during an unanticipated cutting manoeuvre is yet to be elucidated.

2.3.3 Effectiveness of FIFA 11+ when Players are Experiencing Fatigue

The average duration of preventive training is 20 minutes, to avoid the negative impact of fatigue. However, in a game situation this may not be realistic (Michaelidis &

Koumantakis, 2014). It has been observed that better conditioned female footballers have greater neuromuscular control for longer time periods in games, as compared to less conditioned players who display longer reflex latencies and decreased muscle activation around the knee joint (Alentorn-Geli et al., 2009). As well as this, decision making is key in the prevention of non-contact ACL injuries and is negatively affected by fatigue; however the FIFA 11+ does not include any decision making or reaction drills and therefore would not improve or train decision making in a fatigued state. Therefore, it may be necessary for prevention programmes to induce a certain level of fatigue which would still provide positive injury prevention stimulus (Michaelidis & Koumantakis, 2014). Although previous research has determined the FIFA 11+ effective in reducing the risk of injury in youth female footballers, there is not currently any research on the effectiveness of injury prevention programmes on the ability of these players to resist the effects of acute fatigue. With fatigue posing a risk factor for ACL injury and most injuries occurring in the final moments of a game, it is imperative that the positive effects of a prevention programme are sustained when a female footballer is in a fatigued state. Therefore, research is needed to investigate the effectiveness of injury prevention programmes in youth female footballers experiencing fatigue mimicking that of match-play.

2.3.4 Effect of Prevention Programmes on Cutting Strategies

ACL injuries in female footballers typically occur in a non-contact situation, most commonly during an unanticipated cutting manoeuvre. Researchers have observed a decrease in the number of non-contact knee injuries after prevention programme training; this could indicate that the kinetic and electromyographic variables displayed by youth female footballers during these non-contact situations are improved (Michaelidis &

Koumantakis, 2014; Walden et al., 2011). However, there is no specific research studying the effects of the FIFA 11+ on unanticipated cutting manoeuvres in both youth and adult female footballer's pre and post-intervention. Therefore, the effects of injury prevention programmes on the kinetic and electromyographic variables displayed by youth female footballers during an unanticipated cutting manoeuvre are yet to be elucidated.

2.4 SUMMARY

ACL injuries are serious injuries usually requiring surgical intervention and long term rehabilitation, characterised by difficulty in returning the athlete to pre-injury performance levels (Hewett et al., 2006). Electromyographic and kinetic variables such as; peak GRF, loading rates, and H:Q co-activation ratios play an important role in the aetiology of ACL injury and can predispose female footballers to ACL injury (Cowley et al., 2006; Hanson et al., 2008; Palmieri-Smith et al., 2009). Previous research has identified sub-optimal electromyographic and kinetic variables produced by youth and adult female footballers performing a variety of dynamic movements including; drop-jump landings, pre-planned cutting manoeuvres and unanticipated cutting manoeuvres (Cortes et al., 2011; Lucci et al., 2011; Quatman et al., 2010). Although it is well documented that sporting activities are performed in a reactive manner and the most common ACL injury mechanism in female football is a cutting manoeuvre, there is limited research utilising an unanticipated cutting manoeuvre to assess the electromyographic and kinetic variables that may increase ACL injury risk. Some research has observed detrimental effects of fatigue on the electromyographic and kinetic variables produced by female footballers, however many researchers have not utilised football-specific fatigue protocols to mimic the energy demands of football match-play (Cortes et al., 2014; Gehring et al., 2009; Krustrup et al., 2002; Weiss & Dickin, 2013). Therefore, electromyographic and kinetic variables employed by youth female footballers during an unanticipated cutting manoeuvre and the effect of football-specific fatigue on ACL injury risk is yet to be elucidated.

Despite developments in neuromuscular prevention training, knee injuries remain predominant in female footballers, specifically youth. Previous research has recognised and acknowledged the benefits of various neuromuscular prevention programmes, particularly the FIFA 11+, in reducing the risk of injury in youth male and female footballers (Mandelbaum et al., 2005; Michaelidis & Koumantakis, 2014; Myer et al., 2005; Soligard et al., 2008; Soligard et al., 2010; Steffen et al., 2013; Walden et al., 2011). However, as of yet, the effectiveness of the FIFA 11+ in improving the ability of youth female footballers to resist the effects of football specific fatigue on electromyographic and kinetic variables that may increase the risk of ACL injury is yet to be elucidated. It would be beneficial to identify the electromyographic and kinetic variables employed by youth female footballers during an unanticipated cutting manoeuvre, the effect of acute football specific fatigue, and the ability of the female footballers to maintain any beneficial effects of the FIFA 11+ when experiencing football specific fatigue.

2.5 HYPOTHESES OF THE THESIS

Based on the previous literature, it was hypothesised for this thesis that:

1. Youth female footballers will display sub-optimal electromyographic and kinetic variables during the unanticipated cutting manoeuvre characterised by quadriceps dominance, large GRF's and short GCT

2. Fatigue will have a significantly detrimental effect on the electromyographic and kinetic variables employed by youth female footballers during an unanticipated cutting manoeuvre; increasing GRF, loading rates, and GCT, and decreasing muscular activation of the quadriceps and hamstrings muscles during pre-activation and immediate feedback mechanisms.
3. The FIFA 11+ will significantly improve electromyographic and kinetic variables employed by the youth female footballers during the unanticipated cutting manoeuvre with better co-activity of hamstrings, increased medial knee activation in comparison to lateral knee activation, and decreased GRF. However, these improvements will not be as effective when fatigued.

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Chapter 3: Study 1

Reliability of Kinetic and Electromyographic Variables of Youth Female Footballers during an Unanticipated Cutting Manoeuvre

3.1 INTRODUCTION

Anterior cruciate ligament (ACL) injuries are prevalent in both male and female football, with research showing that females are up to eight times more likely to sustain an ACL injury than their male counterparts (Hughes, 2006). Research shows that young females aged 16 - 18 years old are at the highest risk of ACL injury (Hughes, 2006) and that approximately 70 - 80% of ACL injuries are non-contact in nature (Cowley et al., 2006; Landry, 2007; Silvers 2007). Non-contact ACL injuries are typically caused by a dynamic knee valgus action, involving a combination of hip adduction and internal rotation, knee abduction, tibial external rotation and anterior translation, and ankle eversion (Hewett et al., 2006). From a mechanistic perspective, a variety of kinetic (e.g. ground reaction force) and electromyographic (e.g. activation ratios of the hamstrings and quadriceps) variables have been proposed as major risk factors, which lead to an increased risk of dynamic valgus and ACL injury in female footballers. Traditionally, these variables have been measured using surface electromyography (sEMG) in combination with kinetic data (Cowley et al., 2006; Landry, 2007; Silvers 2007), namely during jump and land testing protocols. However, due to the dynamic nature of football, there is often the need to rapidly decelerate and change direction in response to an external stimulus (Brophy et al., 2010, Cowley et al., 2006), which can expose players to an increased risk of injury. Specifically, research shows that there is an increased loading on the knee joint during unanticipated cutting manoeuvres in comparison to pre-planned cutting manoeuvres (Besier et al., 2001). In light of the prevalence of ACL injuries in female footballers

(Cochrane et al., 2007) and because unanticipated cutting is a commonly performed task within the game (Reilly, 2003) and is associated with non-contact ACL injury (Cochrane et al., 2007), research is required to examine the electromyographic and kinetic variables of female footballers during an unanticipated cutting manoeuvre.

Before the variables of female footballers performing an unanticipated cutting manoeuvre can be examined, the reliability of the measures used to examine such variables must be determined. The reliability of a sEMG measurement is dependent on intrinsic and extrinsic factors (Eston & Reilly, 2001). The reliability of sEMG data has been established for many isometric exercises, however less is known about the reliability of the measures during dynamic exercises (Bolgla et al., 2010; Christ et al., 1994; Kadaba et al., 1989; McCarthy et al., 2008; Pitcher et al., 2008). Furthermore, the measurement error of sEMG in combination with kinetic data during an unanticipated cutting manoeuvre is unknown, especially in female youth. The literature that has investigated sEMG during dynamic tasks has typically studied muscular activation during jump and land tasks, and linear running protocols (Bolgla et al., 2010; Fauth et al., 2010). These studies have determined sEMG to be reliable for assessing muscular activation during dynamic tasks, with large to nearly perfect intraclass correlation coefficients (ICC) (≥ 0.5) (Bolgla et al., 2010; Fauth et al., 2010).

Running activities in football are rarely performed in a linear fashion and often require a player to rapidly change direction in response to a stimulus. Besier et al. (2001) observed differences in the performance of pre-planned and unanticipated cutting manoeuvres due to the anticipatory effects of cutting. With the reactive nature of unanticipated cutting manoeuvres including sudden changes of direction, it cannot be assumed that the reliability observed in previous research utilising linear running, jump and land, or pre-planned cutting protocols can be applied to the measures of the current study. It is therefore essential to identify the reliability of measures during unanticipated cutting in order to be able to determine worthwhile changes in performance following for example, an acute fatigue protocol or training intervention, to eliminate changes that simply reflect the noise of the measure.

Alenezi et al. (2014) studied the reproducibility of ground reaction force during running and cutting manoeuvres. The cutting manoeuvre utilised by Alenezi et al. (2014) required the participants to perform a straight running approach (10 m) towards the force platform at a speed between 3.5 m/s and 5.5 m/s, contact the force platform, and cut to the left at a 90 ° angle. Participants were tested twice a day on two days, separated by a week. The findings of Alenezi et al. (2014) agreed with previous research with greater within-day reliability (ICC = 0.97) than between-day reliability (ICC = 0.92) for peak vertical ground reaction force (vGRF) (Ferber et al, 2002). Research by Alenezi et al. (2014) and Ferber et al. (2002) utilised similar protocols and found kinetic measures from the protocol to be reliable with ICC's ranging from large (<0.5) to nearly perfect (<0.9). However, while similar, there are some differences between the protocols used in the previous research and the current protocol including; approach distance and running speed. These factors may have an effect on the reliability of the current protocol with differences in run-up distance, and higher running speeds increasing the chance of task failure (Vanrenterghem et al, 2012), as well as, the unanticipated nature of the task in the current study (Besier et al., 2001).

To date, there has not been a study that has examined the reliability of a combination of electromyographic and kinetic variables to measure ACL injury risk factors during unanticipated cutting manoeuvres in females. Therefore, the current study aimed to determine the test-retest reliability of the measures within a cohort of female footballers during an unanticipated cutting manoeuvre.

3.2 METHODS

3.2.1 Participants

Thirty-four female footballers (mean ± *sd*: age = 22.5 ± 2 years, stature = 165 ± 5.05 cm, body mass = 67.3 ± 8.35 kg) who played in the South West Women's Football League (SWWFL) participated in the study. All participants were required to complete a health questionnaire (Appendix 3.1) in accordance with the University of Gloucestershire Sport and Exercise Laboratory procedures. Acceptance to the study was approved if the participants satisfied criterion as described in the health questionnaire flow chart (Appendix 3.2). On each testing occasion the participants were asked to review their answers to the questionnaire and date and sign it again if circumstances had not changed since the health questionnaire was initially completed. However, if circumstances had changed the participants were required to complete another health questionnaire. Participants were excluded from the study if they were injured or rehabilitating from injury at the time of testing. Injury was defined as any physical ailment preventing the player from participating in their normal football routine. Participants were instructed not to: i) perform vigorous exercise 48 hours prior to testing sessions, ii) drink alcohol in the final 24 hours before testing, iii) drink caffeine in the final 12 hours before testing.

Written informed consent was obtained from each of the female footballers and their parents/guardians (if under the age of 18 years) prior to beginning the research. In the case of a participant under the age of 18 years, participant assent was also obtained. Verbal consent was also obtained from the club prior to approaching players. Participants were given an information sheet as well as verbal explanations of the procedures involved (Appendix 3.3). Ethical approval for the study was obtained from the University of Gloucestershire's Research Ethics Committee (RESC). RESC approved laboratory procedures and University guidelines for working with children were followed at all times and all researchers involved in the study had obtained a Criminal Record Bureau (CRB) check before beginning data collection. Participants were made aware that they could withdraw from the study at any point without affecting their relationship with the University, research team or their club. All the data collected was stored on a computer using an ID code and only accessible by the research team. Where the club required access, consent from the players must have been approved prior to allowing club access. Participant anonymity was maintained at all times and hard copies of data were stored in a locked container only accessible by the principal researcher.

3.2.2 Habituation Session

Participants attended a single habituation session at their facility prior to data collection sessions, in order to provide an opportunity to become familiar with the unanticipated cutting manoeuvre and the data collection procedures. Participants were asked to attend the session in shorts, t-shirt and comfortable running shoes. The participants performed a ten minute warm-up routine led by the club coach which they typically performed before their team training sessions. The researcher instructed the participants in the unanticipated cutting manoeuvre, and then each participant was allowed to perform the manoeuvre seven times completing one entire testing protocol. The testing protocol consisted of seven manoeuvres to ensure randomisation of direction and to allow data to be collected at least twice in the direction of analysis. Anthropometrics were measured during the habituation session and leg dominance was determined by asking the participants which leg they would prefer to use to kick a ball. Following the habituation session, participants attended two data collection sessions for the researcher to collect experimental data. Data was collected on two separate occasions separated by 5 days.

3.2.3 Testing Procedures

3.2.3.1 Anthropometry

Age (years) was computed from date of birth to the date of testing. Stature (cm) was measured using a stadiometer (SECA gmbh and co Ltd, Hamburg Germany) and determined to the nearest millimetre. Participants stood barefooted with toes and heels together and with their back to the stand. The researcher then applied gentle pressure to the mastoid processes while encouraging the participant to stand tall and look straight ahead. Body mass (kg) was assessed using calibrated balance beam scales (Seca 700 Beam column scale, seca gmbh and co Ltd, Hamburg, Germany) and calculated to the nearest 100 g, with participants barefoot wearing t-shirt and shorts.

3.2.3.2 Unanticipated Cutting Manoeuvre

Prior to data collection, all participants completed a ten minute warm up procedure that they performed on a regular basis with their club. For the unanticipated cutting manoeuvre, the researcher instructed the participants to run an approach distance of 15 m over a force platform seven times at an approach speed of approximately 4 m/s, paced by a quartz metronome (SQ-44, Seiko, UK) set at 60 beats per minute (Vanrenterghem et al., 2012; Andersen et al., 2012). Vanrenterghem et al. (2012) studied the relationship between speed, meaningful knee loading, and task achievement of a cutting manoeuvre performed at 2 m/s, 3m/s, 4m/s, and 5m/s by female athletes. The researchers found that an approach speed of 4m/s provided meaningful knee loading with detriment to task achievement; whereas higher speeds placed dangerously high loads through the knee and had a negative effect on task achievement and lower speeds did not load the knee sufficiently (Vanrenterghem et al., 2012).

Further to this, Besier et al. (2001) observed significant differences in varus and valgus knee loads in female athletes performing the same cutting manoeuvre (sidestepping 60° cut (S60) and sidestepping 30° cut (S30)) but at different speeds. Those that experienced a large valgus load performed the manoeuvre 0.25 m/s slower that those that experienced a large varus load. Fredericks et al. (2015) investigated the effect of speed on knee joint angles of recreational runners and observed greater knee flexion at foot strike and greater knee extension at toe-off when participants were treadmill running at higher speeds (2.5 m/s – 4 m/s). Changes in joint angles can influence joint moments and stiffness implicating the risk of ACL injury. Munro et al. (1987) also studied a group of recreational runners running in a linear fashion at varying speeds (2.5-5.5 m/s). The researchers observed GCT increased with decreasing speeds, vGRF, impact peak, and loading rate increased with increasing speeds, and there was no significant relationship between medial-lateral GRF and speed. Previous research has observed implications of speed on various knee loading and biomechanical variables showing a need for a standardised speed in sports science testing.

The current study utilised a running speed of 4 m/s which may be less than that commonly seen in some sporting situations (5-7 m/s). However, this speed ensured that the unanticipated cutting manoeuvre produced meaningful knee loading and task achievement without producing dangerously high loads. The mass of each participant could have produced differing loading causing some variability around the mean load exerted at each approach speed. However, the average mass of the participants utilised by Vanrenterghem et al. (2012) establishing a standardised approach speed was 57.5 ± 6.9 kg, similar to the participants in study 1 (67.3 ± 8.35 kg) and studies 2 and 3 (62.3 ± 9.96 kg). Previous research utilising male soldiers performing running and walking tasks carrying varying loads (12 – 50 kg) observed high positive correlations between body mass plus load, vGRF and joint reaction forces (Polcyn et al., 2000). Additionally, increases in knee and hip flexion were noted as weight was increased, thus these joints may be more efficiently shock absorbing. The study displayed that a 7.5% increase in mass can increase vGRF load by approximately 150N (Polcyn et al., 2000). In application to the current study, the range of participant body mass is approximately 12% of the group average in study 1, and 16% in studies 2 and 3. Thus, we could expect variation of 150N or greater between subjects. The variance in body mass in the current study is similar to that in the study by Vanrenterghem et al. (2012) (12%) establishing a standardised approach speed.

Importantly, the change in mass with each approach speed is relative to each individuals mass.

A new protocol was set-up by Fusion Sport for the Smart Speed System (Fusion Sport, QLD, Australia). Ten separate variations of the protocol were devised, each with a specific gate allocation pattern for randomisation of the protocol. All protocols ensured the participant was directed to cut in the left and right directions at least two times out of the seven gate allocations of each pattern variation. However, participants were not aware of this. There were three directional indicator gates (Smartspeed, Fusion Sport, QLD, Australia) set-up 3 m from the force platform; straight ahead of the force platform, ahead right of the force platform, and ahead left of the force platform. Those directional gates to the left and right of the force platform were set-up with the centre of the gate at an angle of 45° from the far corner of the force platform measured using a goniometer (MIE Medical Research Ltd., Leeds, UK). Previous protocols utilising an unanticipated cutting manoeuvre have positioned a trigger 1.5 - 2.0 m from the cutting foot placement area (Beaulieu et al., 2009; Besier et al., 2001; Cortes et al., 2011; Pollard et al., 2004; Pollard et al., 2005). Therefore, directional indicator gates were cued by a trigger gate placed 2 m before the participant was due to strike the force platform.

Participants were told by the researcher that the directional indicators of the Smart Speed System (Fusion Sport, QLD, Australia) would randomly provide the participants with a visual cue to perform a straight forward run through the force platform or an unanticipated cut, left or right, at an angle between 35° and 55° marked by tape (Beaulieu et al., 2009; Besier et al., 2001; Cortes et al., 2011; Pollard et al., 2004; Pollard et al., 2005).

Participants were instructed to run with their head up and facing forwards at all times. Once the participants noticed the cue they cut left, right or continued in their straight track through the specified gate, adhering to the cue signal. The timing gates provided the cutting cue approximately 0.5 s before the lead foot was due to land onto the force platform, when the participant passed the cue gate 2 m from the force platform (Beaulieu et al., 2009; Besier et al., 2001; Cortes et al., 2011; Pollard et al., 2004; Pollard et al., 2005). Participants were instructed to contact the force platform by the fourth beat of the Quartz metronome (SQ-44, Seiko, UK).

Participants were allocated a 15 s recovery period between runs, to enable the participant to make their way back to the start line and for the researchers to save data and reset the trial. The leading leg was the limb under assessment. Therefore, during a cut to the right the left leg was the leading leg as this is the leg that would plant and pivot on the force platform to allow the player to move to the right and initiate the cutting motion. Likewise, during a cut to the left, the right leg was the leading leg and the limb under assessment. All runs in which the limb under assessment was not the non-dominant leg, or whereby the participant was cued to run straightforward were disregarded immediately. Figure 3.1 shows the laboratory set up used for the unanticipated cutting manoeuvre.

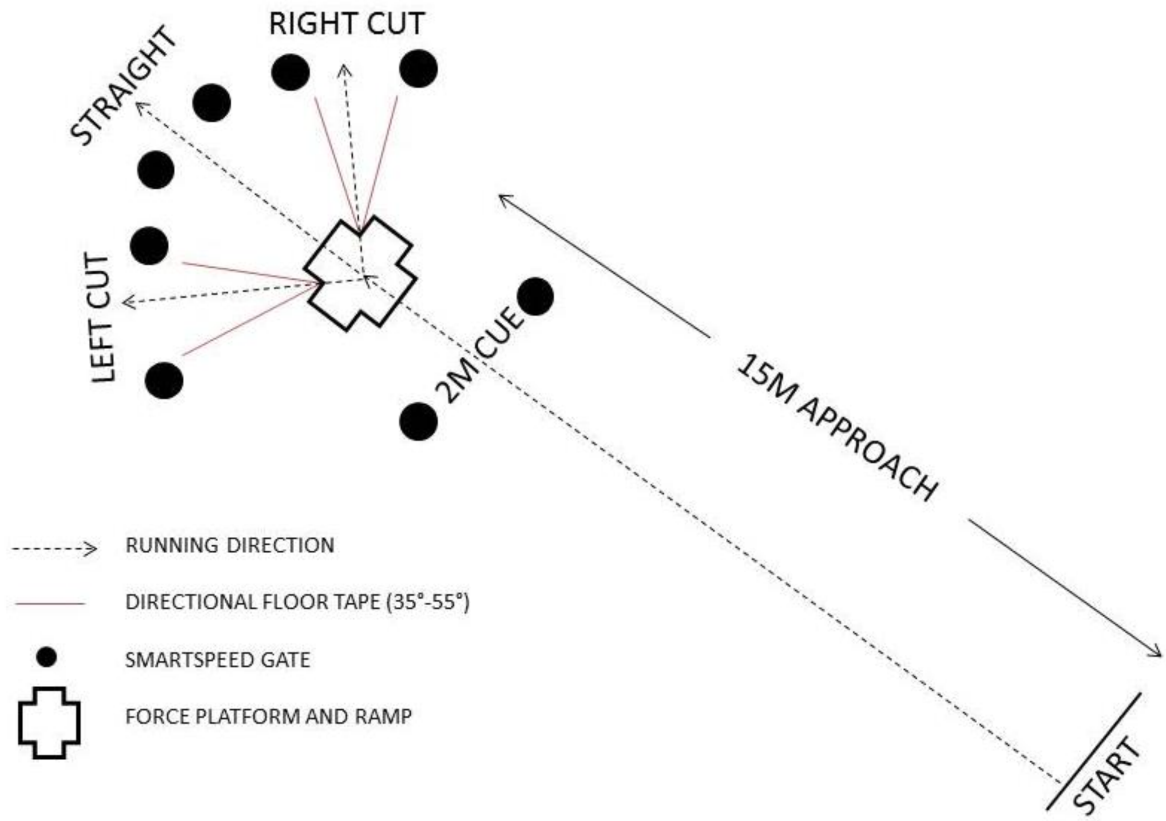

Figure 3.1 The equipment set-up during the unanticipated cutting manoeuvres.

A cutting trial was deemed successful if: i) the participants' foot of the leading limb contacted the force plate during the cutting manoeuvre, ii) the participant cut within the designated cutting angle of 35° - 55°, iii) the participant maintained a running speed of 4 m/s paced by the quartz metronome (SQ-44, Seiko, UK) reaching the platform within 4 s (min: 3.5 s, max: 4.5 s) and iv) the leading limb in contact with the force platform was the non-dominant limb.

3.2.3.3. Kinetic variables

Vertical ground reaction forces (vGRF) and anterior-posterior ground reaction forces (apGRF) were measured using a portable force platform (PS-2142, PASCO Scientific, CA, USA). In the current literature, it is not standard practice to calibrate the force platform (Hori et al., 2009; Padua & DiStefano, 2009). However, the portable force platform utilised in the current thesis is annually checked and calibrated as per manufacturer's guidelines through the Capstone software. The portable force platform was turned on before testing started to warm up the platform negating the drift of strain gauge plates, and the portable force platform was zeroed between participants. Due to the inability to sub-mount the force platform in the field, a small custom ramp was used to frame the platform to decrease the step-up onto the force platform and minimize alterations in participant mechanics (Figure 3.2).

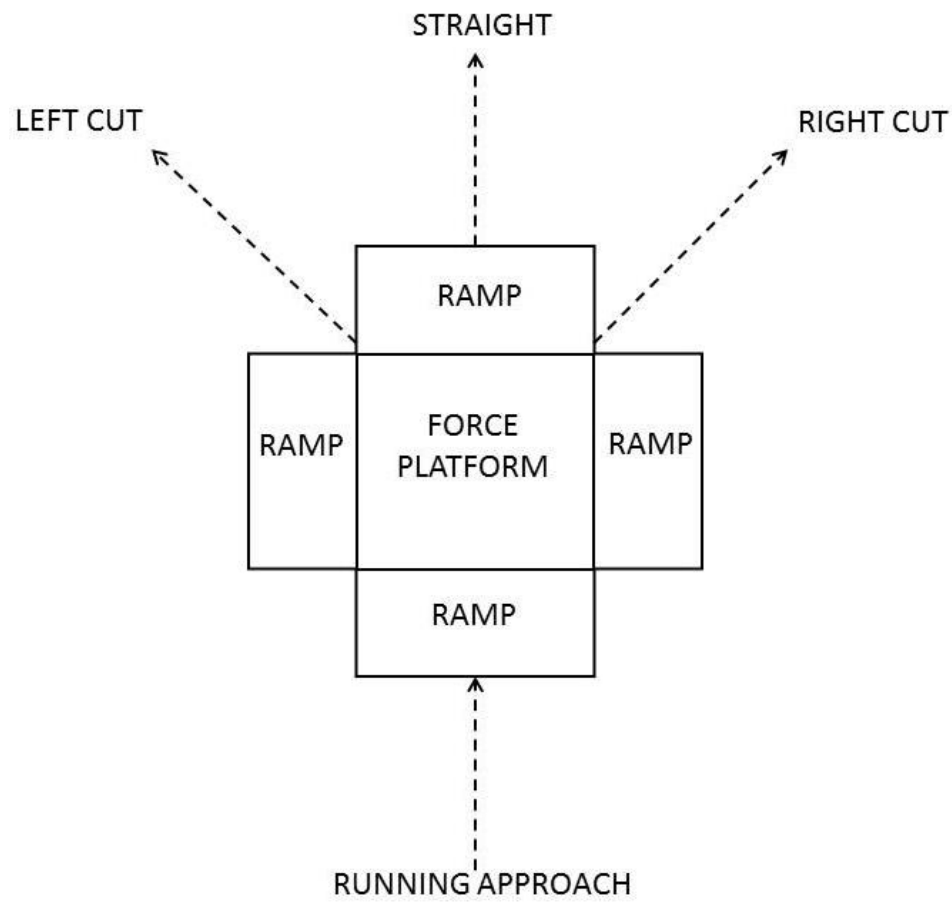

Figure 3.2 Schematic of force platform in a custom built ramp

The researcher zeroed the force platform prior to each trial run. Kinetic data collection onset was triggered by Biometrics EMG (Biometrics Ltd, Newport, United Kingdom) using a sync cable so data was time-aligned (Appendix 3.4).

The force platform transferred vGRF and apGRF data to a connected Toshiba Laptop (L20, Toshiba Corp. Tokyo, Japan). Raw data was acquired at 1000 Hz and filtered with a Pasco Capstone software acquisition and analysis system (version 2.2.2) (PASCO Scientific, CA, USA). Kinetic variables analysed from the force platform were; peak vGRF, time to peak vGRF, peak apGRF, time to peak apGRF, vGRF loading rate, apGRF loading rate, and ground contact time. Ground contact time was determined using a threshold of 10 N, beginning when vGRF ≥ 10 N and ending when vGRF ≤ 10 N (Harrison et al., 2009, Oliver et al., 2014). Loading rates were determined utilising equation 3.1 (Harrison et al., 2009), where GRF_{PK} represents peak GRF, GRF_{IC} represents the GRF at initial contact, and $TimeGRF_{PK}$ represents time to peak force:

$$GRF_{PK} - GRF_{IC}/TimeGRF_{PK}$$

Equation 3.1 Loading rate

3.2.3.4 Electromyographic Variables

Surface electromyography (sEMG) was quantified with an eight-channel Biometrics EMG telemetry system (Biometrics Ltd, Newport, UK) and used to collect muscular activation of the hamstrings and quadriceps muscles. Participants were prepared for EMG electrode placement by the researcher. The skin was cleaned with an isopropyl alcohol wipe to reduce impedance and hair was shaved using a razor if necessary (Hermens et al., 2000; Konrad, 2005; SENIAM). Participants were also asked not to apply any type of moisturiser on their legs prior to or during testing. These preparatory methods were adopted to improve application of the electrodes and reduce the acceptable impedance to below 5 kΩ. To reduce any interference from clothing, the researcher clipped any of the participant’s loose clothing out of the way of the electrodes.

The measurement unit was secured around the waist of the participant, and data was transmitted via a cable connection to a laptop computer. Following questioning of the female footballers to determine limb dominance, six single reference pre-gelled $Ag^{+}/Ag^{+}Cl^{-}$ surface electrodes were placed on the vastus medialis (VM), vastus lateralis (VL), rectus femoris (RF), biceps femoris (BF), semitendinosus (ST) and semimembranosus (SM) muscles of the participant's non-dominant limb. A reference electrode was placed over the styloid process of the ulna. All electrodes were positioned 2.5 cm apart parallel with the muscle fibres over the midpoint of the muscle belly of each chosen muscle, determined by manual palpation, as validated by SENIAM (Figure 3.3). Manual muscle testing techniques with the participants in a prone lying position were employed to verify proper electrode placement (Appendix 2.1). Excess wiring from the surface electrodes was taped together with an aim to reduce interference with the participants running technique and decrease artefact noise on the EMG signal.

EMG data was analysed during the preparatory and loading phase of the unanticipated cutting manoeuvre. The preparatory phase was defined as the 100 ms period before ground contact and provides an observation of feed-forward (preparatory) mechanisms, and the loading phase was defined as ground contact and provides an observation of feedback (reactive) mechanisms (Landry et al., 2007; Lloyd et al., 2012; Oliver et al., 2014). The loading phase was further split into latency phases; 0 - 30 ms representing background muscle activity, 31 - 60 ms representing short latency reflexes, 61 - 90 ms representing intermediate/medium latency reflexes, and 91 - 120 ms representing long latency reflexes (Lloyd et al., 2012, Oliver et al., 2014). The muscle activity for overall ground contact time was also observed, as well as peak muscle activity and time to peak muscle activity throughout ground contact time. Pre-activation and ground contact periods were defined by the time of loading on the force platform, which was synced and time-aligned with sEMG data collection.

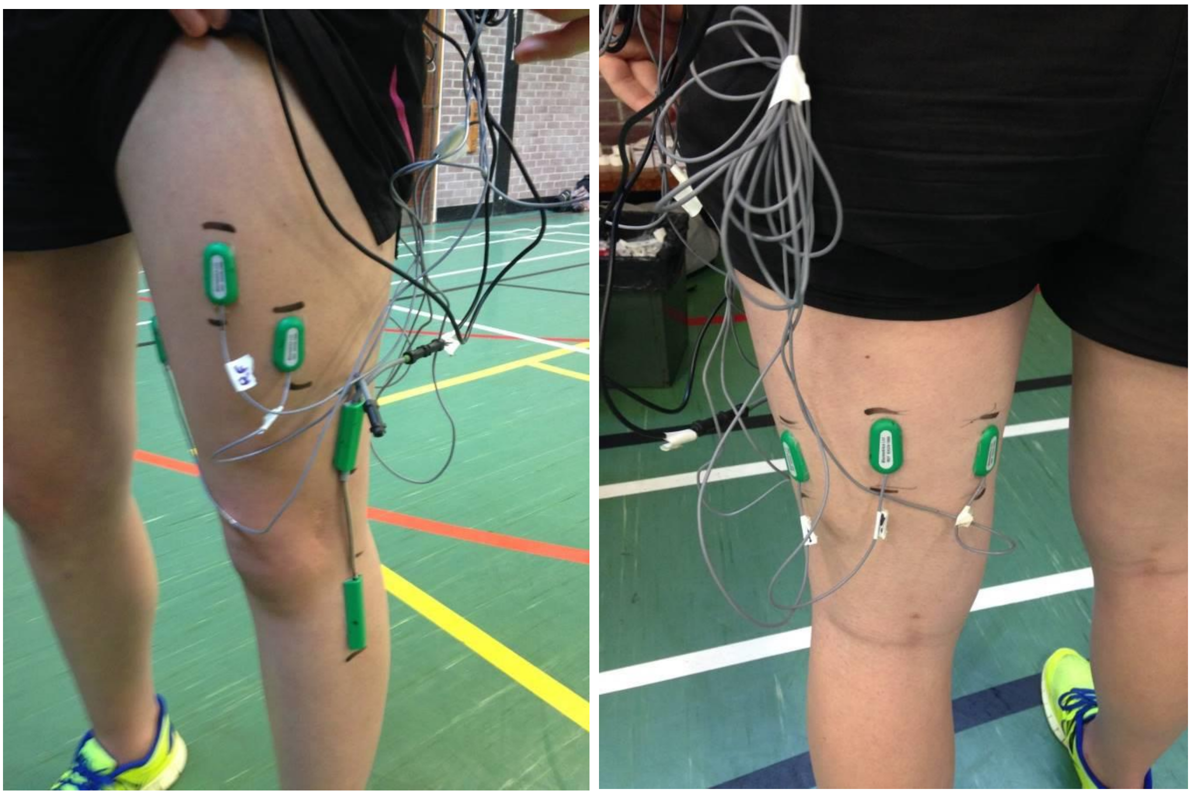

Figure 3.3 EMG electrode positioning on the VM, RF, VL, SM, ST and BF

The same researcher applied all electrodes and used a permanent marker pen to draw around the placement of each electrode to reduce the chances of error. All electrodes were zeroed before each trial with the participant in a static standing relaxed state. Raw sEMG data was collected at a sampling frequency of 4600 Hz and sent directly to the Biometrics software package set up on a Toshiba Laptop (L20, Toshiba Corp. Tokyo, Japan). The EMG unit included a common mode rejection ratio of < 80 dB and an amplifier gain of

1000 dB. Raw EMG data was band pass filtered at 20 – 460 Hz using the Biometrics Acquisition Software.

The root mean square (RMS) of all data was calculated using Biometrics Software with a window of 40 m/s. The average RMS was then integrated by multiplying the RMS value by ground contact time. Integrated EMG values for pre-activation and ground contact time were utilised for analysis. The data from each latency phase was then normalised using integrated EMG values. Normalisation of EMG data was achieved by expressing muscle activity during the individual latency phases, as a percentage of total muscle activity throughout GCT (equation 3.2) (Lloyd et al., 2012; Oliver et al., 2014; Oliver & Smith, 2010).

$$LP_{norm} = (LP/GCT_{mean})*100$$

Equation 3.2 Normalisation of EMG activity during pre-activation and background muscle activity individual latency phases (LP)

Previous research comparing dynamic normalisation procedures with the traditional method of using MVIC for EMG normalisation has observed greater reliability with dynamic methods (i.e. squat jumps, straight forward running) (Ball & Scurr, 2010; Suydam et al., 2016). The current method of normalisation uses the same electrode configuration as the testing protocol meaning that factors affecting EMG signals are the same. Therefore, a relative measure of the activation compared to the reference value is validly obtained (Halaki & Ginn, 2012). There is no consensus as to which test produces maximal activation in all individuals in any given muscle, therefore by using EMG values over GCT, the current study removes the difficulty of selecting a reference muscle activity. The reference value used in the current study is relative to the task and not to the maximum capacity of the muscle. Also many studies report EMG levels that are >100% MVIC indicating that the normalization test used to generate MVIC is not accurately revealing the maximum muscle activation capacity, which could lead to an overestimation of activation levels. MVIC is only reliable providing that maximum neural activation is achieved in all muscles and individuals tested. Therefore, the method utilised in the current study reduces the possibility of obtaining normalized EMG levels during a task greater than 100% and decreases variability between individuals compared to using raw EMG data or MVIC. (Ball & Scurr, 2010; Halaki & Ginn, 2012; Suydam et al., 2016).

The hamstring:quadriceps co-activation ratio (H:Q) was calculated during pre-activation, 0 – 30 ms, 31 – 60 ms, 61 – 90 ms, 91 – 120 ms, GCT and peak H:Q ratio over GCT. The following equation was used to calculate the H:Q co-activation ratio (H:Q), where H_{mean} represents the mean normalised activation of the hamstrings, and Q_{mean} represents the mean normalised activation of the quadriceps (Hanson et al., 2008; Palmieri-Smith et al., 2009; Wright et al., 2009):

$$H{:}Q = H_{mean}/Q_{mean}$$

Equation 3.3 H:Q co-activation ratio

3.2.3.5 Statistical Analysis

Within-subject mean ± standard deviations were calculated for each testing session as well as 95% confidence intervals (CI) of the mean difference. Paired samples t-tests were used to test for systematic bias between the test-retest trials. Intra-class correlation coefficients (ICC) were calculated to determine the rank order repeatability of all characteristics. The magnitude of the ICC values was quantified based on the following thresholds: trivial (0.0), small (0.1), moderate (0.3), large (0.5), very large (0.7), nearly perfect (0.9), or perfect (1.0) (Cohen, 1988; Hopkins 2000; Hopkins, 2009). Mean coefficients of variation (CV%) were calculated to represent the typical error between sessions (Hopkins, 2000). Acceptable typical error values were set at a threshold of CV ≤ 10%. All statistical analyses were calculated using log-transformed data, while statistical significance was set at an alpha level of $p < 0.05$. Paired samples t-tests were processed using SPSS ® (V.21. Chicago Illinois), while all reliability data was computed through Microsoft Excel© 2010 using a commercially available spreadsheet (Hopkins, 2007).

3.3 RESULTS

3.3.1 Kinetic Variables

Means ± standard deviations, mean % difference (95%CI), CV% and ICC for all kinetic variables are presented in table 3.1. There were no significant mean differences between individual testing sessions for all kinetic variables ($p > 0.05$). All kinetic variables displayed a large, very large or nearly perfect correlation (ICC > 0.5); with the exception of vGRF loading rate (0.50/moderate). Mean CV% revealed acceptable test-retest reliability of kinetic variables, with the exceptions of loading rates and time to peak force

(Table 3.1). However, time to peak force measures of vGRF and apGRF displayed very large and nearly perfect ICC (> 0.7).

Table 3.1 Mean (±SD) results and CV (95% CI) for all kinetic variables across testing sessions

Kinetic Variable	Testing Session 1	Testing Session 2	Mean Difference (%) (95% CI)	CV%	ICC
Peak vGRF (N)	1742 ± 321	1685 ± 346	-3.61 (-7.64 – 0.59)	4.11	0.96
Peak apGRF (N)	544 ± 167	521 ± 145	-3.07 (-9.42 – 3.71)	10.23	0.92
vGRF Loading Rate (N/s)	78975 ± 21703	78901 ± 20924	0.78 (-14.95 - 19.42)	24.21	0.49
apGRF Loading Rate (N/s)	20535 ± 8051	19332 ± 7295	-6.58 (-25.27 – 16.77)	24.51	0.82
Time to Peak vGRF (s)	0.0256 ± 0.0171	0.0236 ± 0.0076	-1.73 (-18.24 – 18.12)	20.55	0.75
Time to Peak apGRF (s)	0.0233 ± 0.0111	0.0274 ± 0.0203	7.57 (-12.14 - 31.69)	17.33	0.88
GCT (s)	0.252 ± 0.0541	0.241 ± 0.0316	-3.75 (-8.91 - 1.71)	6.00	0.88

vGRF = vertical ground reaction force, apGRF = anterior posterior ground reaction force, GCT = ground contact time

3.3.2 Electromyographic Variables

Means and standard deviations for muscular activation at all muscle sites during pre-activation and the latency phases are presented in table 3.2. The majority of data showed no significant mean differences between testing sessions (Table 3.2). However, significant mean differences were observed between testing sessions for VM and VL activation during 91 – 120 ms, and peak muscular activation of ST and VL. All normalised electromyographic variables displayed a large, very large or nearly perfect correlation (ICC > 0.5, Table 3.3), with the exception of RF activation during 91 - 120 ms, SM activation during 31 - 60 ms, ST activation during 31 - 60 ms and GCT, BF activation during 31 - 60 ms, 61 - 90 ms, and time to peak activation of SM and ST (trivial to moderate ICC) (Cohen 1988; Hopkins, 2002). Mean CV% for electromyographic variables were greater than 10%. However, some of those electromyographic variables with CV% values in excess of 10% displayed large, very large or nearly perfect ICC's (preactivation; VM, RF, VL, SM, ST, BF, 0 - 30 ms; VM, RF, VL, SM, ST, BF, 31 - 60 ms; VM, RF, VL, 61 - 90 ms; VM, RF, VL, SM, ST, 91 - 120 ms; VM, VL, SM, ST, BF, GCT; VM, RF, VL, SM, BF, Peak; all muscle sites, time to peak; VM, RF, VL, BF). Table 3.3 displays the CV% and ICC of the normalised electromyographic variables.

Table 3.2 The % difference in mean score (95%CI) for all normalised electromyographic variables between testing sessions

	PA (%)	0 – 30 ms (%)	31 – 60 ms (%)	61 – 90 ms (%)	91 – 120 ms (%)
VM	-19.9 (-34.4- - 2.29)	-13.9 (-30.0-5.96)	-9.83 (-24.59-7.83)	8.21 (-5.23-23.55)	21.14 ^{A} (3.07-42.38)
RF	-26.03 (-39.1 - -10.1)	-12.8 (-26.8-3.86)	2.92 (-13.48-22.43)	2.74 (-9.64-16.80)	6.74 (-9.42-25.79)
VL	-16.1 (-29.9 – 0.539)	-5.66 (-21.4-13.2)	1.69 (-8.52-13.04)	1.10 (-11.52-15.52)	10.78 ^{A} (-6.75-31.60)
SM	-6.34 (-17.2 – 5.96)	-9.95 (-20.2-1.55)	-1.77 (-14.39-12.71)	6.09 (-4.87-18.30)	8.20 (-3.00-20.70)
ST	4.23 (-9.23-19.7)	-4.57 (-14.7—6.72)	-8.71 (-21.51-6.18)	-5.89 (-17.25-7.02)	-8.08 (-20.69-6.54)
BF	-2.59 (-14.7-11.3)	-6.32 (-18.3-7.45)	-7.31 (-19.69-6.99)	11.90 (0.63-24.44)	2.75 (-10.87-18.45)

^{A} *denotes significant difference between testing sessions at the $p < 0.05$ alpha level*

VM=vastus medialis, RF= rectus femoris, VL= vastus lateralis, SM= semimembranosus, ST= semitendinosus, BF= biceps femoris

Table 3.3 The CV% and ICC for all normalised electromyographic variables

		PA	0 – 30 ms	31 – 60 ms	61 – 90 ms	91 – 120 ms	GCT	Peak	Time to Peak
VM	CV%	47.4	43.4	17.6	24.3	24.7	39.7	33.0	21.4
	ICC	0.82	0.65	0.90	0.65	0.74	0.53	0.67	0.81
RF	CV%	55.3	41.1	21.1	28.5	36.8	18.4	30.9	21.4
	ICC	0.84	0.76	0.82	0.62	0.49	0.90	0.78	0.87
VL	CV%	44.1	49.2	14.0	33.2	40.7	30.4	31.0	39.2
	ICC	0.83	0.57	0.91	0.55	0.50	0.79	0.83	0.51
SM	CV%	31.5	24.0	36.4	19.3	23.8	38.6	41.5	55.9
	ICC	0.70	0.79	0.42	0.59	0.51	0.72	0.74	0.49
ST	CV%	19.9	19.6	40.8	24.7	31.4	55.9	41.6	129.2
	ICC	0.90	0.78	0.26	0.72	0.55	0.49	0.62	0.34
BF	CV%	21.7	29.5	35.4	22.0	25.1	41.0	37.8	60.3
	ICC	0.89	0.49	0.48	0.49	0.65	0.53	0.67	0.61

VM=vastus medialis, RF= rectus femoris, VL= vastus lateralis, SM= semimembranosus, ST= semitendinosus, BF= biceps femoris

3.4 DISCUSSION

It would appear that this is the first study to assess the reliability of electromyographic and kinetic variables using sEMG and kinetic data during an unanticipated cutting manoeuvre in female footballers. Most kinetic variables showed very strong test-retest reliability with a lack of significant mean difference and large to nearly perfect ICC's (≥ 0.5) between testing sessions. Loading rates and time to peak forces (CV = 17.33% - 24.51%) showed greater typical error than GRF and GCT (CV = 4.11% - 10.23%). The majority of electromyographic variables showed similar ICC (≥ 0.5) to the measured kinetic variables. However, some electromyographic variables displayed weaker reliability, than the measured kinetic variables, reflected by significant mean differences between testing sessions and higher typical errors (CV = 14% - 129.2%).

3.4.1 Kinetic Variables

The means of the measured kinetic variables displayed a lack of significant differences between testing sessions, suggesting that systematic bias was not present during the study. The lack of systematic bias would suggest that the habituation session performed by the participants was adequate, and that there were no fatiguing effects from the repetition of the unanticipated cutting manoeuvre (Hopkins, 2000). Similar to previous research, the majority of kinetic variables displayed large to nearly perfect correlations, with the greatest ICC observed for peak vGRF (Alenezi et al., 2014; Ferber et al, 2002). Research utilising pre-planned dynamic tasks such as running or cutting have identified nearly perfect ICC values for vGRF (0.92-0.96) and apGRF (0.91), which was replicated by the female footballers performing the unanticipated cutting manoeuvre in the current study (vGRF = 0.96, apGRF = 0.92) (Alenezi et al., 2014; Ferber et al., 2002; Walsh et al., 2006). This shows that the unanticipated nature of the task in the current study did not detrimentally affect the ICC of kinetic data, in comparison with previous research utilising pre-planned cutting and running tasks (Alenezi et al., 2014; Ferber et al., 2002, Walsh et al., 2006). From a kinetic viewpoint, previous research has focused on purely GRF's (vertical, horizontal and sagittal) and joint angles during dynamic tasks (Alenezi et al., 2014; Ferber et al, 2002; Walsh et al., 2006), rather than the wider range of kinetic variables the current study chose to investigate, which makes direct comparison with previous literature somewhat challenging. However, the current study provides reliability data to allow future research to utilise unanticipated dynamic tasks to determine changes in performance or the effects of fatigue or a training intervention. Additionally, the data have provided practitioners with typical error values for a range of kinetic variables, from which measures from routine monitoring can be interpreted to distinguish between actual worthwhile changes and fluctuations resulting from noise, which provide practical applications for injury prevention, sports performance and rehabilitation.

Some typical error values were < 10% and in-line with previous research (peak vGRF, peak apGRF, and GCT). However, time to peak force and loading rates displayed greater variance with larger typical error than the other kinetic variables. As well as larger typical errors, loading rates also displayed larger variance in comparison to other kinetic variables. This heightened between-subject variation could have been caused by differences in subject approach speed or body composition; faster approaches result in greater loading (Vanrenterghem et al., 2012) and the larger the loading rate the lower the body mass (De Sousa et al., 2015). Besier et al. (2001) studied the anticipatory effects of cutting and observed greater knee flexion angles during unanticipated cutting manoeuvres, which has previously been linked to lower vGRF, which could also affect loading rates (Podraza & White, 2010; Yu, Lin & Garrett, 2006). The variance in loading rates could also be related to the reactive nature of the unanticipated cutting manoeuvre in comparison to the pre-planned cutting and running manoeuvres utilised in previous research (Alenezi et al., 2014; Ferber et al., 2002, Walsh et al., 2006). Although the loading rates of participants in the current study displayed greater typical error and larger variance than any other kinetic variables, loading rates displayed large and very large ICC's. Specifically, vGRF loading rate also displayed the smallest mean difference of all the kinetic variables showing reproducibility of the measure.

The typical errors of the kinetic variables measured in the current study were greater than previous research (Alenezi et al., 2014; Ferber et al, 2002; Walsh et al., 2006). This shows greater random variation in the kinetic variables than previous research. Research by Cormack et al. (2008) studied the reliability of various kinetic variables including; power, vGRF, jump height and flight time, during single and repeated countermovement jumps. The researchers observed typical error for inter-day peak vertical ground reaction force (CV = 2.2%) to be lower than those reported in the current study (CV = 4.11%) (Cormack et al., 2008). The greatest typical error in the current study (loading rates and time to peak force) was similar to the average findings of previous research assessing reliability of various kinetic variables. Hori et al. (2009) observed lower ICC and higher typical errors for variables such as time to peak force and loading rate compared with peak vGRF, peak power and peak velocity. The typical error of loading rate represented in the data of Hori et al. (2009) was similar to the current study (CV = 24% *versus* 24.21% respectively), but the typical error for time to peak force was greater in the current study than Hori et al. (2009)

(CV = 20.55% *versus* 11.4% respectively). Hori et al. (2009) utilised a range of sampling frequencies (25 Hz – 500 Hz) and observed strong positive correlation for loading rate (*r* > 0.99) and vGRF (*r* > 0.96) between 500 Hz and all other sampling frequencies, noticing a break-off point of 200 Hz where any sampling frequency lower than 200 Hz displayed mean differences > 2%. As Hori et al. (2009) used much lower sampling frequencies; the quality of data would not be as robust as the current study sampling at 1000 Hz. Therefore, based on sampling frequency and the correlations of Hori et al. (2009) similar or greater reliability results could be expected in the current study.

The difference in outcome of some kinetic variables in the current study compared to the previous research utilising countermovement jumps could be due to the task performance. Specifically, the participants from the research by Hori et al. (2009) performed a pre-planned countermovement jump which is vertical in nature and tests power, whereas the cutting task in the current study was unanticipated in nature, produces mostly horizontal force, and tests reactive agility. There are many aspects of the unanticipated cutting manoeuvre that could have caused higher typical error for some kinetic variables including; speed of movement and increased task demands. The speed of movement at which the unanticipated cutting manoeuvre was performed could have had an effect on the higher typical error computed for vGRF and time to peak vGRF. Vanrenterghem et al. (2012) studied the effect of running speed (2 - 5m/s) on task achievement and mechanical loading of a pre-planned cutting manoeuvre. The researchers observed lower ground contact times, larger GRF and greater variance of outcomes with increasing speeds (Vanrenterghem et al., 2012). The researchers determined that performing a cutting manoeuvre at 4 m/s (the velocity used in the current study), provided a balance between mechanical loading and task achievement. Lower speeds would be preferred for task achievement and reproducibility; however they do not load the knee sufficiently during dynamic tasks assessing knee loading mechanisms, or replicate the speed of football match-play (Vanrenterghem et al., 2012).

As well as the speed of movement, the consistency of performance of an unanticipated cutting manoeuvre must be considered when interpreting typical error. Due to the reactive nature and task demands of the unanticipated cutting manoeuvre (Besier et al., 2001); higher typical error could be present. Previous researchers have observed a learned feed-forward motor control mechanism in pre-planned actions that is utilised as a pre-programmed plan by the central nervous system (Beaulieu & Xu, 2008; Besier et al., 2001b; Bouisset & Zattara, 1987). The anticipation of a task can produce an altered reflex response and postural adjustments to provide control and effectively complete task performance. It has been observed that reactive tasks, such as an unanticipated cutting manoeuvre, require the longest time for postural adjustments (Weiss & Dickin, 2013). The time it takes an individual to perceive and process a stimulus, and consequently formulate a decision and modulate a response to meet the requirements of a task, can be dictated by physiological (intensity of perception, speed of information processing and transmitting, and neuromechanical capabilities) and psychological (past experiences, current state of mind, and fatigue condition) conditions (McLean et al., 2010; Ozyemisci-Taskiran et al., 2008). In an unanticipated task these physiological and psychological conditions may vary greater than pre-planned tasks. In comparison to pre-planned dynamic tasks, unanticipated cutting manoeuvres could display greater typical error and trial to trial fluctuations due to the increased task demands (sprinting, cognitive decision making, sudden change of direction). The unanticipated cutting manoeuvre also produces greater degrees of freedom arising from the large range of ways the muscles, joints and limbs can be controlled through motor co-ordination and the considerable set of possible solutions available to participants performing the reactive task (Todorov & Jordan, 2002). Despite the unanticipated cutting manoeuvre being potentially the most difficult task for reproducibility due to the multiple constraints, the current study was able to show acceptable levels of reliability.

3.4.2 Electromyographic Variables

In the current study, the majority of electromyographic variables displayed a lack of significant differences between testing sessions, suggesting an absence of any systematic bias, supporting the need for an adequate habituation session. It also suggests that the participants did not experience neuromuscular fatigue during the repeated performance of trials, and the participant's levels of effort and motivation were similar across testing sessions (Hopkins, 2000). The majority of electromyographic variables displayed large to nearly perfect ICC showing repeatability of the measure, however most of the variables displayed CV ≥ 10% displaying some typical error.

The current study observed the majority of electromyographic variables of the hamstrings and quadriceps muscle groups displayed a large to nearly perfect correlation (ICC ≥ 0.5). Previous research exploring the reliability of sEMG for measuring muscular activation has observed slightly higher ICC values, with all characteristics ranging from large (0.5) to nearly perfect (0.9) ICCs (Bolgla et al., 2010; Fauth et al., 2010; Knutson et al., 1994;

Larsson et al., 2003; Pitcher et al., 2008; Smoliga et al., 2010). However, the majority of these studies have analysed maximal voluntary isometric contractions, not dynamic tasks. Those studies that have used a variety of dynamic tasks reported weaker reliability represented by lower ICC's (Fauth et al., 2010; Houck, 2003; Smoliga et al., 2010). For example, Houck (2003) observed a pattern of decreasing ICC with increasing task complexity; from straight running, to sidestep cutting, to crossover cutting (Houck, 2003). Therefore, the lower ICC values observed in the current research compared with previous research could be attributed to the greater task demands and complexity of the unanticipated cutting manoeuvre in comparison with isometric contractions, straight running and pre-planned sidestep cutting utilised in previous research (Fauth et al., 2010; Goodwin et al., 1999; Houck, 2003; Smoliga et al., 2010). The rate of change of muscle length and tension affects the magnitude of sEMG measures (Goodwin et al., 1999; Houck, 2003); the rapid and unanticipated movement in the current study could have predisposed participants to varying patterns of motor unit recruitment and greater variance in muscle activation due to the larger set of possible motor co-ordination solutions, compared with slow, pre-planned and controlled tasks. The dynamic task in the current study was unanticipated, which is novel to previous research that has only examined the reliability of pre-planned tasks and MVIC (Bolgla et al., 2010; Fauth et al., 2010; Knutson et al., 1994; Larsson et al., 2003; Pitcher et al., 2008; Smoliga et al., 2010). Besier et al. (2001) studied the anticipatory effects of cutting and concluded that athletes performing unanticipated cutting manoeuvres display greater knee flexion and twice the magnitude of varus/valgus and internal/external moments compared to pre-planned manoeuvres (Besier et al., 2001). An unanticipated cutting manoeuvre will produce a random and reactive pattern of muscle activation, whereas a pre-planned, simple, and closed skill exercise is likely to produce more consistent muscle activation (Besier et al., 2001, Goodwin et al., 1999). Therefore, the reactive nature of the task and the difference in joint position and velocity during an unanticipated manoeuvre compared to pre-planned manoeuvres could attribute to a greater variance of ICC values (Besier et al., 2001, Goodwin et al., 1999).

Also, ICC statistics can be affected by the heterogeneity of the values between participants and the sample used for measurement (Hopkins, 2000), with samples of a homogenous nature demonstrating lower ICC values. The participants in the current study are heterogenous in some ways (i.e. position specific fitness, age) but reflect a more homogeneous sample (i.e. SWWFL female footballers, quantity of training, level of club, sex, and type of training), whereas previous research has used heterogeneous samples (Bolgla et al., 2010; Fauth et al., 2010; Knutson et al., 1994; Larsson et al., 2003; Pitcher et al., 2008; Smoliga et al., 2010). This could provide explanation for the low ICC values for some kinetic and electromyographic variables in the current study as it is less likely that a homogenous sample will maintain a rank order (Hopkins, 2000). Atkinson & Nevill (1998) reported that data from a less heterogenous sample produces a poorer ICC measure. Therefore, ICC includes the variance term for individuals and is affected by heterogeneity. Applying this to the current study, the strength of using ICC on a homogenous sample rather than a heterogenous sample is that with a heterogenous sample a high correlation may still mean unacceptable measurement error overestimation of the reliability of a measure (Atkinson & Nevill, 1998). Similar to the findings of Goodwin et al. (1999), all ICC values ≤ 0.5 were for sEMG measures of the hamstrings, with the exception of the RF activation during 0 – 30 ms, showing weaker reliability of the hamstrings muscles compared to the quadriceps muscles. This could be due to bi-articulation of the hamstrings and the eccentric action of the hamstrings to decelerate flexion of the femur at the hip and extension of the tibia at the knee (Goodwin et al., 1999).

The electromyographic variables in the current study displayed higher typical error than previous research utilising dynamic running tasks (Fauth et al., 2010; Smoliga et al., 2010). Smoliga et al. (2010) studied the intra-session reliability of sEMG of 12 muscle sites of male runners including; VL, RF and SM. The typical error measurement values for RF, VL, and SM ranged from 9% to 29%, whereas the current study computed typical values of these muscles to range from 18.4% to 55.3% across all time phases (Smoliga et al., 2010). However, the study by Smoliga et al. (2010) utilised a range of muscles from the leg, arm and torso and a linear treadmill running protocol. When comparing the reproducibility of muscle pre-activation, the participants in the current study produced a larger typical error (CV% = 19.9% - 55.3%) than previous literature utilising a pre-planned cutting task (CV% = 20.50% - 45.60%) (Fauth et al., 2010), for RF, VL, lateral and medial hamstrings displaying lower reliability than previous research. However, CV% observed during the unanticipated cutting manoeuvre in the current study were within close range to the pre-planned manoeuvre of previous research considering the greater task demands and reactive nature of the unanticipated cutting manoeuvre (Fauth et al., 2010). The majority of electromyographic variables that displayed larger typical error than previous research studying pre-planned cutting manoeuvres were measures of hamstrings activation, which could be due to the articulations of the hamstrings and the role of the hamstring in the movement (Fauth et al., 2010), as well as the variance in protocols.

3.5 PRACTICAL APPLICATIONS

The current study has provided data on the reliability of electromyographic and kinetic data measurements for electromyographic and kinetic variables of female footballers performing an unanticipated cutting manoeuvre. For the majority of characteristics, large to perfect ICCs were reported, as well as no significant mean differences. Typical errors of kinetic and electromyographic variables were greater than those reported in previous research, with electromyographic variables showing the greatest variance (Bolgla et al., 2010; Cormack et al., 2008; Hori et al., 2009; Knutson et al., 1994; Larsson et al., 2003; Fauth et al., 2010; Pitcher et al., 2008; Smoliga et al., 2010). Muscle activation is a physiological measure from which we would expect greater amounts of natural variation. All participants in the current study and study two and three were post-pubertal, however training and playing age is greater in the participants of the current study. While previous literature has demonstrated that younger children are typically associated with greater movement variability (Gerodimos et al., 2008), there is no literature showing significant differences in neuromuscular performance between 16 year old and 21 year old females. Neuromuscular performance changes with puberty and training (Myer et al., 2011; Quatman-Yates et al., 2012). As all participants were post-pubertal and activity logs were collated to ensure the participants were not performing any other type of intervention training, the findings from the current study can be applied to studies two and three (Myer et al., 2011; Quatman-Yates et al., 2012). Previous research has observed similar reliability in children and adolescents for a range of kinetic and electromyographic outcomes (Oksanen et al., 2007; Zaino & McCoy, 2008). Further to this, a standardised approach speed, electrode configuration and angle of cut were enforced along with inclusion and exclusion criteria to ensure consistency of the measurement of kinetic and electromyographic variables throughout the studies. Therefore, in line with previous research and standards of reliability, all kinetic and electromyographic variables are deemed acceptable to use in subsequent studies. The protocol of the current study will be used in future research to study the effect of an acute bout of exercise on the electromyographic and kinetic variables that may predispose female footballers to ACL injury. Further to this, the effect of an injury prevention programme on the electromyographic and kinetic variables will also be measured.

3.6 LIMITATIONS

- *Number of test-re-test sessions* - The current study utilised a test-retest reliability study design which required participants to attend a habituation session and a further two testing sessions separated by 5 days. A greater number of testing sessions would have decreased the coefficient of variation (Hopkins, 2001). Hopkins suggests that if your typical error (CV%) is greater than the smallest worthwhile change, then repeat the test with the athlete several times and average the scores to reduce the noise i.e. four tests halves the noise (Hopkins, 2001). A study by Pyne observed that by increasing the number of trials you can decrease CV% therefore a greater number of trials in the current study could have reduced the CV% (Pyne et al., 2004). A test-retest design, as used in the current study, can make is more challenging to confidently detect systematic bias (e.g. learning effects) and the stabilization of the noise of the measured..Systematic variation could have occurred across the two testing sessions through improper use of the testing equipment by the researcher. If the protocol was not set up with exact precision in each testing session for example; placement of electrodes onto the participant's skin, then systematic variation could have occurred. To reduce the chances of systematic errors within the reliability study, all participants attended an habituation session prior to data collection, the same researcher applied all electrodes, skin preparation was performed by the same researcher each time, the protocol was measured for set-up including cutting angle, approach distance, and the positioning of the SmartSpeed system gates, and a marker pen was used to identify electrode placement. Further to this, the current study utilised techniques to try and control the unknown and unpredictable chance of random error including technological and biological errors. Criteria was established to reduce the chances of biological error including; participants were instructed not to: i) perform vigorous exercise 48 hours prior to testing sessions, ii) drink alcohol in the final 24 hours before testing, iii) drink caffeine in the final 12 hours before testing. Additionally, participants were tested at the same time of day for each testing session to minimise fluctuations in neuromuscular function due to circadian rhythms (Schildt et al., 2015; Teo et al., 2011), and inclusion and exclusion criteria was established including; parameters for the performance of the unanticipated cutting manoeuvre.

- *Force platform specification* - The current study and subsequent studies utilised a PASCO portable force plate with technological differences in comparison to a higher end force plate (e.g. KISTLER or AMTI), which may have affected the accuracy and validity of the data. The submounted force platform available for use in the laboratory had a larger surface area for capturing data which may have produced less biomechanical alterations and hesitation from the participants who were focusing on making contact with the platform (AMTI), this may have affected the validity of the outcome measures (AMTI). The current study tried to control for a smaller surface area using a habituation session in which participants were able to run seven trials of the unanticipated cutting manoeuvre with the PASCO portable force platform.

As well as this, higher end force plates have a greater capacity to measure potentially large forces produced during a sporting manoeuvre, such as the unanticipated cutting manoeuvre. A platform such as the KISTLER sub-mounted platform in the laboratory has piezoelectric crystals spread evenly across the plate, whereas the PASCO portable force platform has a strain gauge in each corner, which could have affected the accuracy of the force measure (AMTI). With strain gauges, any deformation of the measuring body is converted to a change in resistance of the strain gauge, and a signal is then generated, whereas piezoelectric crystals generate an electric charge directly proportionate to a force when under load (HBM). The charge produced by the crystals is converted to produce a proportional output voltage. Strain gauges tend to provide better stability, reference force measurement, and higher linearity, and are suggested better for long term or static measures, and piezoelectric sensors tend to be better suited to dynamic applications due to a higher natural frequency, and virtually no displacement (HBM). With a platform such as the KISTLER force platform there is often a drift of 1N/min of the measurement task. The circuit used with strain gauges compensates for error effects (i.e. temperature) enabling accurate static calibration (AZO Sensors). In the current study, the researcher turned the PASCO portable force platform on before use to enable the heating up of the strain gauges attempting to negate drift.

Although piezoelectric crystals have been suggested better suited for the measurement of kinetic variables during dynamic tasks (HBM), previous research by Walsh et al. (2006) determined that a portable force platform produces similar results and high correlations for peak landing force, peak take-off force, and time to maximum force with Pearson correlation coefficients ranging from 0.94 - 0.97 and nearly perfect ICC's for both portable (0.92 - 0.99) and sub-mounted (0.95 - 0.98) force platforms during drop landing and drop jump tasks. This shows that any compensatory mechanisms that may be present when using a portable force platform and the specification differences are insignificant in the measurements of peak force and time to peak force (Walsh et al., 2006). Additionally, the portable force platform is valid and reliable in measuring peak landing force, peak take-off force, and time to maximum force during drop jump and drop landing tasks. Further research by Silveira et al. (2016) established that there was good agreement between a PASCO portable force platform and gold standard platforms for measuring vertical and anterior-posterior components (impulse, peak force and time to peak force). Although less precision and accuracy was observed of the anterior-posterior in comparison to the vertical components, errors were found to be systematic showing good repeatability of the measures (Silveira et al., 2016).

3.7 KEY FINDINGS

1. There were no significant differences in the mean score and large to nearly perfect ICC for all kinetic variables. The majority of kinetic variables displayed a CV% of less than 10%, with the exception of loading rates. The majority of

electromyographic variables met standards of reliability. In comparison to previous research, electromyographic variables displayed a greater range of typical error.

2. For both electromyographic and kinetic variables, the typical error (CV%) could be utilised to determine if a meaningful change has occurred with an acute bout of exercise or injury prevention programme. If the change score of the participant is greater than the characteristics' typical error (CV%) then it could be determined that a meaningful change has occurred as a result of the acute bout of exercise or injury prevention programme, rather than the noise of measurement.

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PRELUDE

Study 1 examined and identified the reliability of various kinetic and electromyographic variables of female footballers performing an unanticipated cutting manoeuvre. The study showed that the majority of variables displayed large to nearly perfect ICC. The majority of kinetic variables displayed acceptable CV with the exception of force loading rates. Electromyographic variables displayed a greater range of typical error in comparison to the kinetic variables, and previous research on electromyographic measures during dynamic tasks. However, the CV% reported in this study can be used in studies 2 and 3 to determine whether changes in any of the measures are due to acute fatigue, or simply reflect random variation. Study 2 will use the methods deemed reliable from study 1 to examine the effect of acute fatigue on the kinetic and electromyographic variables of female footballers performing an unanticipated cutting manoeuvre.

Chapter 4: Study 2

The Effect of Fatigue on the Kinetic and Electropmyographic Variables Associated with ACL Injury Risk in Youth Female Footballers during an Unanticipated Cutting Manoeuvre

4.1 INTRODUCTION

Owing to the knowledge that a greater number of injuries occur towards the end of football match-play, it can be suggested that fatigue is a potential risk factor for injury (Ekstrand et al., 2009; Hiemstra et al., 2001; Junge & Dvorak, 2007). Studies have determined detrimental effects of fatigue on lower limb kinetic and electromyographic variables in female footballers including; increased GRF and decreased knee flexion angles during landing and cutting manoeuvres (Benjaminse et al., 2008; Chagela et al., 2012; Cortes et al., 2011; Ekstrand et al., 2009; Gear et al., 2011; Patrek et al., 2011; Smith et al., 2009). However, the relevance of these studies to youth female footballers is limited as many studies have a population sample of adults and it is well documented that adults experience greater fatigability than children and adolescents (Ratel & Martin, 2015). A limited amount of research has investigated the effect of acute fatigue on lower limb mechanics of an unanticipated cutting manoeuvre, results from such research are contrasting with some researchers observing effects of acute fatigue and anticipation as separate entities, but no combined effects (Collins et al., 2016; Khalid et al., 2015; Landry et al., 2007). However, existing research has not used football specific fatigue protocols, instead utilising gradual and intermittent generic acute fatigue protocols. Therefore these studies arguably do not mimic the physical demands of football, and consequently the specific fatigue experienced by footballers (Brophy et al., 2010; Cowley et al., 2006; Landry et al., 2007; Silvers et al., 2007).

In football match-play, acute fatigue is experienced by players in three phases; (i) temporary fatigue after short term intense periods, (ii) the initial phase of the second half, and (iii) at the end of the match (Mohr et al., 2005). Research on temporary fatigue of top class male and female footballers showed that sprint performance was significantly reduced immediately following an intense bout of match-play (Krustrup et al., 2003; Mohr et al., 2005). This temporary fatigue can be related to an accumulation of potassium within the muscles. Previous research has identified elevated potassium concentration at the point of exhaustion after intense short-term exercise (5 min) in male and female athletes, which has been claimed to be high enough to depolarise the muscle membrane potential and consequently reduce force production (Cairnes & Dulhunty, 1995; Nielsen et al., 2004; Mohr et al., 2004). Researchers have also observed a pattern of decreased work rate and high intensity exercise in the first 5 minutes of the second half of match-play for male and female footballers, which has been related to decreased muscle temperature from the half time interval (Krustrup et al., 2002; Krustrup et al., 2003; Krustrup & Bangsbo, 2001). At the end of the match, researchers have observed a decline in high intensity exercise towards the final 15 minutes in male footballers, and the final 30 minutes of the game in female footballers (Krustrup et al, 2003). This phase of fatigue has been related to peripheral fatigue and depleted muscle glycogen stores towards the end of football match-play (Krustrup et al, 2003; Mohr et al., 2005).

Fatigue at the end of match-play correlates with research that shows female footballers incur significantly more injuries in the final 30 minutes of each half in comparison to the first 15 minutes of each half (Krustrup et al., 2002). Not only do female footballers experience the final phase of fatigue earlier in the match, but their risk of ACL injury due to fatigue is speculated to be greater than males (Jollenbeck et al., 2010). Research studying the effects of fatigue on kinetic and electromyographic variables associated with ACL injury risk has shown fatigue to elicit a greater negative influence on females than males (Gehring et al., 2009; Jollenbeck et al., 2010). Specifically, research has identified the risk of ACL injury to be up to 2.5 times greater in females, compared to males, under fatigued conditions. Within the studies, females displayed decreased muscle force and strength production, increased quadriceps dominance, decreased hamstrings activation, increased knee abduction, and earlier activation of medial thigh muscles than lateral thigh muscles with fatigue (Gehring et al., 2009; Jollenbeck et al., 2010).

Those studies that have measured kinetic and electromyographic variabes during cutting manoeuvres have reported detrimental effects of acute fatigue (Lucci et al., 2011; Sanna & O'Connor, 2008; Shenoy, 2010; Weiss & Dickin, 2014). These studies have utilised a range of manoeuvres including; pre-planned sidestep cutting (Sanna & O'Connor, 2008), unanticipated cutting (Lucci et al., 2011; Weiss & Dickin, 2014), and drop-jump side cutting (Shenoy, 2010). Only one of these studies identified the effect of fatigue on electromyographic variables (Shenoy, 2010). A study on recreational and professional athletes observed fatigue-related decreases in activation of vastus medialis (VM) and gluteal muscles during a pre-planned drop-jump side cutting manoeuvre. In this study, fatigue was produced by loaded barbell squats at a rate of 50 squats per minute until task failure (Shenoy, 2010). Lower activation of medial thigh musculature, such as VM, will increase knee abduction and valgus loads placing greater stress on the ACL, suggesting that neuromuscular fatigue could increase the risk of ACL injury (Shenoy, 2010). Those studying the effects of acute fatigue on the performance of an unanticipated cutting manoeuvre have investigated lower limb mechanical changes including joint angles and moments (Lucci et al., 2011; Weiss & Dickin, 2014). These studies have identified detrimental effects of fatigue on various lower limb mechanics including; decreased knee and hip flexion angles, and decreased hip adductor, and knee extension moments. However, these studies tested older female athletes and utilised generic intermittent shuttle-based fatigue protocols, which fail to replicate the physiologic and metabolic demands of football match-play. Therefore, these studies have not replicated the energy demands of football match-play. Contrary to the findings by Weiss & Dickin (2014) and Lucci et al. (2011), Sanna & O'Connor (2008) observed marginal lower limb mechanical changes in adult female footballers performing a pre-planned sidestep cutting manoeuvre following a progressive shuttle run test and counter movement jump fatigue protocol. Weiss and Dickin (2014) and Lucci et al. (2011) utilised unanticipated cutting manoeuvres, whereas Sanna & O'Connor (2008) utilised a pre-planned manoeuvre. Previous research (Besier et al., 2001; Mornieux et al., 2014; Weinhandl et al., 2014) has established anticipatory effects of cutting which could have caused the difference in findings of fatigue related lower limb mechanical changes (Lucci et al., 2011; Sanna & O'Connor, 2008; Weiss & Dickin, 2014).

Although previous research has observed detrimental effects of fatigue on various kinetic and electromyographic variables during cutting manoeuvres, only a few ACL injury risk factors have been investigated such as; electromyographic activation of gluteal and anterior thigh musculature, lower limb mechanics and vGRF (Cortes et al., 2011; Lucci et al., 2011; Sanna O'Connor, 2008; Shenoy , 2010; Weiss & Dickin, 2014). There has been no research investigating the effect of football-specific fatigue on youth female footballers, and very few studies have utilised an unanticipated cutting manoeuvre. Therefore, the effect of fatigue on kinetic and electromyographic variables of youth female footballers performing an unanticipated cutting manoeuvre is yet to be elucidated. Thus the aims of the current study were;

- To quantify the effect of fatigue on kinetic variables of youth female footballers performing an unanticipated cutting manoeuvre; specifically focusing on peak GRF, loading rates and GCT and the implications on the risk of ACL injury
- To quantify the effect of fatigue on electromyographic variables of youth female footballers performing an unanticipated cutting manoeuvre; specifically focusing on H:Q co-activation ratios, pre-activation and immediate feedback mechanisms of the quadriceps and hamstrings muscles, medial:lateral quadriceps and hamstrings activation, and the implications of these variables on the risk of ACL injury

4.2 METHODS

4.2.1 Participants

Twenty four youth female footballers who play in a women's football development academy (U19) (mean ± *sd*: age 17.87 ± 1.05 years, stature 162 ± 5.00 cm, body mass 62.30 ± 9.96 kg) participated in the current study. All players participated in at least three training sessions and two competitive matches each week. None of the participants reported performing any injury prevention training. Participant recruitment followed the methods stated in section 3.2.

4.2.2 Habituation Session

Participants attended a single habituation session at their facility as outlined in section 3.2.2. Participants then attended one data collection session for the current study. The researchers instructed the participants to attend the testing sessions in shorts, t-shirt, and comfortable running shoes. For the data collection session, participants performed the unanticipated cutting manoeuvre protocol with kinetic and electromyographic data collected as outlined in section 3.2.3

4.2.3 Data Collection Testing Session

Figure 4.1 outlines the testing protocol. Immediately after the participants had completed the testing session protocol for study 1 as outlined in pages 122-131, the youth female footballers performed the SAFT90, a simulated match-play protocol (section 4.2.4). Once the participants had completed the fatigue protocol, they then performed the same testing protocol as they had in the non-fatigued state to assess the effect of fatigue on the kinetic and electromyographic variables of female footballers during unanticipated cutting manoeuvres.

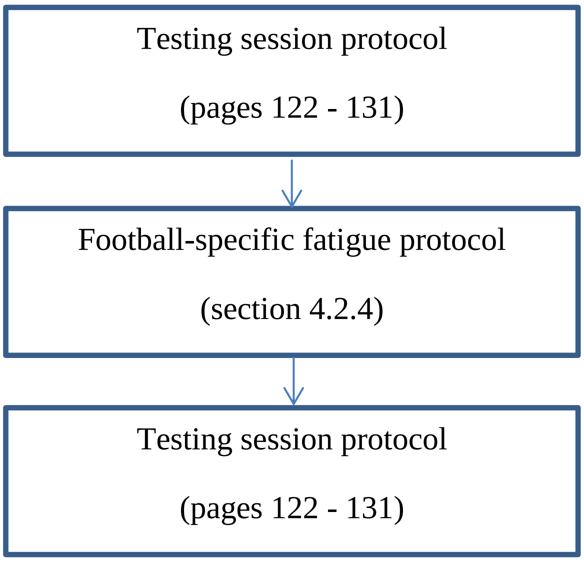

Figure 4.1 Testing protocol

4.2.4 Football Specific Fatigue Protocol

The SAFT90 is a multidirectional, intermittent football specific fatigue protocol based upon match analysis of 2007 English Championship League games (Prozone ®). The protocol incorporates utility movements and frequent accelerations and decelerations over a 20 m shuttle run with the incorporation of four positioned poles that subjects navigate (Figure 4.1). It was developed to replicate the demands of football match-play in professional male players (Prozone®) and has been validated by Lovell et al. (2008). The current study utilised a modified SAFT90 protocol to better replicate the energy expenditure of footballers. Specifically, in addition to the running-based activities in the original SAFT90, the modified SAFT90 utilised in the current study also included 26 instep passes from and to a feeder and eight headers with a jump initiated by a feeder throw, spread evenly across the 90 minute protocol based on activity data by Krustrup et al. (2005). The modified SAFT90 also included a 3 M cut to the left or right at the end of the original protocol. Participants alternated directions of their cut each time they reached the end of the protocol set-up.

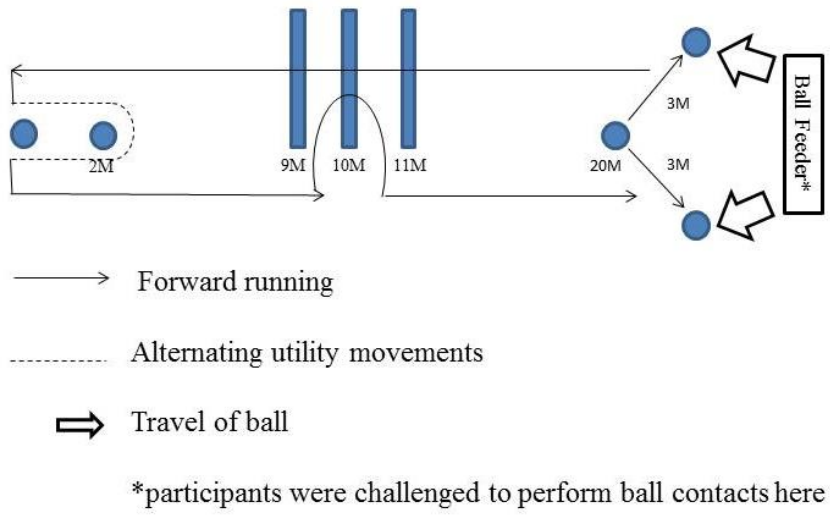

Figure 4.2 Modified SAFT90 protocol set-up

4.2.5 Statistical Analysis

Shapiro-Wilks analysis was used to establish normality of data. Box plot analyses were calculated using SPSS to remove outliers, with extreme values displayed outside of the box plot being removed from the data set. Descriptive statistics (mean ± *sd*) were calculated pre and post fatigue. Inferential statistics were used to examine the qualitative meaning of the observed changes in test variables, with data presented as the mean of the individual change and 90% confidence interval. The smallest worthwhile change was used to determine whether the observed changes were considered negative, trivial or positive and was calculated as a change in score standardised to 0.20 of the between-subject standard deviation. An online spreadsheet (Hopkins, 2007) was used to calculate the probabilistic inference of each observed change being greater than the smallest worthwhile effect using the thresholds 25 - 75% as possibly, 75 - 95% as likely, 95 - 99.5% as very likely and > 99.5% as most likely (Hopkins, Marshalll, Batterham & Hanin, 2009). The outcome was deemed unclear where the 90% confidence intervals of the mean change overlapped both positive and negative outcomes, otherwise the outcome was clear and inference reported as the category (negative, trivial, or positive) where the greatest probability was observed.

4.3 RESULTS

4.3.1 Kinetic Variables

Shapiro-Wilks analysis showed that the data was normally distributed. The descriptive statistics for kinetic variables of youth female footballers (n = 24) performing an unanticipated cutting manoeuvre pre and post-fatigue are presented in Appendix 4.1. Inferential outcomes are shown in table 4.1 and figure 4.3 with mean difference (± 90% CI) from pre to post fatigue. Peak vGRF and peak apGRF demonstrated *possible* and *very likely* increases respectively, following the simulated match-play protocol. The apGRF loading rate, time to peak vGRF and GCT showed *likely* and *very likely* decreases following the simulated match-play protocol.

Table 4.1 Mean difference (90% CI) with fatigue and inferential statistics of the effect of football specific fatigue on the kinetic variables of youth female footballers performing an unanticipated cutting manoeuvre

Kinetic variable	Mean difference (± 90% CI)	Inferential statistic
Peak vGRF (BW)	0.08 (-0.05 – 0.002)	possibly positive
Peak apGRF (BW)	0.09 (0.02 – 0.16)	very likely positive
vGRF loading rate (N/s)	-1193 (-3000 – 650)	unclear
apGRF loading rate (N/s)	-462 (-1000 – 88)	likely negative
Time to peak vGRF (s)	-0.02 (-0.03 – 0.01)	very likely negative
Time to peak apGRF (s)	-0.01 (-0.023 – 0.0047)	unclear
GCT (s)	-0.03 (-0.044 - -0.0098)	very likely negative

vGRF = vertical ground reaction force, apGRF = anterior posterior ground reaction force, GCT = ground contact time

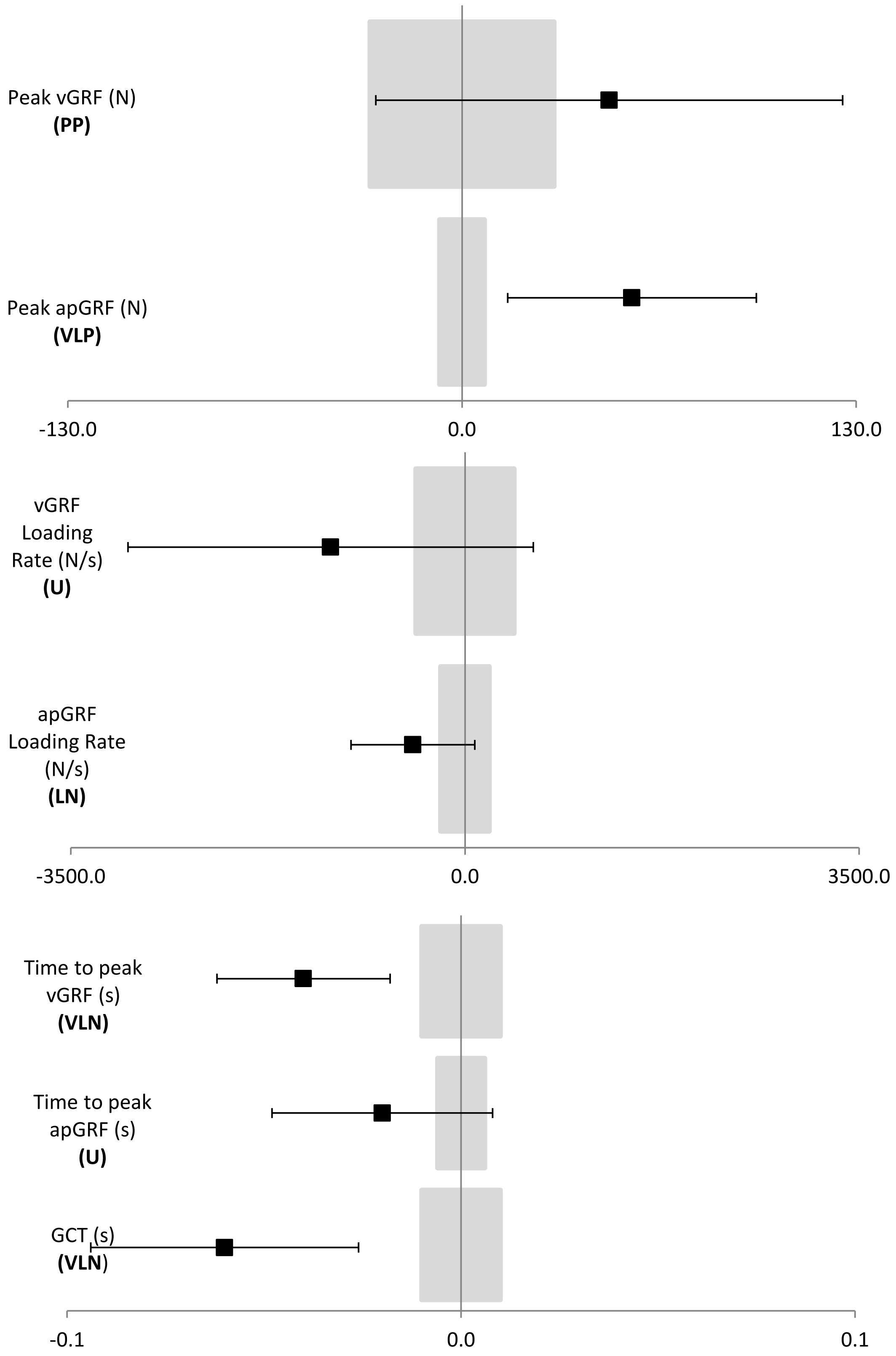

Figure 4.3 Mean difference (90% CI) between pre and post football specific fatigue protocol on the kinetic variables of youth female footballers performing an unanticipated cutting manoeuvre. *vGRF = vertical ground reaction force, apGRF = anterior posterior ground reaction force, GCT = ground contact time, U = unclear, VLN = very likely negative, LN = likely negative, VLP = very likely positive, PP = possibly positive*

4.3.2 Electromyographic Variables

Descriptive statistics for electromyographic variables of youth female footballers performing an unanticipated cutting manoeuvre pre and post-fatigue are presented in Appendix 4.1. Mean difference (± 90% CI) of muscle activation from pre to post fatigue are presented in appendix 4.1. Following the acute fatigue protocol, the majority of muscles showed *likely* or *very likely* increases in activation throughout the latency phases. The effect of the simulated match-play protocol on quadriceps activation was mostly *negative* (*most likely, very likely*), and the effect of the simulated match-play protocol on hamstrings activation were mostly *positive* (*very likely*, *likely*, *possibly*) or *trivial* (*most likely, very likely, likely)* (Figure 4.4). Inferences during feed-forward and immediate feedback mechanisms are shown in figure 4.3. Inferential outcomes for H:Q co-activation ratios following a simulated match-play protocol were *most likely trivial* (PA, 0 – 30 ms), *unclear* (31 – 60 ms and 61 – 90 ms), and *likely negative* (91 – 120 ms).

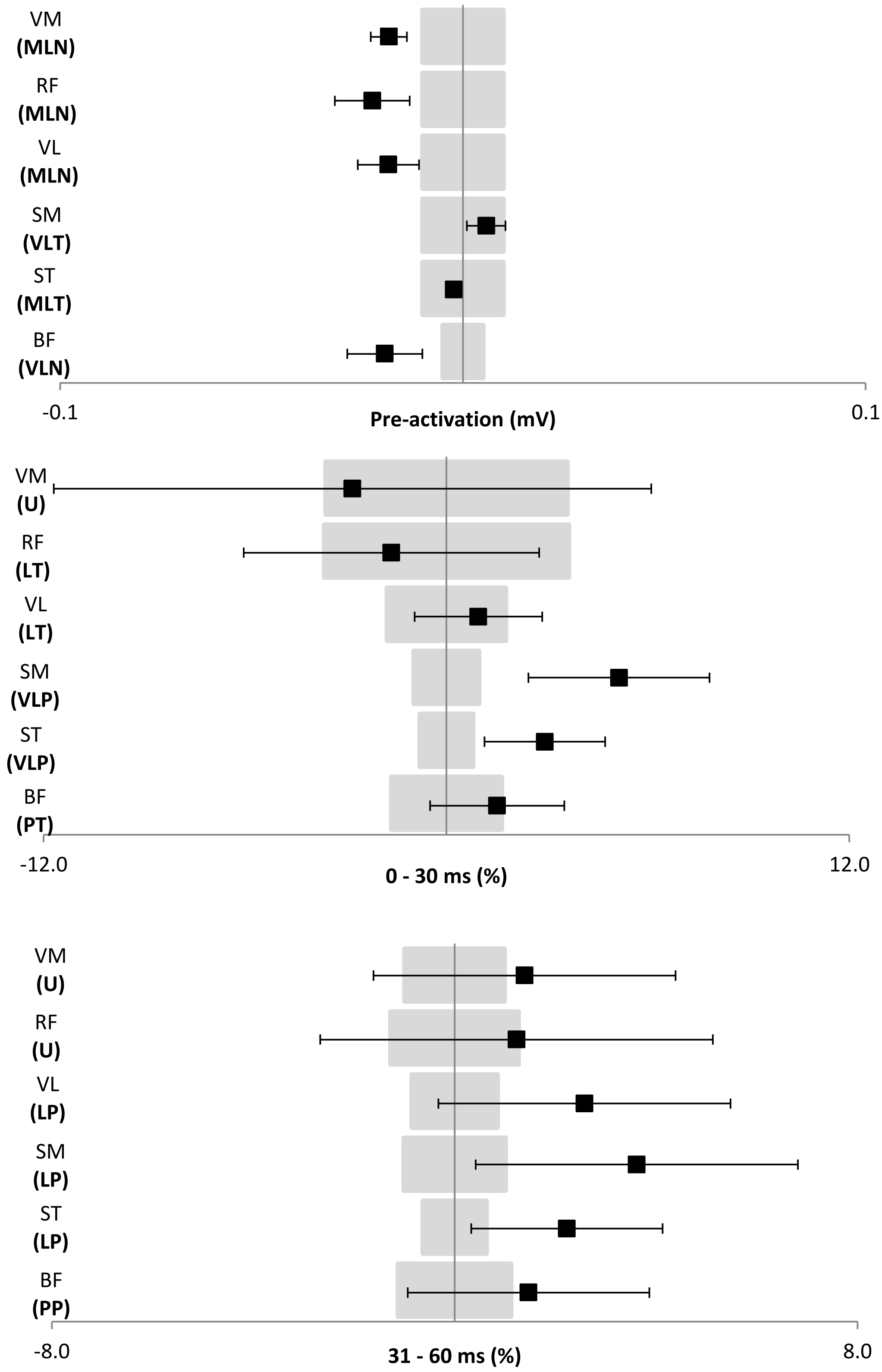

Figure 4.4 Mean difference (90% CI) between pre and post football specific fatigue protocol on the feed-forward and immediate feedback electromyographic variables of youth female footballers performing an unanticipated cutting manoeuvre *Muscle sites; VM = vastus medialis, RF = rectus femoris, VL= vastus lateralis, SM = semimembranosus, ST = semitendinosus, BF = biceps femoris, H:Q= hamstring:quadriceps co-activation ratio. The grey shaded area represents the smallest worthwhile effect. Inferential outcomes; U = Unclear, PP = possibly positive, LP = likely positive, VLP = very likely positive, VLN = very likely negative, MLN = most likely negative, PT = possibly trivial, LT = likely trivial, VLT = very likely trivial, MLT = most likely trivial*

4.4 DISCUSSION

4.4.1. Kinetic Variables

The main findings of the current study showed that the simulated match-play protocol led to a number of detrimental effects on kinetic variables. Specifically, the protocol led to *possible* increases in peak vGRF, *very likely* increases in peak apGRF, *likely* decreases in apGRF loading rate, and *very likely* decreases in time to peak vGRF and GCT. This suggests that upon completion of the football specific fatigue protocol participants were forced to absorb more force in less time, which in line with previous research will have increased their risk of ACL injury (Cowley et al., 2006). All fatigue-related changes in kinetic variables were greater than what would be expected from random variation as observed in Study 1, with the exception of peak vGRF and vGRF loading rate.

Previous research has observed that an increase in vGRF could be associated with a decrease in knee flexion angles (Nigg, 1985; Podraza & White, 2010). With a decreased knee flexion angle, the hamstrings and quadriceps cannot generate as much torque to support dynamic joint stabilisation (Watanabe & Akima, 2011). Further to this, research has identified positive relationships between knee flexion angle and lateral hamstrings activation (Brown et al., 2013), due to the mechanical disadvantage experienced by the hamstrings muscles with an erect posture (Brown et al., 2013; Lucci et al., 2011). Fatigue can induce a reduction in the ability of a muscle to generate force (Chagela et al., 2012). Therefore, an increase in knee flexion angle could help to counteract the reduction in force production commonly seen with fatigue. However, a rise in vGRF post-fatigue protocol in the participants of the current study would increase the risk of ACL injury by increasing the force absorbed at the knee. Females display knee absorption strategies that stress the internal structures of the knee; therefore, greater peak vGRF could place larger amounts of stress on the ACL (Schmitz & Schultz, 2010).

Comparable to the current study, Lucci et al. (2011) observed a non-significant increase in vGRF of collegiate female footballers performing an unanticipated cutting manoeuvre before and after either a Slow Linear Oxidative Fatigue Protocol or a Functional Agility Short Term Fatigue Protocol. The collegiate female footballers were performing the unanticipated cutting manoeuvre with a lower knee flexion angle which could account for the increase in vGRF (Lucci et al., 2011). Lower knee flexion angles in collegiate female footballers performing an unanticipated cutting manoeuvre under fatigued conditions were also observed by Cortes et al. (2013) and Weiss & Dickin (2013) who utilised the Functional Agility Short-Term Fatigue Protocol and the Yo-Yo Intermittent Running Test. The decrease in knee flexion angle and increase in vGRF observed in previous research have been observed to increase the risk of ACL injury at initial contact (up to 100ms of GCT), due to a decrease in knee flexion causing augmented anterior tibial shear force (Cortes et al., 2013; Lucci et al., 2011; Weiss & Dickin, 2013). The fatigue protocols utilised by previous research on collegiate female footballers are intermittent protocols that are not sport-specific. It is possible that football-specific fatigue protocols such as the modified SAFT 90 protocol used in the current study could produce even greater detrimental lower limb mechanical changes than those utilised by previous research due to the possibly greater energy demands (Cortes et al., 2013; Lucci et al., 2011; Weiss & Dickin, 2013). In the current study, these greater lower limb mechanical changes could have led to participants experiencing increased peak vGRF during ground contact when in a fatigued state, thereby increasing their risk of ACL injury.

Further to the differences in fatigue protocol between the current study and previous research, Cortes et al. (2011) determined that the demands placed upon the lower limb are task dependent. The researchers observed significant differences in lower limb mechanics and GRF's between a pivot task, sidestep cutting manoeuvre and drop-jump landing in collegiate female footballers (Cortes et al., 2011). The current study utilised sidestep cutting manoeuvres with a running approach, an unanticipated cue 2 M before the force platform and a cutting angle between 35 - 55 degrees. However, there was a methodical difference in limb dominance. The current study was novel in utilising the non-dominant limb of the participants, however Cortes et al. (2013) and Lucci et al. (2011) utilised the dominant limb, while Weiss & Dickin et al. (2013) utilised both limbs. Limb dominance is crucial in ACL injury risk as the majority of ACL injuries occur on the non-dominant limb of female footballers (Brophy et al., 2010; Le Gall et al., 2008; Silvers et al., 2007). Previous research has identified greater valgus angles in the non-dominant limb of adolescent females landing from a jump, which is often coupled with decreased knee flexion angles contributing to larger vGRF (Brophy et al., 2010; Nigg et al., 1985). This greater valgus in the non-dominant limb accounts for asymmetrical muscular control of GRF and consequently, force could be absorbed through the ligaments of the knee (Ford et al., 2003). ACL loading and rupture could occur more often during a cutting motion than drop vertical jump manoeuvres, as the former typically facilitates greater knee valgus angles and torques (Blackburn & Padua, 2009; Cortes et al., 2013; Ebben et al., 2010; Kulas et al., 2010). Weiss & Dickin (2013) have observed greater negative effects of fatigue on vGRF in the dominant limb compared to the non-dominant limb of female footballers performing an unanticipated cutting manoeuvre. Therefore, a greater detrimental effect of fatigue on the dominant limb (Cortes et al., 2013; Lucci et al., 2011) compared with the non-dominant limb measured in the current study would be expected.

Contrary to the current study, Smith et al. (2009) and Gerlach et al. (2005) observed beneficial effects of fatigue on peak vGRF, reflected by a decrease in peak vGRF during pre-planned jump landing and linear running tasks. These studies utilised dynamic tasks that differed from the current study, which could further support the claim that demands placed on the lower limb are task dependent (Cortes et al., 2011). As well as this, contradicting research did not utilise intermittent fatigue protocols, instead using gradual fatiguing protocols of exhaustive treadmill running or MVIC (Gerlach et al., 2005; Smith et al, 2009). Therefore, it could be suggested that intermittent fatigue protocols and sport-specific fatigue protocols as used in the current study and previous research (Cortes et al., 2013; Lucci et al., 2011; Weiss & Dickin, 2013) produce similar detrimental effects of fatigue on peak vGRF that differ to the effects observed in research using gradual fatiguing protocols (Gerlach et al., 2005; Smith et al, 2009).

Alongside the fatigue-induced increases in peak vGRF observed in the current study, time to peak vGRF displayed a *very likely* decrease (-28.6%). The production of higher forces over a shorter period of time allows female footballers to perform a skill more quickly, but may increase the risk of ACL injury (Cowley et al., 2006). Previous research has determined that the maximum ACL strain occurs sequentially with peak GRF (Cerilli et al., 2003; Lamontagne et al., 2005), and is related to a dynamic valgus stress at the knee. Following the acute fatigue protocol the participants of the current study had less time to sufficiently activate feedback neuromuscular control mechanisms to reduce valgus stress at the knee and minimise the strain on the ACL before peak vGRF was experienced (Cowley et al., 2006; Ford et al., 2003). ACL loading, deformation and rupture could occur more often in female footballers performing a cutting manoeuvre due to larger valgus moments, related to a neuromuscular inability to control GRF (Cowley et al., 2006). Increased peak vGRF and decreased time to peak vGRF, will lead to the body being forced to manage greater loads and with less time to control the increased forces. It is also possible that female footballers learn inefficient neuromuscular control patterns for cutting manoeuvres due to repetition of poor technique in training and competition, which are detrimentally enhanced by fatigue leading to greater forces (Cowley et al., 2006).

Previous research has identified detrimental effects of fatigue on medial quadriceps activation during box drop cutting manoeuvres (Shenoy et al., 2010), which could lead to greater knee abduction loads and valgus stress at the knee. Thus, it could be speculated that fatigue further inhibits neuromuscular control, reducing the ability of the muscles to control GRF and could account for the changes in peak vGRF and time to peak vGRF observed following the acute fatigue protocol in the current study (Cowley et al., 2006; Ford et al., 2003; Shenoy et al., 2010). Previous research has identified that dynamic valgus stress at the knee is the only single factor that could rupture the ACL without multi-factorial involvement. Therefore, greater peak vGRF and decreased time to peak vGRF could increase the risk of ACL injury through a valgus mechanism. Reducing the increase in peak vGRF and decrease in time to peak vGRF following a simulated match-play protocol are important factors in preventing injuries with previous research identifying decreases in vGRF with injury prevention training (Hewett et al., 1996; Irmischer et al., 2004; Prapavessis et al., 2003). Therefore, the increased peak vGRF and decreased time to peak vGRF observed following the acute fatigue protocol in the current study must be addressed with injury prevention training to reduce the risk of ACL injury in youth female footballers experiencing football match-play fatigue.

In the current study, negative effects of fatigue were observed for peak apGRF following the simulated match-play protocol with a *very likely* increase in peak apGRF. Sell et al. (2007) demonstrated that peak impact posterior GRF during stop-jump landings significantly relates to peak proximal tibial anterior shear force, which is a major ACL-loading mechanism (Markolf et al., 1995; Sell et al., 2007; Quatman, 2010; Yu & Garrett, 2005). ACL injuries occur across a variety of dynamic sporting tasks characterised by a sharp deceleration, which is represented by apGRF. The greatest apGRF in female footballers has been observed during the performance of an unanticipated sidestep cutting manoeuvre, when compared to drop-jump landings and pivot tasks (Cortes et al., 2011). Peak apGRF present during deceleration occurs before peak vGRF and peak knee flexion angle (Andrews et al., 1977; Sell et al., 2007). The body pre-activates the quadriceps to generate the deceleration power, which is vital for absorbing eccentric forces during ground contact (Benvenuti et al, 1997; Colby et al., 2000). However, without sufficient co-activation of the hamstring muscles, the tibia will be pulled anteriorly by the force of the quadriceps and place greater stress on the ACL (Hewett et al., 2000). An increase in apGRF following the football specific fatigue protocol could increase anterior tibial shear which could increase the strain on the participants ACL, and heighten their risk of ACL injury.

The current study observed increases in peak apGRF (*very likely*) following the acute fatigue protocol similar to previous research by Lucci et al. (2011) and Kellis et al. (2006). Increases in peak apGRF observed by Lucci et al. (2011) were non-significant, which could have been affected by the level of fatigue experienced by the participants performing either a Slow Linear Oxidative Fatigue Protocol or a Functional Agility Short Term Fatigue Protocol (Lucci et al., 2011). The current study and the research by Kellis et al. (2006) utilised fatigue protocols replicating football match-play and both observed substantial or significant increases in peak apGRF following the acute fatigue protocols. The dynamic tasks utilised by Kellis et al. (2006) and the current study, an in-step kick and unanticipated cutting manoeuvre respectively, require deceleration power. This could account for similar fatigue-induced changes in peak apGRF.

In the current study, the apGRF loading rates during the unanticipated cutting manoeuvre displayed a *likely* decrease with fatigue, which reflects a positive protective mechanism in response to acute fatigue. Comparably, Gerlach et al. (2005) observed decreases in GRF's and loading rates in female runner's post-exhaustive treadmill running protocol. A decrease in cadence and increase in step length with fatigue has been related to decreases in GRF and loading rate reportedly produced by changes of running mechanics, specifically ankle plantarflexion and knee flexion (Gerlach et al., 2005; Verbitsky et al., 1998). Weinhandl et al. (2014) observed greater plantarflexion angles during unanticipated cutting manoeuvres contributing to ACL loading, therefore if the participants in the current study did approach the force platform and performed the cutting manoeuvre with reduced ankle plantarflexion compared to their non-fatigued performance, they could have decreased the load on the ACL through this mechanism (Weinhandl et al., 2014).

However, previous research has observed decreased step length during sprinting following the original SAFT90 protocol in males and therefore, it could be suggested that the contribution of step length and cadence in reducing plantarflexion and apGRF loading rate is questionable (Small et al., 2009). As well as this, the current study utilised a method to calculate loading rates dependent of peak forces and time to peak forces (Equation 3.1). Therefore, although peak apGRF increases with fatigue the time to this peak force must increase proportionally or more, to decrease apGRF loading rate, which will allow more time for neuromuscular feedback mechanisms to dynamically control the peak apGRF. Contrary to the suggestion by Cortes et al. (2011) that lower limb demands are task dependent, the changes in loading rate during unanticipated cutting in the current study were similar to those reported by Gerlach et al. (2005) who utilised a treadmill running protocol.

The effect of fatigue on GCT was *very likely* negative, with a decrease in time (-14.2%). During sporting performance, dynamic tasks are performed at a high velocity producing a sharp deceleration with a change of direction as quickly as possible, which would place potentially dangerously high loads over a shorter period of time (Andrews et al., 1977; Cowley et al., 2006; Sell et al., 2007). This could increase the risk of ACL injury as the footballer would have less time to produce feedback neuromuscular mechanisms to control knee motion and counter the larger force absorbed at the knee, which could display as an inability to control GRF by the muscles subsequently increasing the valgus stress at the knee (Cowley et al., 2006; Ford et al., 2003).

4.4.2 Electromyographic Variables

In the current study, the simulated match-play fatigue protocol caused *most likely* decreases in pre-activation of all three quadricep muscle sites and *very likely* decreases in pre-activation of BF of participants performing an unanticipated cutting manoeuvre, which was greater than random variation of these measures observed in Study 1. Pre-activation of the quadriceps and hamstrings musculature is key to dynamic stabilisation of the knee joint in preparation to absorb GRF's and decrease the stress on the ligaments of the knee (Hewett et al., 2005). Imbalanced or inefficient pre-activation of the hamstrings and quadriceps musculature may place the non-dominant limb in a position that puts the youth female footballers' ACL under increased stress and risk of injury (Hewett et al., 2005). Generally, ACL injury occurs too quickly for reflexive muscle activity to stabilise the knee with the point of ACL injury occurring in the background muscle activity and short latency reflex phases, specifically between 17 ms and 50 ms (Hewett et al., 2005; Krosshaug et al., 2007). However, pre-activation may reduce the risk of injuries caused by unexpected perturbations (Hewett et al., 2005). Therefore, a decrease in pre-activation of the quadricep and hamstring muscles will likely increase the risk of ACL injury.

A reduction in the electromyographic activation of the quadricep muscles could indicate decreased deceleration power, which is vital for absorbing eccentric forces during GCT (Benvenuti et al, 1997; Colby et al., 2000). The increase in apGRF (+26.7%) observed in the fatigued female footballers of the current study is representative of greater deceleration and places stress on the ACL (Andrews et al., 1977). However, a reduction in the pre-activation of the quadriceps decreases the participants' ability to control the increased apGRF and absorb the eccentric forces during a shorter GCT effectively. Thus, greater stress will be absorbed through the knee joint; specifically the ACL with an increase in anterior tibial shear due to apGRF (Andrews et al, 1977; Quatman, 2010). Contrary to previous research, pre-activation of VM decreased with fatigue in the current study. Kellis et al. (2011) observed significantly increased VM activation during the impact phase of running following an isokinetic fatigue protocol (Kellis et al., 2011)**.** The increase in activation observed by Kellis et al. (2011) could have been due to the isokinetic fatigue protocol reducing the force generation capacity of VM and the muscle producing a compensatory response to this reduction. The difference in findings between the current study and Kellis et al. (2011) could be due to the difference in fatigue protocols and dynamic tasks studied. Kellis et al. (2011) utilised an isokinetic fatigue protocol requiring maximal contraction and force generation from the participants, which would have fatigued Type II muscle fibres due to their role in explosive, high force generation, and powerful movements. These fibres fatigue more quickly than Type I fibres, and are in greater proportion in ratio to Type I fibres in adults, compared to children and adolescents. The current study utilised a protocol that would have fatigued both Type I and Type II fibres (Ratel & Martin, 2015). Therefore, it would be expected that force generation capacity would have been influenced more by a maximal contraction fatigue protocol, like the study by Kellis et al. (2011). Lower peak valgus angles have been positively related to pre-activation of VM (Palmieri-Smith et al., 2008). In the current study, decreases in pre-activation of VM (-263%) in the participants following the acute fatigue protocol could increase their dynamic valgus angle. Weinhandl et al. (2014) observed ACL loading during unanticipated cutting manoeuvres was largely due to the sagittal plane, and as such valgus forces alone could load the ACL sufficiently to rupture the ligament causing serious injury (Weinhandl et al., 2014). Therefore, pre-activation of VM would appear vital in reducing the risk of valgus collapse and ACL injury risk, thus fatigue has a detrimental effect on the

ACL injury risk of youth female footballers performing unanticipated cutting manoeuvres (Palmieri-Smith et al., 2008; Weinhandl et al., 2014).

The role of the hamstrings in reducing ACL injury is particularly important as the muscle group works as an antagonist to anterior tibial shear, and reduces the stress on the ACL (Zebis et al., 2011). This antagonistic work of the hamstrings is particularly important during pre-activation when the deceleration phase of a cutting manoeuvre produces a forceful quadriceps contraction that exhibits an anterior pull on the tibia and stresses the ACL (Quatman, 2010; Zebis et al., 2011). Previous research has observed that an increase in ACL loading under unanticipated conditions, compared to pre-planned conditions, is primarily due to sagittal plane components including hamstrings co-activity and patella tendon anterior shear (Weinhandl et al., 2014). Applying the results of the current study, the effects of a simulated match-play protocol on pre-activation of BF could increase ACL load of youth female footballers. The *most likely* decrease in pre-activity of BF (-269%) following the acute fatigue protocol in the current study was similar to previous research on handball players performing a pre-planned cutting manoeuvre pre and post simulated handball match fatigue (Zebis et al., 2011). Zebis et al. (2011) observed significant decreases in pre-activation of BF with simulated handball match-play fatigue in female handball players. The similar findings between Zebis et al. (2011) and the current study could be due to the cutting manoeuvre, rather than anticipatory effects of the dynamic task, and the sport-specific fatiguing protocols utilised in both studies. Therefore, the detrimental effects of sport-specific fatigue on pre-activation of BF in high risk populations performing sport-specific sidestep cutting manoeuvres could be a risk factor for ACL injury.

There were *very likely* and *most likely trivial* changes in pre-activation of ST (-4.83%) and SM (+17.2%) which may be reflective of a protective mechanism of the hamstrings in terms of ACL injury. Changes that did occur in this measure could have been down to random variation as the difference in ST and SM pre-activation was lower than the CV% observed in study 1 (SM: 31.5%, ST: 19.9%). In female athletes, non-contact ACL injuries typically involve a valgus collapse in an erect position (Zebis et al., 2011). This valgus collapse is representative of the lower limb muscles' ability to control GRF. Specifically, pre-activation of ST before a side cutting manoeuvre could compress the medial knee joint, thereby decreasing the risk of valgus collapse and ACL injury (Zebis et al., 2011). Females produce disproportionate medial to lateral activation patterns compared to males, displaying significantly greater activation of the lateral thigh musculature compared to the medial thigh musculature, which can cause higher knee abduction loads, and valgus collapse at the knee (Myer et al., 2014; Palmeiri-Smith et al., 2009; Zhang & Wang, 2001). An ACL protective strategy produced by sustaining ST pre-activity when fatigued would be especially important for female athletes during unanticipated cutting manoeuvres. Females tend to produce increased lateral trunk flexion as a result of performing a cutting manoeuvre reactively which is directly related to higher knee abduction loads and a valgus collapse (Jamison, Pan & Chaudhari, 2012; McLean et al., 2010; Mornieux et al., 2014; Palmieri-Smith et al., 2009; Zhang & Wang, 2001). Therefore, maintenance of ST pre-activation by the female footballers following the acute fatigue protocol serves as a protective mechanism to reduce the risk of valgus collapse and ACL injury. Injury prevention training should focus on developing increases in ST and SM pre-activation following a simulated match-play protocol.

Following pre-activation, a continuation of feed-forward activity during background muscle activity (0 - 30 ms) and the immediate feedback mechanisms of the hamstrings and quadriceps during 31 - 60 ms are important in reducing ACL injury risk, as the point when ACL injury commonly occurs during dynamic tasks such as cutting manoeuvres and drop-jump landing tasks (17 - 50 ms) fall within these phases (Krosshaug et al., 2007). Following the acute fatigue protocol in the current study, *very likely* increases for SM (+27.2%) and ST (+16.2%) activation were displayed during 0 - 30 ms, and *likely* increases were displayed for SM (+21.1%) and ST (+13.5%) activation during 31 - 60 ms. The increases noted in SM activation during 0 - 30 ms were indicative of fatigue-induced changes as the difference was greater than what would be expected from random variation observed in Study 1 (24.0%), however changes of ST during 0 - 30 ms and 31 - 60 ms, and SM during 31 - 60 ms could be due to random variation. These increases in activation show an ACL protective mechanism from SM and ST throughout pre-activation, 0 - 30 ms, and 31 - 60 ms. The increased activation of SM and ST during the time that ACL injury commonly occurs (17 - 50 ms) compresses the medial knee further allowing the valgus load to be carried by articular forces protecting the ligaments and reducing the risk of valgus collapse (Krosshaug et al., 2007; McLean et al., 2010; Palmieri-Smith et al., 2006; Rozzi et al., 1999; Zebis et al., 2011). Increases in muscle activation have been suggested to occur as a compensatory mechanism for the reduced force production properties of fatigued muscles due to the need of recruiting a greater amount of motor units to sustain the same force (Kellis et al., 2011; Zebis et al., 2011).

Contrary to the current study, Iguchi et al. (2014) observed a decreased pre-activation of SM in male and female footballers performing unanticipated cutting manoeuvres following the completion of a repetitive counter-movement jump fatigue protocol. This decrease in medial hamstring activity would predispose the fatigued footballers to valgus collapse; a predominant ACL injury mechanism. However Iguchi et al. (2014) utilised a fatiguing jump protocol until participants could not reach 70% of their maximum height in two consecutive trials, which does not replicate the intermittent energy demands of football match-play. Iguchi et al. (2014) also used the commonly dominant kicking limb of participants; previous research has observed that the dominant limb experiences greater detrimental effects of fatigue than the non-dominant limb (Weiss & Dickin, 2013). Additionally, a study observing the effect of fatigue on an unanticipated cutting manoeuvre found no combined effects of fatigue and anticipation of a dynamic task, but did observe an increase in peak knee abduction angles post-fatigue in the performance of an unanticipated cutting manoeuvre. This increased angle could indicate increasing medial to lateral activation patterns that would promote a valgus collapse and increase the risk of ACL injury (Collins et al., 2016). However, Collins et al. (2016) and Iguchi et al. (2014) utilised fatigue protocols that were not sport-specific such as the intermittent shuttle run test (Collins et al., 2016) and a repetitive jumping fatigue protocol (Iguchi et al., 2014). These differing protocols could have produced differing levels of hamstring fatigue to the current study, thus different levels of compensatory electromyographic activation (Collins et al., 2016; Iguchi et al., 2014; Kellis et al., 2011; Zebis et al., 2011).

In the current study, there were *very likely* increases in the peak H:Q co-activation ratio (+73.5%) of the youth female footballers performing an unanticipated cutting manoeuvre with fatigue. This finding shows that peak hamstrings activity increased to a greater extent than peak quadriceps activation. This increase in activation of the hamstrings could be a compensation for the decreased force generation of the hamstrings inflicted by the modified SAFT90 (Kellis et al., 2006; Small et al., 2009). Previous research has observed a reduced eccentric force generation capacity of the hamstrings following the original SAFT90 protocol (Small et al., 2008). The modified SAFT90 protocol utilised in the current research was designed to place higher energy demands on the participants by including; ball contacts, cutting manoeuvres, and jump and heading tasks. The increased activation of the hamstrings muscles in comparison to the quadricep muscles creates a hamstring dominant strategy, which is not usual in females. Previous research has observed quadricep dominant strategies displayed by females which increase anterior tibial shear and risk of ACL injury (Ebben et al., 2010; Hanson et al., 2008; Hewett et al., 2005; Quatman, 2010). However, despite participants in the current study displaying hamstrings dominance in all latency phases both pre and post fatigue, there was an exception of a quadricep dominant strategy during the background muscle activity (0 - 30 ms) phase. The predominance of quadriceps activation observed during the first 30 ms of ground contact could predispose the footballers to increased anterior tibial shear and stress on the ACL at a time when ACL injury commonly occurs (Krosshaug et al., 2007; Quatman, 2010). Baratta et al. (1988) suggested a quadriceps dominance tendency could occur due to muscle hypertrophy of the quadriceps, generally in high performing athletes, with less hamstring co-activation being due to an inhibitory effect on reciprocal antagonistic muscles (Baratta et al., 1988). It could be suggested that the training sessions performed by the youth female footballers do not overload the quadriceps (Baratta et al., 1988).

Contrary to the current study, Zebis et al. (2011) observed impaired hamstrings activation in female handball players performing side cutting manoeuvres after a 50 minute handball-specific fatigue protocol. Taj & Chatterjee (2015) observed differences in the dominant leg of collegiate male football and volleyball players with greater H:Q co-activation ratios in volleyball players in comparison to footballers (Taj & Chatterjee, 2015). Sport difference could account for the findings of Zebis et al. (2011) testing handball players, and the current study utilising footballers.

The difference in findings of hamstrings dominance between the current study and previous research (Ebben, et al., 2010; Hanson et al., 2008; Hewett et al., 2005; Landry et al., 2007; Quatman, 2010; Zebis et al., 2011) could be explained by the findings of Russel et al. (2008) and Sigward and Powers (2006). Sigward and Powers (2006) studied the effect of athletic experience on H:Q co-activation ratios during a preplanned sidestep cutting maneuvre performed by novice (five years or less experience) and experienced (more than five years experience) youth female athletes (14 - 16 years old). The researchers identified that novice female athletes display significantly greater H:Q co-activation during early deceleration of a sidestep cut (pre-activation) than experienced athletes. The researchers also observed a negative relationship between the number of years experience and the H:Q co-activation ratio; suggesting that those females with greater years of experience performed the cutting task with less muscle co-activation. In comparison to the research of Sigward & Powers (2006), the participants in the current study produced less quadricep dominant characteristics and more muscle co-activation of the hamstrings than the experienced footballers (at least five years experience) who participated in previous research (Sigward & Powers, 2006). Therefore, it could be suggested that the participants in the current study are novice footballers (less than five years experience) responding to the task with the principles of skill acquisition (i.e. mass co-activation) (Sigward & Powers, 2006).

The larger H:Q co-activation ratio observed in the female footballers during pre-activation compared to background muscle activity (0 - 30 ms) could be due to age and learned feed-forward mechanisms. Russell et al. (2008) observed that adult participants (female and male) displayed larger H:Q co-activation ratios than children during the pre-activation phase of a two footed landing. These findings could indicate a learned feed-forward mechanism in adults, which the participants in the current study are beginning to learn at a post-pubertal/late adolescent age (Russell et al., 2008). In the current study, the co-activation characteristics of the hamstrings musculature employed by the participants during pre-activation provide support to the ACL reducing the risk of injury (Hewett et al., 2005). However, the background muscle activity (0 - 30 ms) co-activity of the hamstrings do not provide this support and are of concern due to the time of ACL injury occurrence (17 - 50 ms). Further to the findings from Sigward & Powers (2006) and Russell et al. (2008), the current study utilised an unanticipated cutting manoeuvre to measure the electromyographic variables of the participants. Therefore, the anticipatory effects of cutting may have an effect on the comparisons of H:Q co-activation ratio observed in the current study to previous literature which utilised pre-planned manoeuvres, particularly the effect of increased knee flexion with unanticipated tasks (Besier et al., 2001; Ebben et al., 2010; Ford et al., 2011; Hanson et al., 2008; Hewett et al., 2005; Mornieux et al., 2014). Intuitively, performing an unanticipated cutting manoeuvre with greater knee flexion would reduce the risk of ACL injury, as the hamstrings are more effective at reducing the stress on the ACL produced by anterior tibial translation with higher degrees of knee flexion (Shelburne & Pandy, 1997; Onishi et al., 2002).

In analysing the descriptive data of the H:Q co-activation ratios of the female footballers performing an unanticipated cutting manoeuvre, it was observed that pre-fatigue and post-fatigue the ratios increased throughout the latency phases with the H:Q co-activation ratios being smallest during 0 - 30 ms and greatest during 91 - 120 ms. This shows delayed activation of peak hamstring co-activity. This finding is comparable to previous research by Xie et al. (2013) on female basketball players. Xie et al. (2013) observed the collegiate players performing a pre-planned sidestep cutting manoeuvre with significantly lower H:Q co-activation from initial contact to maximum knee flexion, than from maximum knee flexion to toe-off (Xie et al., 2013). Similar findings were found for mean knee valgus angle. Consequently, the risk of ACL injury in collegiate female basketball players was greater during initial contact to maximum knee flexion, which is in line with previous research defining the common time of ACL injury as 17 - 50 ms after initial contact (Krosshaug et al., 2007; Xie et al., 2013). Previous research has not determined the H:Q co-activation ratio pre and post-simulated match-play protocol, thus the H:Q co-activation ratio findings of the current study are unique.

Significant delays in feedback mechanisms could increase the risk of ACL injury due to the importance of immediate feedback mechanisms in reducing the stress on the ACL during the time of ACL injury (17 - 50 ms). The current study observed *unclear* changes in time to peak BF activation, (+1.32%), *possibly* trivial changes in time to peak ST activation (-7.94%), and *possibly* negative changes in time to peak SM activation (-

18.75%), which could be detrimental to ACL injury risk. A delay in hamstrings activation could reduce the ability of the hamstrings to work as antagonists to ACL stress at crucial times during the unanticipated cutting manoeuvre. The changes in time to peak hamstring activation are less than what would be expected from random variation (SM: 55.92%, ST: 129.19%, BF: 60.30%), thus it cannot be determined whether the change is fatigue-induced.

In the current study, the football specific fatigue protocol produced *likely* increases in time to peak RF activation (+29.03%) which were greater than random variation observed in Study 1 (21.41%), thus fatigue related. However, *possible* decreases in the time to peak VL activation (-19.10%) and time to peak VM activation (-11.82%) following the football specific fatigue protocol were lower than the observed random variation of the measure in Study 1 (VM; 21.37%, VL; 39.23%). Therefore, it is not certain that these changes are fatigue-induced. Females tend to display greater and earlier VL activation than their male counterparts, which can be related to increased anterior tibial shear forces and direct loading of the ACL (Hanson et al., 2008; Quatman, 2010). The decrease in time to peak VL activation (-19.10%) observed in the current study, if not proportionately matched by VM, could put the ACL at risk of injury through a valgus mechanism and increased anterior tibial shear (Palmieri-Smith et al., 2009). The lack of fatigue-related changes in time to peak hamstring activation in comparison with previous research could be due to the increased demands on the quadriceps muscles in the current study protocol that included 26 instep passes. Instep passes require deceleration forces of the quadriceps particularly when a player displays improper swing control, which could have occurred with fatigue (Shan & Zhang, 2011). This could have caused a greater force-generation reduction in the quadriceps than the hamstrings, which could have affected electromyographic activation of the quadriceps, potentially decreasing time to peak activation of VL (Kellis et al., 2011). However, this would not apply to RF in which an increased time to peak activation was observed. This increased time to peak RF activation (+29.03%) has been observed in previous research studying drop-landing tasks (Haddas et al., 2015). The difference in findings between the quadriceps muscles could be due to the role of RF in hip flexion activities.

4.5 PRACTICAL APPLICATIONS

From an ACL injury prevention perspective, the current study would suggest that injury prevention programmes should be tailored to improve the fatigue resistance of young female footballers and reduce the risk of ACL injury. The study showed increases in peak vGRF and apGRF, and reductions in time to peak vGRF, apGRF loading rate, and GCT following the acute fatigue protocol. In light of these findings, it is suggested that female footballers need to be trained to better tolerate impact from cutting when in a fatigued state to ensure they can safely attenuate larger loads over shorter periods of time. Injury prevention programmes including training that develops eccentric and reactive strength such as; plyometric and heavy resistance training, could be beneficial (Chimera et al., 2004; Hewett et al., 1994; McLaughlin, 2001). Decreased pre-activation of the quadriceps following the acute fatigue protocol reduces the female footballer’s ability to control GRF, specifically decreases in medial quadriceps activation could increase the risk of valgus collapse (Ford et al., 2003; Palmieri-Smith et al., 2009). Thus, training to improve a female footballer’s ability to pre-activate the quadriceps to help control the greater loads from increased GRF’s post-fatigue would be beneficial in reducing ACL injury. Plyometric training that can further enhance the increases in H:Q co-activation ratios and the protective activation of ST and SM during pre-activation, background activity (0 - 30 ms) and immediate feedback (31 - 60 ms) following the acute fatigue protocol would help to compress the medial knee joint and reduce anterior tibial shear. This training should also address the decreases in H:Q co-activation during 0 - 30 ms when ACL injury commonly occurs (Krosshaug et al., 2009). Injury prevention programmes including training that develops pre-activation of the quadriceps and co-activity of the hamstrings such as; plyometric training, balance training, and eccentric hamstring training, have been shown to be beneficial in improving the fatigue resistance of female footballers (Chimera et al., 2004; Gioftsidou et al., 2004; Hewett et al., 1994; Marshall et al., 2015; McLaughlin, 2001; Riva et al., 2016).There were various unclear outcomes in the current study. An unclear outcome means that a positive or negative cannot be determined. The outcomes reported as unclear in study 2 could be due to various factors including; the inability to control a complex and complicate task such as the unanticipated manoeuvre. Although, there were uncontrollable factors within the study, measures were put in place to control as much as possible i.e. cutting angle, approach speed, homogenous group, inclusion/exclusion criteria.

4.6 LIMITATIONS

- *Sample size.* The current thesis utilised a small sample size which can make it more difficult to generalise findings to a larger population. However, magnitude based inferences (MBI) were used as a statistical approach as this approach is effected to a lesser extent by smaller sample sizes (Batterham & Hopkins, 2006).

- *Football specific fatigue protocol* – Although the current study utilised the SAFT90, to mimic football specific fatigue, with some modifications such as ball contacts, jumping and cutting to increase football specific energy demands, the protocol was not tested for reliability and validity. However, the main activity profile of the SAFT90 was not modified thus overall load and associated fatigue would be only slightly influenced. The modifications to the SAFT90 protocol for the current study were purely technical elements commonly seen in match play (i.e. cutting, jump and heading a ball, ball contacts). Therefore, such modification would not necessarily influence the reliability and validity of the already established activity profile of the SAFT90 (Lovell et al., 2008). Testing participants pre and post football match-play may provide the optimal chance for researchers to understand the effects of football specific fatigue on electromyographic and kinetic variables of female footballers performing an unanticipated cutting manoeuvre. Further to this, female footballers experience the highest number of injuries when experiencing fatigue in the last 30 minutes of match-play (Ekstrand et al., 2009; Hiemstra et al., 2001; Junge & Dvorak, 2007), so research investigating sequential level of fatigue experienced and the effects of fatigue within this last 30 minutes could provide a clear picture of fatigue as a risk factor in ACL injury risk of youth female footballers. However, when studying match-play scenarios the researcher loses control of workloads and exposure time, whereas the SAFT90 protocol used in the current study enabled the researcher to control these factors. Future research may want to use the Youth SAFT90 (YSAFT90) for youth footballers which has been produced since the current study was conducted, and is suitable and relevant to the football specific fatigue experienced in the youth population (Barratt et al., 2013).

4.7 KEY FINDINGS

1. Youth female footballers display a *very likely* increase in apGRF with fatigue, which would place greater stress on the ACL.
2. Following the fatigue protocol, there were *very likely* increases in peak H:Q co-activation ratios, and H:Q co-activation ratios increased throughout the latency phases of an unanticipated cutting manoeuvre. However, during the first 30 ms following initial contact, when there is a high risk of ACL injury, the fatigue protocol produced quadriceps dominant H:Q co-activation ratios.
3. *Most likely* decreases in pre-activation of the quadriceps muscle group and *very likely decreases* in pre-activation of BF occurred with fatigue; however there were no substantial changes in pre-activation of SM and ST, which could be a protective mechanism to ACL injury.

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PRELUDE

Study 2 examined the effect of a football specific fatigue protocol on the kinetic and electromyographic variables of female footballers performing an unanticipated cutting manoeuvre. The study showed that fatigue produced detrimental effects on force absorption, but a safer muscle recruitment strategy in the female footballers, with the exception of H:Q co-activation ratios during 0 - 30 ms. It would be favourable for an injury prevention training programme to train female footballers to better tolerate impact from cutting to ensure they can safely tolerate larger loads over shorter periods of time. Training should also focus on enhancing the positive effects of fatigue on muscle recruitment strategies, specifically ST activation and H:Q co-activation ratios during feed-forward and immediate feedback phases. Study 3 will examine the effect of a neuromuscular training intervention on the fatigue resistance of the kinetic and electromyographic variables of female footballers performing an unanticipated cutting manoeuvre.

Chapter 5: Study 3

The Extent of which the FIFA 11+ is Effective in Improving the Fatigue Resistance of the Kinetic and Electromyographic Variables of Youth Female Footballers Performing an Unanticipated Cutting Manoeuvre

5.1 INTRODUCTION

With a greater understanding of modifiable ACL injury risk factors, organisations such as FIFA, have been able to produce injury prevention programmes to try to reduce the risk of injury in football (Bizzini et al., 2013; Mandelbaum et al., 2005; Steffen et al., 2013; Vescovi & Vanheest, 2010). Various researchers have studied the effect of the implementation of an array of intervention programmes in minimising the risk of injury and have observed positive outcomes in both male and female populations (Michaelidis & Koumantakis, 2014). Specifically, researchers have observed a decrease in the number of non-contact ACL injuries after the implementation of such training interventions (Michaelidis & Koumantakis, 2014; Soligard et al., 2008; Walden et al., 2011). A systematic review of the effects of injury prevention programmes on ACL injuries in female athletes identified nine prevention programmes that have been implemented in female footballers (Michaelidis & Koumantakis, 2014). Of the nine programmes, only three injury prevention programmes were found to reduce the rate of ACL injuries in female footballers; the Prevent Injury and Enhance Performance (PEP), Harmoknee Preventative Training (HPT), and the Knäkontroll. All three programmes utilised a variety of training components (i.e. plyometrics, strength, balance, flexibility) and also incorporated football-specific drills (Michaelidis & Koumantakis, 2014). Common indicators of a successful prevention programme identified were; multi-component and sport-specific programmes, 15-20 minutes in length replacing the participants' usual warm-up routine two-three times per week, and education and feedback to participants on correct technique (Grimm et al., 2015; Michaelidis & Koumantakis, 2014; Yoo et al., 2010). Further research has observed that training two to three times per week for six weeks is the smallest dosage needed to see an adaptation to a neuromuscular training programme (Wilderman et al., 2009). In the review by Michaelidis & Koumantakis (2014), the FIFA 11 was observed to be unsuccessful in reducing knee injuries. Since the original FIFA 11 (2003) was produced, FMARC have developed the FIFA 11+ (2006) which incorporates the common indicators of a successful prevention programme identified (Grimm et al., 2015; Michaelidis & Koumantakis, 2014; Yoo et al., 2010). The FIFA 11+ is a complete warm-up programme implemented as a mode of prevention to reduce injury rates of male and female footballers aged 14 years and older (F-MARC).

Since the FIFA 11+ was developed, various researchers have identified the effectiveness of the prevention programme in reducing injury risk in youth male and female footballers (Owoeye et al., 2014; Soligard et al., 2008; Steffen et al., 2013). Soligard et al. (2008) observed injury risk in youth female footballers aged 13 - 17 years, who performed the FIFA 11+ twice weekly throughout a regular football season, was reduced by about ~33% and severe injuries reduced by up to 50% (Soligard et al., 2008). Therefore, programmes aimed at increasing strength, landing technique awareness and neuromuscular control should be introduced at an early age, as soon as children start playing organised football (Mendiguchia, 2013; Myer et al., 2012; Soligard et al., 2008; Rossler et al, 2016). Further research on injury incidence has observed the FIFA 11+ to be effective in reducing injury rate of those players that highly adhere to the programme (80% participation), emphasising the importance of collecting adherence data. In doing so, researchers can determine whether changes/no changes have occurred due to the FIFA 11+ or adherence to the programme (Soligard et al., 2010; Steffen et al., 2008; Steffen et al., 2013). Applying the Reach Efficacy Adoption Implementation Maintenance (RE-AIM) framework, O'Brien and Finch (2014) observed that a major barrier to successful injury prevention programmes were convincing players to participate and adhere to the programme. Using the RE-AIM framework, O'Brien and Finch (2014) identified the importance of substantial adherence to an injury prevention programme for a desired effect and reduction in injury incidence to occur (O'Brien & Finch, 2014). Although injury incidence has been shown to reduce with adherence to the FIFA 11+, there is limited research identifying the mechanisms of this change in incidence, particularly the effect of the FIFA 11+ on electromyographic and kinetic variables of female footballers.

Previous research on adult male footballers has identified improvements in H:Q co-activation ratios, increased torque of non-dominant hamstrings, and decreased vGRF as mechanisms of injury risk reduction by prevention programmes (Britoa et al., 2010; Hewett et al., 1996; Irmischer et al., 2004; Prapavessis et al., 2003). However, female footballers have a greater deficit to overcome in terms of the same variables in comparison to males performing various dynamic tasks (Ebben et al., 2010; Hanson et al., 2008). A recent study by Zebis et al. (2016) studied the effect of an evidence based prevention programme on various electromyographic and kinetic variables at initial contact of an anticipated side cutting manoeuvre in adolescent female handball players and footballers. The researchers observed between-group differences in VL and ST pre-activity, but no between-group differences for maximal knee joint valgus moment and knee valgus angle at initial contact. In the intervention group, medial hamstring (ST) pre-activity increased compared to lateral quadriceps (VL) 10 ms prior to foot-strike during anticipated sidestep cutting (Zebis et al., 2016). This increased pattern of ST pre-activity would provide protection against non-contact ACL injury. Conversely, in the control group, increased activity occurred in the lateral quadricep muscle (VL) which is associated with a higher risk of ACL injury (Zebis et al., 2016). The study by Zebis et al. (2016) was not specific to female footballers studying a combination of 15 - 16 year old female football and handball players, and utilised a handball-based prevention programme with football specific adaptations. Therefore, the effect of the FIFA 11+ on the electromyographic and kinetic variables of youth female footballers performing an unanticipated cutting manoeuvre following a simulated match-play protocol remains to be elucidated.

Due to the increased risk of ACL injury in youth female footballers experiencing fatigue, it is important to ensure that injury prevention programmes train a fatigue resistance of electromyographic and kinetic ACL injury risk factors (Krustrup et al., 2003). Female footballers sustain the majority of injuries from 60 minutes into the game, coinciding with a decrease in high intensity running and increase in fatigue (Krustrup et al., 2003; Mohr et al., 2005). However, the average duration of preventive training is 20 minutes (Michaelidis & Koumantakis, 2014) to avoid the negative impact of fatigue, thus it could be speculated that prevention training does not aim to improve electromyographic and kinetic deficits in fatigued footballers (Krustrup et al., 2003; Michaelidis & Koumantakis, 2014; Mohr et al., 2005). It has been observed that better conditioned female footballers have greater neuromuscular control for longer time periods in games in comparison to less conditioned players who display longer reflex latencies and decreased muscle activation around the knee joint (Alentorn-Geli et al., 2009). Therefore, it may be necessary for injury prevention programmes to induce a certain level of fatigue which would still provide positive injury prevention stimuli ultimately improving neuromuscular resilience of the athlete (Michaelidis & Koumantakis, 2014). Although there is some research on the effectiveness of injury prevention programmes, including the FIFA 11+, in reducing injury incidence in female footballers, the effect of such programmes on the modifiable electromyographic and kinetic variables present in youth female footballers during an unanticipated cutting manoeuvre is yet to be elucidated. As well as this, the effect of a short-term training intervention on the fatigue resistance of youth female footballers on a range of injury risk factors is unknown. Therefore, the aims of this study were to:

- Quantify the effects of the FIFA 11+ on kinetic variables of youth female footballers performing an unanticipated cutting manoeuvre
- Quantify the effects of the FIFA 11+ on electromyographic variables of youth female footballers performing an unanticipated cutting manoeuvre
- Quantify the ability of youth female footballers to display fatigue resistance in a range of electromyographic and kinetic variables following FIFA 11+ training for two to three times weekly for eight weeks

5.2 METHODS

5.2.1 Participants

Twenty four youth female footballers who played within a women's football under-19 (U19) development academy (mean ± *sd*: age 17.87 ± 1.05 years, height 162 ± 5.00 cm, weight 62.30 ± 9.96 kg) volunteered to participate in the study. The participants for the current study were the same female footballers that participated in study 2 (chapter 4).

Three participants were absent for post-intervention testing due to leaving the development academy set-up.

5.2.2 Data Collection Testing Sessions

Participants performed the data collection testing session for study 3 as outlined in pages 122-131. Following this data collection session, the participants were evenly and randomly assigned to one of two groups; an experimental group (FIFA 11+) and a control group. Players were split into groups by playing position then randomly assigned to one of the two groups. The experimental group completed the FIFA 11+ injury prevention programme (Appendix 2.2), two - three times weekly for eight weeks in substitution for the team's usual warm-up, while the control group performed their normal team warm-up, as outlined in figure 5.1. The team coach ensured the control and experimental group were separated for their warm-ups.

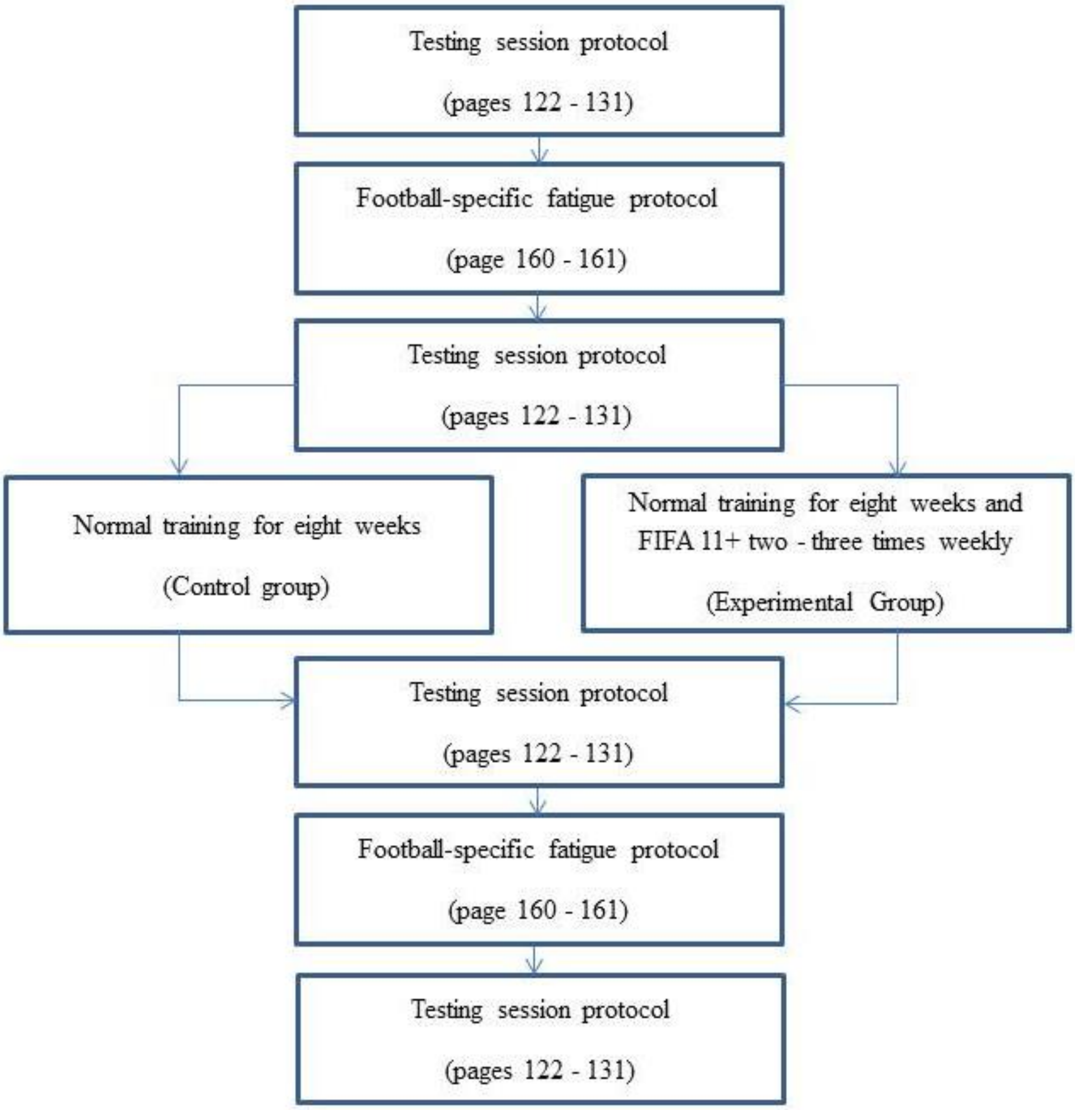

Figure 5.1 Testing protocol

5.2.3 Intervention

Participants in the experimental group had access to the FIFA 11+ manuals and hand-outs (available at http://f-marc.com/11plus/manual/ [figure 5.2]). The FIFA 11+ consists of six warm up running exercises, three strengthening exercises, one balance exercise and two plyometric exercises with three levels of difficulty and three further running exercises. All players started on level one. Progression through the difficulty levels of the strengthening, plyometric, and balance exercises was granted by the Level 2 Football Coach who was also a qualified Sports Therapist (BSc.). Once a player could perform an exercise with correct technique and without technical breakdown for the specified duration and number of repetitions advancement onto the next level was granted. Coaches were asked to encourage and emphasise correct form and proper technique over quantity of exercises, paying full attention to correct posture and good body control.

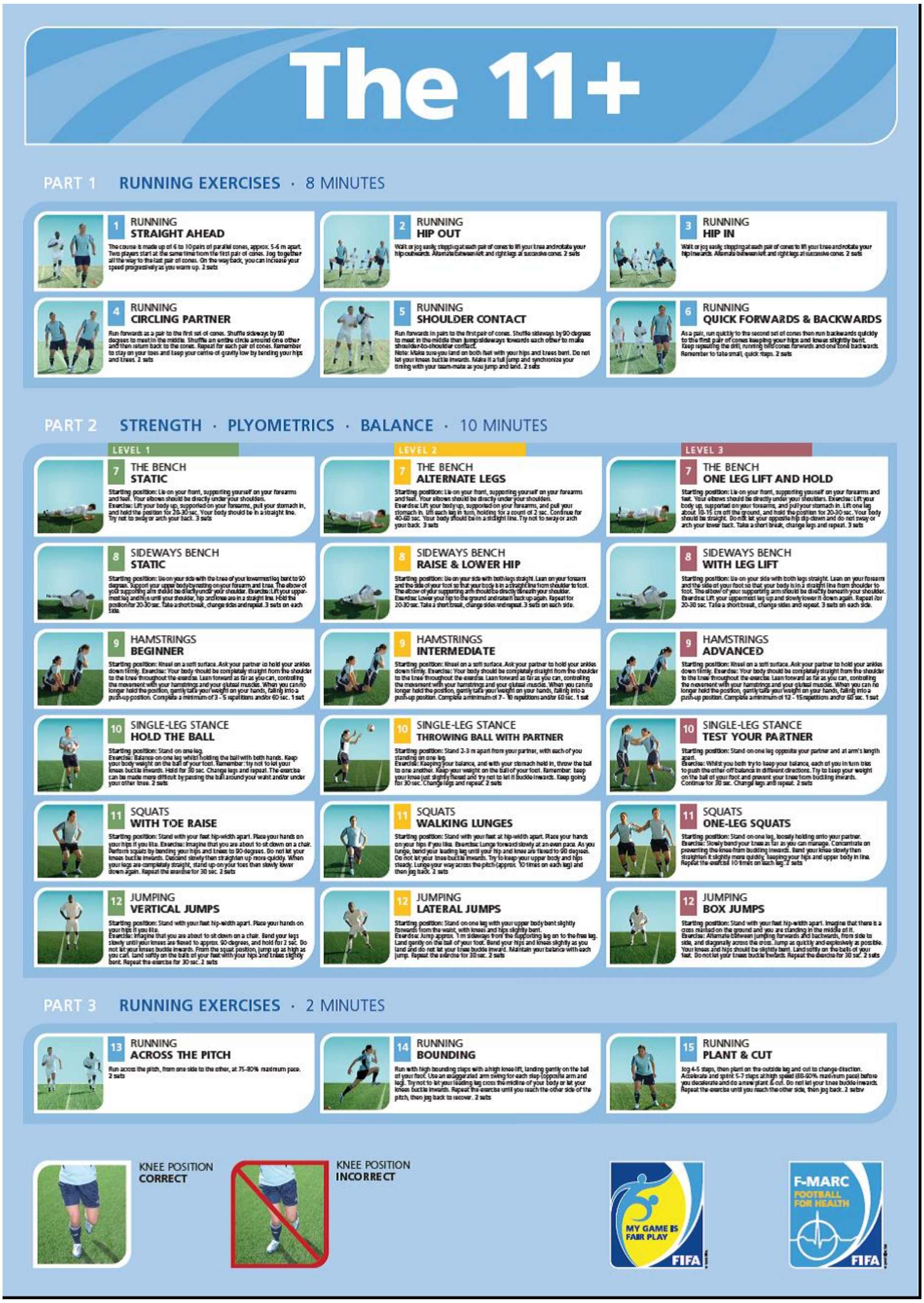

Figure 5.2 FIFA 11+ handouts

5.2.4 Activity log and compliance

Coaches of the experimental group were requested to collect compliance data for each intervention session using a compliance log supplied by the researcher (Appendix 5.1). The compliance log included information on; week and session number, total number of participants completing the session, the amount of reps and sets per exercise per session, and if applicable, the number of participants completing each difficulty level. Participants were included in post-intervention data collection based on two criteria; i) that they were not injured, and ii) that they attended and performed at least 80% of sessions (Soligard et al., 2010).

A further activity log was used as a descriptor of other training that the participants may have been performing outside of the research intervention. The activity log was completed by the participants in experimental and control groups during week one, week four and week eight of the intervention (Appendix 5.2). This information was collected and used as inclusion criteria. Participants were included in the study if they performed between two and four football based sessions per week and were not performing any other form of prevention training.

5.2.5 Statistical Analysis

Three participants were not available for post-intervention data collection sessions having left the development academy during the intervention training period. All other participants met the inclusion criteria and thus were included in subsequent analysis. Descriptive statistics (mean ± *sd*) were calculated for acute fatigue differences (post-fatigue measure-pre-fatigue measure) before and after the eight week training intervention. Inferential statistics were used to examine the qualitative meaning of the observed fatigue differences in test variables from pre to post intervention within and between-groups, with data presented as the mean of the individual change and 90% confidence interval. The smallest worthwhile effect was used to determine whether the observed changes were considered negative, trivial or positive. For within-group analysis, the smallest worthwhile effect was calculated as a change in score standardised to 0.20 of the between-subject standard deviation. For between-group analysis, the smallest worthwhile effect was calculated as 0.20 of the pooled between-group standard deviation at baseline. An online spreadsheet (Hopkins, 2007) was used to calculate the probabilistic inference of each observed change being greater than the smallest worthwhile effect using the thresholds 25 - 75% as possibly, 75 - 95% as likely, 95 - 99.5% as very likely and > 99.5% as most likely (Hopkins et al., 2009). The outcome was deemed unclear where the 90% confidence interval of the mean change overlapped both positive and negative outcomes, otherwise the outcome was clear and inference reported as the category (negative, trivial or positive) where the greatest probability was observed.

5.3 RESULTS

5.3.1 Kinetic Variables

Raw data for kinetic variables pre and post intervention for the effects of the acute fatigue protocol are displayed in appendix 5.3. Within-group analysis revealed mostly *negative* (*very likely, likely*) and *trivial* (*most likely, very likely, likely*) outcomes for the experimental group and *unclear, trivial* (*very likely, likely*), *negative* (*likely*) and *positive* (*very likely*) outcomes for the control group. Table 5.1 shows the mean difference ± SD and inferential outcomes within-group pre to post-intervention. Between-group inferences showed *unclear* effects on all kinetic variables following the completion of the intervention period, with the exception of peak apGRF (*likely negative*). Between-group outcomes are displayed in figure 5.3.

Table 5.1 Mean difference ± *sd* pre to post-intervention inferential outcomes of fatigue difference scores for force variables

	Experimental Group (n = 11)	**Control Group (n = 10)**
Peak vGRF (BW)	0.07 ± 0.64 PT	0.04 ± 0.45 VLT
Peak apGRF (BW)	-0.16 ± 0.26 VLN	0.12 ± 0.08 VLP
vGRF loading rate (N/s)	-388 ± 13040 MLT	-4750 ± 9611 LN
apGRF loading rate (N/s)	-359 ± 5617 VLT	207 ± 1869 LT
Time to peak vGRF (s)	-0.21 ± 0.58 LN	-0.46 ± 0.09 U
Time to peak apGRF (s)	-0.15 ± 0.39 LN	-0.44 ± 0.08 U
GCT (s)	0.05 ± 0.11 LP	0.22 ± 0.05 U

vGRF = vertical ground reaction force, apGRF = anterior posterior ground reaction force, GCT = ground contact time, U = unclear, VLN = very likely negative, LN = likely negative, VLP = very likely positive, LP = likely positive, MLT = most likely trivial, VLT = very likely trivial, LT = likely trivial, PT = possibly trivial

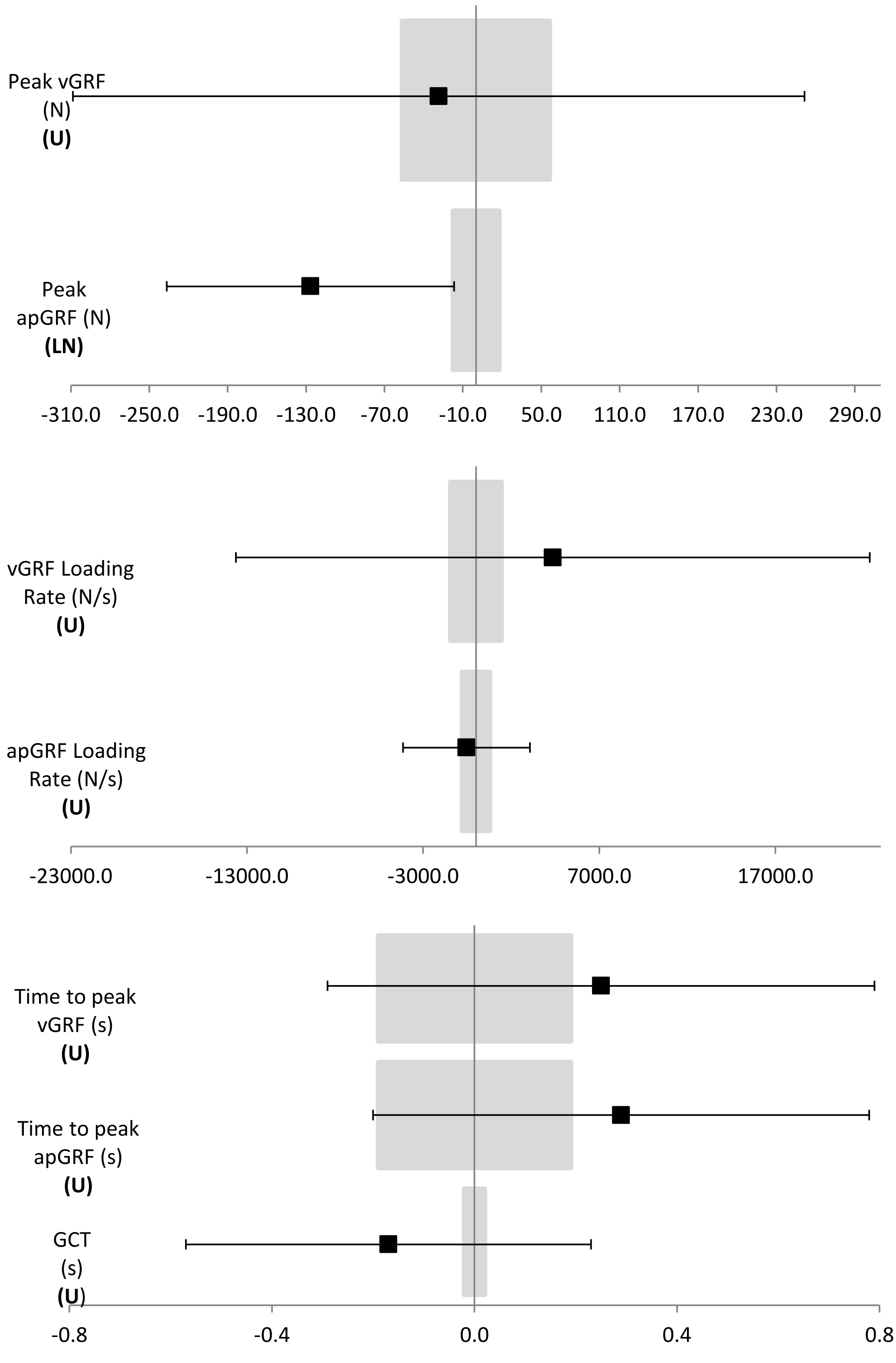

Figure 5.3 Between group inferential outcomes for kinetic variables. *vGRF = vertical ground reaction force, apGRF = anterior-posterior ground reaction force, GCT = ground contact time. Grey shaded area represents smallest worthwhile change, U=unclear, LN = likely negative*

5.3.2 Electromyographic Variables

Raw data for electromyographic variables pre and post-intervention for effects of the acute fatigue protocol are displayed in appendix 5.4. Within-group differences for electromyographic variables displayed mostly *negative* (*very likely, most likely, likely, possibly)* outcomes for the control group with a small amount of *unclear, trivial* (*most likely, very likely and likely*) and *positive* (*most likely, likely and possibly)* outcomes. The experimental group displayed equal amounts of *negative* (*very likely, possibly, likely*) and *positive* outcomes (*most likely, very likely, likely, possibly*) with few *trivial* (*most likely, very likely, possibly*) and *unclear* outcomes. Within-group inferential outcomes are displayed in table 5.2. The majority of between group outcomes were *possibly, likely,* and *most likely negative* for quadriceps activation and *very likely, likely or possibly positive* for hamstrings activation. Between-group inferential outcomes are displayed in figure 5.4. H:Q co-activation ratios displayed mostly *positive* outcomes (*very likely*; pre-activation, *most likely*; 0 – 30 ms, *possibly*; 31 – 60 ms, *likely;* 91 – 120 ms) with the exception of 61 – 90 ms (*possibly negative*).

Table 5.2 Mean difference ± *sd* pre to post-intervention inferential outcomes of fatigue difference scores for electromyographic activation throughout the latency phases

Muscle Site	Time Phase	Experimental Group (n=11)		Control Group (n=10)	
VM	PA (mV)	-0.60 ± 1.20	VLN	-0.14 ± 1.02	VLT
	0-30 ms (%)	1.68 ± 4.63	VLP	8.90 ± 6.29	LP
	31-60 ms (%)	0.55 ± 8.49	VLT	7.39 ± 4.46	MLP
	61-90 ms (%)	-2.02 ± 6.08	U	-1.63 ± 6.24	U
	91-120 ms (%)	-4.51 ± 7.73	U	0.36 ± 6.00	VLT
RF	PA (mV)	0.02 ± 0.02	LP	0.33 ± 0.29	MLP
	0-30 ms (%)	-0.05 ± 10.62	MLT	-3.76 ± 10.92	PN
	31-60 ms (%)	-3.33 ± 9.03	PN	2.11 ± 10.43	PP
	61-90 ms (%)	-1.35 ± 8.85	PT	-0.16 ± 5.03	MLT
	91-120 ms (%)	-5.52 ± 6.50	LN	-6.50 ± 5.73	U
VL	PA (mV)	0.01 ± 0.03	PP	0.02 ± 0.03	MLP
	0-30 ms (%)	-3.98 ± 11.79	U	-0.15 ± 8.46	MLT
	31-60 ms (%)	-5.49 ± 7.89	LN	0.03 ± 6.22	MLT
	61-90 ms (%)	-3.00 ± 5.52	LN	-3.82 ± 9.05	LN
	91-120 ms (%)	-6.86 ± 5.31	VLN	-4.40 ± 6.02	LN
SM	PA (mV)	0.05 ± 0.08	LP	-0.07 ± 0.09	LN
	0-30 ms (%)	-1.94 ± 8.17	PN	-6.88 ± 14.12	LN
	31-60 ms (%)	-5.54 ± 7.21	LN	-2.44 ± 11.67	PN
	61-90 ms (%)	-3.21 ± 6.24	LN	-3.02 ± 5.84	U
	91-120 ms (%)	10.62 ± 32.86	PP	-2.78 ± 7.88	PN
ST	PA (mV)	0.04 ± 0.08	LP	-0.07 ± 0.09	LN
	0-30 ms (%)	4.94 ± 5.96	LP	-6.99 ± 5.86	VLN
	31-60 ms (%)	3.64 ± 6.32	U	-3.44 ± 8.68	PN
	61-90 ms (%)	1.37 ± 6.24	U	-3.29 ± 2.37	LN
	91-120 ms (%)	2.44 ± 5.21	U	-1.33 ± 4.30	PN
BF	PA (mV)	0.02 ± 0.02	VLP	-0.01 ± 0.02	VLN
	0-30 ms (%)	-3.84 ± 13.18	PN	1.97 ± 4.18	LP
	31-60 ms (%)	-1.85 ± 7.12	PN	4.28 ± 4.00	LP
	61-90 ms (%)	-1.61 ± 10.37	PT	-3.90 ± 5.85	U
	91-120 ms (%)	-4.96 ± 10.68	U	-1.38 ± 4.46	U
H:Q Co-activation ratio	PA (%)	-0.23 ± 1.44	PT	-3.51 ± 1.56	MLN
	0-30 ms (%)	0.39 ± 0.29	MLP	-0.62 ± 0.86	VLN
	31-60 ms (%)	0.11 ± 0.36	PP	0.06 ± 0.58	LT
	61-90 ms (%)	0.09 ± 0.30	PP	0.33 ± 0.52	LP
	91-120 ms (%)	0.74 ± 0.66	VLP	0.05 ± 0.29	PT

Muscle sites; VM = vastus medialis, RF = rectus femoris, VL= vastus lateralis, SM = semimembranosus, ST = semitendinosus, BF = biceps femoris, H:Q = hamstring:quadriceps. Time phase; PA = pre-activation, Inferential outcomes;MLN = most likely negative, VLN = very likely negative LN = likely negative, PN = possibly negative, MLP = most likely positive, VLP = very likely positive, LP = likely positive, PP =possibly positive, MLT = most likely trivial, VLT = very likely trivial, PT = possibly trivial, LT = likely trivial, U = unclear

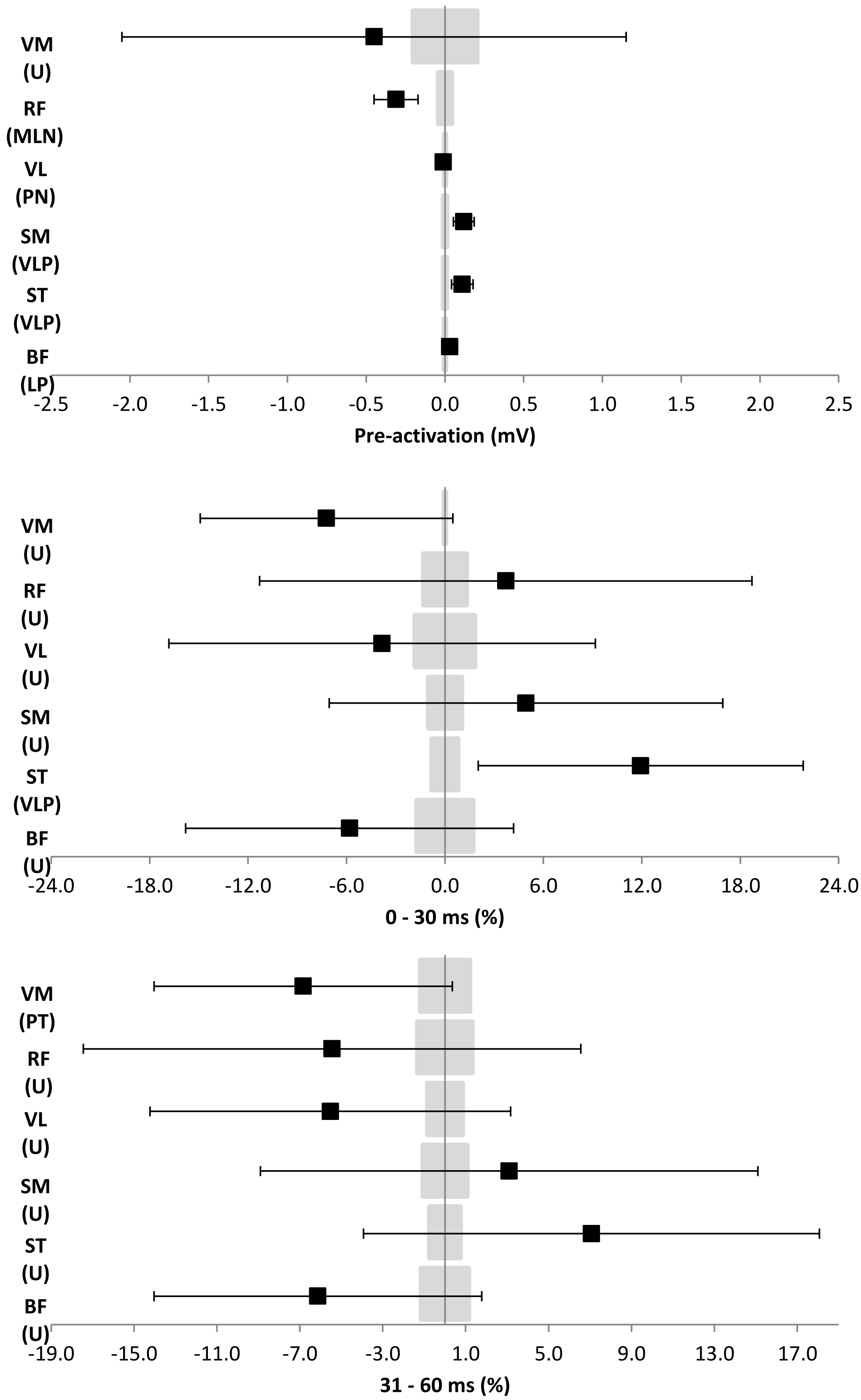

Figure 5.4 Between-group inferential outcomes for electromyographic activation during pre-activation and immediate feedback mechanisms. *Muscle sites; VM = vastus medialis, RF = rectus femoris, VL= vastus lateralis, SM = semimembranosus, ST = semitendinosus, BF = biceps femoris. The grey shaded area represents the smallest worthwhile effect. Inferential outcomes; U = unclear, MLN = most likely negative, PN = possibly negative, VLP = very likely positive, LP – likely positive, PT =possibly trivial*

5.4 DISCUSSION

5.4.1 Kinetic Variables

Data showed that after completion of the eight week training intervention, peak apGRF's following a simulated match-play protocol were *likely* lower in the experimental group in comparison to the control group. Given that data from study 2 showed that the SAFT90 protocol *likely* increased peak apGRF it would appear that from an injury risk factor perspective, the training intervention adopted in the current study elicited favourable changes for the participants.

The peak apGRF observed in an unanticipated cutting manoeuvre is representative of deceleration forces, therefore it could be suggested that the experimental group performed the unanticipated cutting manoeuvre with a decrease in deceleration forces post-intervention following a simulated match-play protocol (Andrews, 1977). The deceleration phase of a cutting manoeuvre decreases momentum of the player using the largest amount of force production possible over the shortest period of time (Andrews, 1977). Pre-activation of the quadriceps muscles develops the deceleration power (Benvenuti et al, 1997; Colby et al., 2000) and this can lead to large GRF's and increases in GCT to attenuate the large forces (Hewit et al., 2011). Data showed the apGRF's following a simulated match-play protocol were *very likely* lower and GCT was *likely* greater in the experimental group after the eight week training intervention in comparison to data collected pre-intervention. The larger GCT will attenuate the lower apGRF force over a longer period of time, producing less stress on ligamentous structures (Hewit et al., 2011). Characteristically, an unanticipated cutting manoeuvre is performed with greater force absorbed over a shorter period of time to produce a quick and sharp movement; however this would place a high amount of stress through the knee joint quickly (Cowley et al., 2006). This would demand greater reflexive muscle activity of the youth female footballers to control these forces (Cowley et al., 2006; Ford et al., 2003). Further to the ability of a larger GCT to attenuate large GRF's during the deceleration phase of an unanticipated cutting manoeuvre, a longer GCT would also provide more time for reflexive muscle control to dynamically stabilise the knee joint (Cowley et al., 2006; Ford et al., 2003). It is difficult to compare the findings of the current research with previous literature as there are no other studies looking at the effect of an injury prevention training programme on kinetic variables following a simulated match-play protocol. Therefore, the current study would appear to provide novel findings within the literature based on the effect of a training intervention on apGRF in youth female footballers performing an unanticipated cutting manoeuvre following a simulated match-play protocol.

Data showed that after completion of the eight week training intervention, the between-group differences for peak vGRF's following a simulated match-play protocol were *unclear*. Given that data from study 2 showed that the SAFT90 protocol *possibly* increased peak vGRF it would appear that from an injury risk factor perspective, the training intervention adopted in the current study showed no quantifiable effect. Previous research provides contradicting findings on the effect of a neuromuscular training programme on peak vGRF, with some studies observing no significant change in peak vGRF following an intervention (Hewett et al., 1996; Irmischer et al., 2004; Prapavessis et al., 2003), and other studies have observed significant decreases in peak vGRF following an intervention (Chappell and Limpisvasti, 2008; Herman at al., 2008; Lephart et al., 2005). Four of the six studies from previous research utilised integrated training programmes consisting of basic strength, balance and plyometric training (Chappell and Limpisvasti, 2008; Hewett et al., 1996; Lephart et al., 2005; Prapavessis et al., 2003), whereas two studies (Herman et al., 2008; Irmischer et al., 2004) utilised isolated methods (strength training and plyometric training). However, those studies that noted significant decreases in peak vGRF following an intervention had the participants perform an integrated training programme under direct supervision (Chappell and Limpisvasti, 2008; Herman at al., 2008; Lephart et al., 2005). Those previous studies that observed decreases in peak vGRF instructed coaches to deliver verbal or auditory feedback aimed at proper landing technique and reducing landing forces (Chappell and Limpisvasti, 2008; Herman at al., 2008; Lephart et al., 2005).

It is possible that the difference in training methods between interventions utilised in previous research and the current study could be a rationale for differences on the effect of a training intervention on vGRF. Previous research utilised jump-landing manoeuvres as a testing protocol and emphasised landing technique during intervention training (Chappell and Limpisvasti, 2008; Herman at al., 2008; Lephart et al., 2005). By training the movement utilised in the testing protocols, participants in previous research would have developed learned responses and proper techniques to reduce landing forces during the testing protocols, which could have improved feed-forward and feedback neuromuscular activity to control the vGRF (Beaulieu & Xu, 2008; Besier et al., 2001b; Bouisset & Zattara, 1987; Ford et al., 2003). Whereas, the FIFA 11+ includes one cutting activity and does not replicate an unanticipated cutting manoeuvre commonly seen in match-play and injury situations (Brophy et al., 2010). Thus a lack of specific movement based training and the reactive nature of the testing protocol meant participants could not develop a learned response to reduce planting and cutting forces during the testing protocol (Beaulieu

& Xu, 2008; Besier et al., 2001b; Bouisset & Zattara, 1987). Therefore, a lack of substantial change in vGRF following a simulated match-play protocol could have been due to the ineffectiveness of the FIFA 11+ in training learned responses and safe technique for the performance of cutting manoeuvres and the reactiveness of the testing protocol. Further to this, previous research has not identified the effect of a training intervention on vGRF following an acute bout of fatigue. Therefore, it would appear the finding of the current study is novel to the current literature.

5.4.2 Electromyographic Variables

Data showed that after completion of the eight week training intervention, pre-activation of the quadriceps following a simulated match-play protocol were *unclear* (VM), *most likely* (RF) and *possibly* (VL) lower in the experimental group in comparison to the control group. Given that data from study 2 showed that the SAFT90 protocol *most likely* decreased quadriceps pre-activation it would appear that from an injury risk factor perspective, the training intervention adopted in the current study did not improve the fatigue resistance of feed-forward quadriceps control and prove beneficial for the participants. However, data showed that after completion of the eight week training intervention pre-activation of the hamstrings following a simulated match-play protocol was *very likely* and *likely* greater in the experimental group in comparison to the control group. Considering that data from study 2 showed that the SAFT90 protocol *very likely* decreased BF activation and produced *trivial* changes in ST and SM activation, the training intervention performed by the participants in the current study produced favourable effects on hamstring activation. During background muscle activity (0 - 30 ms), a continuation of feed-forward activation, differences between the control and experimental group were mostly *unclear*, with the exception of ST activation. Data showed that after completion of the eight week training intervention, background muscle activity of ST following a simulated match-play protocol was *very likely* greater in the experimental group compared to the control group. These findings display further favourable effects of the training intervention on the fatigue resistance of the hamstrings related to feed-forward neuromuscular activation.

Feed-forward mechanisms of the hamstrings and quadriceps muscle groups prepares to dynamically stabilise the knee for loading absorbing GRF's and decreasing stress on the ligaments of the knee (Hewett et al., 2005). From pre to post-fatigue, feed-forward muscular activation generally increases due to reduced muscular force capacity (Kellis et al., 2011). However, following a simulated match-play protocol in study 2, the quadricep muscles produced a decrease in activation during feed-forward mechanisms and the hamstring muscles displayed a decrease in pre-activation, but increase in background muscle activity (0 - 30 ms). In many instances, ACL injury occurs too quickly for reflexive muscle control and therefore feed-forward responses of knee joint dynamic stabilisers is crucial in the prevention of ACL injury (Krosshaug et al., 2007).

The *most likely* (RF) and *possibly* (VL) lower quadriceps pre-activation of the experimental group, compared to the control group, could contribute to decreased deceleration power in the experimental group which is vital for absorbing eccentric forces during GCT (Benvenuti et al, 1997; Colby et al., 2000; Hewit et al., 2011). The positive effects of the eight week training intervention on the fatigue resistance of peak apGRF in the experimental group could be linked to the reduction in pre-activation of the quadriceps muscles decreasing deceleration power (Hewit et al., 2011). A reduction in quadriceps activation during pre-activation may be a protective mechanism of the female footballers to reduce the risk of ACL injury. This protective mechanism of the quadriceps is evident in the findings of the effect of the training intervention on H:Q co-activation ratios following a simulated match-play protocol. Data showed that following the eight week training intervention, the experimental group produced a *very likely* increase in the H:Q co-activation ratio during pre-activation in comparison to the control group. In study 2, data showed a *most likely trivial* effect of a simulated match-play protocol on H:Q co-activation ratios during pre-activation, indicating the training intervention performed by the participants in the current study produced favourable effects. Large deceleration forces produced by the quadriceps can produce large GRF's, and powerful quadriceps contraction can cause anterior tibial shear, which if not matched by antagonistic hamstring co-activity will place a great amount of stress on the ACL (Hewitt et al., 2011; Zebis et al., 2011). Previous research has established that ACL injury commonly occurs within 17 – 50 ms after initial contact, therefore neuromuscular activation during 0 - 30ms would be crucial in reducing the risk of ACL injury. The current study observed that following the eight week training intervention, the differences between experimental and control groups on background muscle activity of the quadriceps were unclear after a simulated match-play protocol. However, the current study identified that following the eight week intervention the H:Q co-activation ratio during background muscle activity (0 - 30 ms) after a simulated match-play protocol was *most likely* greater in the experimental group, in comparison to the control group. Considering H:Q co-activation ratios during background muscle activity were quadriceps dominant following the acute fatigue protocol in study 2, an increase in the experimental group compared to the control group shows favourable effects of the eight week training intervention. It has previously been suggested that females are quadriceps dominant which can place them at a higher risk of ACL injury (Ebben et al., 2010). The training effects of increased H:Q co-activation during pre-activation and background muscle activity (0 - 30 ms) could be beneficial in reducing anterior tibial shear at the time ACL injury commonly occurs (Hewit et al., 2011; Krosshaug et al., 2007).

The hamstring muscles are important antagonists to the anterior shear of the tibia minimising stress on the ACL (Zebis et al., 2011). The antagonistic action of the hamstrings musculature is of particular importance during pre-activation when a powerful quadriceps contraction exhibiting an anterior force on the tibia is present with the deceleration phase of the unanticipated cutting manoeuvre (Quatman, 2010; Zebis et al., 2011), and during 0 - 30 ms when ACL injury commonly occurs (17 - 50 ms) (Krosshaug et al., 2007). In comparison to anticipated conditions, the unanticipated cutting manoeuvre produces a greater risk of ACL injury due to sagittal plane components such as hamstrings co-activity and patella tendon anterior shear (Weinhandl et al., 2014). In the current study, the eight week training intervention produced *very likely* (SM & ST) and *likely* (BF) higher pre-activation of the hamstrings following a simulated match-play protocol in the experimental group, compared to the control group, showing a favourable effect of the intervention.

Previous research on the effect of neuromuscular training on quadriceps and hamstrings activation during the performance of a side cutting manoeuvre observed significant increases in lateral hamstring activation 10 ms after initial contact in high school female athletes (Waxman et al., 2016). The researchers utilised a six week training programme which had been previously shown to reduce ACL injury risk, and a side cutting manoeuvre performed bilaterally. Although, significant increases in lateral hamstring activation were produced in the dominant limb of the high school female athletes, similarly to the current study there were no significant differences observed in the lateral hamstrings of the non-dominant limb immediately following initial contact (Waxman et al., 2016). The non-dominant limb is the most commonly injured limb in non-contact ACL injury of female athletes (Brophy et al., 2010; Cowley et al., 2006; Landry et al., 2007; Silvers et al., 2007). Contrary to the lateral hamstring findings of the current study, previous research has observed significant improvements in non-dominant peak hamstring torque following the FIFA 11+, which has been related to greater electromyographic activity and an increase in Type II muscle fibres (Komi & Tesch, 1979; Britoa et al., 2010). The differences in findings between the current study and Britoa et al. (2010) could be due to the intervention and dynamic pre and post testing protocol utilised. The participants in the experimental group of the current study performed the intervention two to three times weekly for eight weeks and participants of Britoa et al. (2010) performed the FIFA 11+ three times weekly for ten weeks. It could be suggested that longer training interventions are necessary to realise training effects in the lateral hamstrings of the non-dominant limb (Britoa et al., 2010). It could be speculated that changes occur quicker and more easily in the dominant limb than the non-dominant limb which needs longer term training and higher adherence to an intervention (Britoa et al., 2010; Steffen et al., 2013).

Further to this, the current study utilised an unanticipated cutting manoeuvre as a pre and post dynamic testing protocol, whereas Britoa et al. (2010) utilised isokinetic dynamometry. Isokinetic dynamometry does not replicate ACL injury mechanisms in football match-play, thus the relevance to ACL injury risk during football match-play is questionable. In comparison to the current study, the isokinetic dynamometry testing protocol is not as dynamic as the unanticipated cutting manoeuvre and does not require reactive decision making to perform the skill. The anticipatory effects of pre-planned dynamic tasks have been studied and it is suggested that participants performing an anticipated cutting manoeuvre produce a feed-forward mechanism, showing a pre-planned modification by the CNS system for anticipated conditions (Besier et al., 2001). This learned feed-forward response could be better improved with training in the dominant limb, compared to non-dominant limb. In the current study, the *likely* increases in BF pre-activation in the experimental group compared to the control group, display that even with an unanticipated cutting manoeuvre, a trained response can be exhibited by the female footballer. From an ACL injury risk perspective the FIFA 11+ can produce favourable effects on lateral hamstring pre-activation in the non-dominant limb of female footballers performing an unanticipated task.

Increases in pre-activation and immediate feedback activation of BF have also been observed with increased running speed (Kyrolainen, 2007). Research has observed that two-joint muscles increased in electromyographic activity with increased speed, whereas single joint muscles did not, suggesting that increased activity of the two-joint muscles produces a more powerful force production (Kyrolainen, 2007). Previous research has found that originally ‘The 11’ produced significant improvements in speed over 20 m in young footballers (Kilding et al., 2008), but contradictory to this the FIFA 11+ has been found to have no significant effects on player speed (Impellizzeri et al., 2013). Therefore, it can be suggested that any increased activity of two joint muscles following the eight week training intervention is not associated with increases in speed. The increased activation observed in the current study during pre-activation would decrease the risk of ACL injury inflicted by hamstrings co-activity. However, due to the relationship between medial and lateral activation and valgus collapse, any increases in BF would need to be proportionally increased or greater increased in the medial hamstrings (ST & SM).

Data showed that following the eight week training intervention, the experimental group displayed *very likely* greater pre-activation of ST and SM following a simulated match-play protocol, compared to the control group. The improvements in fatigue resistance of ST were also displayed during 0 - 30 ms with data showing *very likely* greater activation in the trained experimental group, compared with the control group, following a simulated match-play protocol. Considering the control group displayed *very likely* and *likely* decreases in pre-activation and background muscle activity (0 - 30 ms) of the medial hamstrings (SM & ST) following a simulated match-play protocol from pre to post eight week training intervention, and the experimental group experienced *likely* and *very likely* increases, from an ACL injury risk perspective the training intervention appears to have had beneficial effects on feed-forward neuromuscular control of the hamstrings. The medial hamstring musculature, specifically ST, plays an important role in compressing the medial knee joint and decreasing the risk of valgus collapse during sidestep cutting manoeuvres (Palmieri-Smith et al., 2009). A valgus collapse alone has been suggested to be enough to rupture the ACL, whereas knee extension moments and anterior shear force loads are not sufficient enough alone to cause ACL injury (Zebis et al., 2011). As well as this, lateral trunk flexion is increased with unanticipated conditions which have been linked to increases in knee valgus angles, thus an unanticipated cutting manoeuvre predisposes female footballers to an ACL injury. Therefore, it is important for prevention programmes, like the FIFA 11+, to increase the feed-forward response of ST in youth female footballers to reduce the risk of ACL injury during cutting manoeuvres.

Zebis et al. (2016) also observed improved pre-activation of ST in adolescent female football and handball players during a sidestep cutting manoeuvre following a neuromuscular training programme. Zebis et al. (2016) also observed better coactivity of ST:VL with a significant decrease in the difference between the two muscles pre-activation. In the current study, data showed that following the training intervention the experimental group displayed *very likely* higher pre-activation of ST and possibly *lower* pre-activation of VL in comparison to the control group, following a simulated match-play protocol. Therefore it can be suggested that the difference between the two muscles pre-activation would have decreased with the intervention, as observed by Zebis et al. (2016). These changes could protect the adolescent female athletes against non-contact ACL injury with greater medial compression of the knee, lower risk of valgus collapse, and increased hamstrings co-activity (Jamison, Pan & Chaudhari, 2012; Mornieux et al., 2014; Palmieri-Smith et al., 2009; Zebis et al., 2016).

The intervention utilised by Zebis et al. (2016) was a handball specific programme including similar exercises to the FIFA 11+ (balance, sports-specific exercises, and Nordic hamstrings) performed in the current study, and the handball exercises were adapted for the footballers utilising ball dribbling rather than handball throwing. It has been previously identified that those neuromuscular training programmes that are effective in reducing injury incidence in female athletes are 15-20 minutes in duration, performed two-three times weekly, sport-specific, and multi-component (Michaelidis & Koumantakis, 2014).

Both the FIFA 11+ utilised in the current study and the handball neuromuscular training programme utilised by Zebis et al. (2016) contain these components for effectiveness, and effects of the programmes on medial knee pre-activation are similar. Wilderman et al. (2009) observed that six weeks of training four times weekly was enough training to establish a change in ST pre-activation during a sidestep movement. Zebis et al. (2016) utilised a 12 week training programme which produced an upregulation of ST pre-activation in the experimental group compared to the control group. This upregulation of ST pre-activation was replicated in the current study that had an eight week training intervention period. Therefore, it could be suggested that longer training periods of eight weeks or more may establish a more ACL protective strategy than six week training periods. Contradicting previous research has utilised a six week programme, which might not have been long enough for a quantifiable or established improvement of ST pre-activation (Waxman et al., 2016). Zebis et al. (2016) is the only previous research to utilise a sidestep cutting manoeuvre in the analysis of the effects of an intervention on neuromuscular activation, similar to the current study. However, the research (Zebis et al., 2016) did not investigate the ability of neuromuscular training programmes to train a fatigue resistance in the electromyographic variables of female athletes. Whereas, the similar findings from the current study represent the ability of the FIFA 11+ to minimise the effects of fatigue on ST pre-activation in youth female footballers performing an unanticipated cutting manoeuvre. In the current study, in a non-fatigued state, the youth female footballers did not show any improvements in ST pre-activation following the acute fatigue protocol.

The two interventions used in the current study and previous research (Zebis et al., 2016) had both been proven to reduce ACL injury incidence. However, the programme utilised in previous research (Zebis et al., 2016) is much more comprehensive than the FIFA 11+. The handball specific neuromuscular training programme (Zebis et al., 2016) includes; a greater number of exercises, sport-specific, game realistic movement based technique training developing learned responses to ACL injury situations and match-play situations, the use of equipment to develop balance training, and a greater number of cutting based activities replicating the common ACL injury mechanism in female football and handball players (Zebis et al., 2016). The handball specific neuromuscular training programme (Zebis et al., 2016) contains twenty-two movement based exercises including; four cutting exercises with and without a ball, turning under pressure, and dribbling and passing on the move. In comparison to the FIFA 11+ which provides nine movement based exercises including; one cutting exercise without a ball or any opponent pressure, and no dribbling or passing exercises. The more sport-specific and match realistic movement based exercises included in the handball-specific neuromuscular training programme could develop learned responses in the participants which they are able to utilise in a sidestep cutting manoeuvre post-intervention (Zebis et al., 2016).

Following a simulated match-play protocol, the learned responses of the hamstrings are enhanced in the experimental group with greater feed-forward activation (pre-activation, 0 – 30 ms) after the eight week training intervention, compared to the control group. It is possible that the Nordic Hamstring exercise prescribed in the FIFA 11+ could have produced learned responses in the fatigued participants of the current study. Specifically, the Nordic Hamstring exercise has been observed to induce hamstring fatigue with significantly reduced torque and EMG activity changes after only one set of five repetitions in adult amateur male soccer players (Marshall et al., 2015). Subsequently the participants that performed the FIFA 11+ in the current study could have experienced hamstring fatigue whilst performing the intervention training (Marshall et al., 2015). Specifically, the EMG activity changes observed in the adult amateur male footballers after performance of the Nordic Hamstring exercise were increases in activity during the descent phases (eccentric) and decreases during the ascent phase (concentric) (Marshall et al., 2015). During an unanticipated cutting manoeuvre, there is an eccentric quadriceps force during the deceleration phase of the manoeuvre to create a deceleration power. This eccentric quadriceps contraction is quickly followed by a concentric quadriceps contraction, and eccentric hamstrings contraction immediately following initial contact. Therefore it could be suggested that in the current study, improvements in the fatigue resistance on hamstrings activation and H:Q co-activation ratios of the experimental group during background muscle activity (0 - 30 ms, eccentric hamstring phase) following the eight week training intervention could be due to the hamstring muscles experiencing fatigue with the Nordic Hamstring exercise, and thus increasing EMG activity of the hamstrings eccentrically and producing a fatigue resistance of hamstrings activity during background muscular activity (0 - 30 ms) (Marshall et al., 2015).

Based on descriptive data, the improvements in feed-forward activation of the hamstrings in the experimental group following a simulated match-play protocol were not present before the acute fatigue protocol. This could have been due to a lack of movement based training in the FIFA 11+ (Marshall et al., 2015). Further to this, the prevention programme used by Zebis et al. (2016) have four variations of cutting movements replicating the dynamic task utilised pre and post-intervention testing. The programme also included a double hop with ball squeeze between knee exercise, which could be suggested to target medial knee activation during a dynamic task to help prevent valgus collapse (Jamison, Pan & Chaudhari, 2012; Mornieux et al., 2014; Palmieri-Smith et al., 2009). Repetition of faulty mechanics during any dynamic based exercise sets poor feed-forward learning and increases the risk of ACL injury, whereas repetition of correctly performed dynamic tasks will develop learned responses that will reduce the risk of ACL injury (Chimera et al., 2004). Thus, the greater repetition of the cutting manoeuvre performed by the participants in the study by Zebis et al. (2016), in comparison to the current study, could produce better learned responses without fatigue present.

Data from the current study shows a fatigue resistance of ST to produce improved feed-forward mechanisms before and immediately following initial contact of the unanticipated cutting manoeuvre in the experimental group, displaying favourable effects of the training intervention. Following the eight week training intervention, the experimental group displayed a protective effect of ST with improved pre-activation following a simulated match-play protocol. Previous research on the effect of a neuromuscular training programme on neuromuscular fatigue is limited. In female young adults, plyometric training has been observed to increase the onset rate of fatigue in comparison to weight-training programmes (McLaughlin, 2001). The FIFA 11+ and many other neuromuscular training programmes contain plyometric exercises to develop neuromuscular adaptations, but it is possible that the plyometric exercises included could reduce the onset of fatigue and maintain or improve muscle activation levels when experiencing fatigue (McLaughlin, 2001). Thus, improvements in fatigue resistance identified in the current study could be attributed to plyometric training contained within the eight week training intervention (McLaughtlin, 2001).

Following the feed-forward responses, it is important that the youth female footballers are able to produce effective feedback responses to react to the dynamic task and stabilise the knee throughout the unanticipated cutting manoeuvre. An important latency phase of feedback neuromuscular control is 31 – 60 ms, overlapping the time when ACL injury usually occurs (17 - 50 ms). During this latency phase, all tested muscle sites displayed *unclear* differences between the experimental and control groups. From an injury risk factor perspective, this shows no substantial effect of the eight week training intervention on immediate neuromuscular feedback. The experimental group who undertook FIFA 11+ training two - three times weekly for eight weeks, displayed *possibly* and *likely* lower activation of RF, VL, SM and BF during immediate feedback (31 - 60 ms) following acute fatigue. During a time when ACL injury commonly occurs (17 - 50 ms), efficient neuromuscular activation of the hamstrings and quadriceps is vital in reducing the risk of ACL injury, and lower activation of the hamstrings muscles particularly would heighten the risk of ACL injury.

Subsequently, following the eight week training intervention the experimental group experienced no substantial differences in H:Q co-activation ratio during 31 – 60 ms in comparison to the control group, with the data showing *unclear* results. This finding would indicate no effect of the training intervention on H:Q co-activation ratio during a time when ACL injury commonly occurs (Krosshaug et al., 2009). Previous research has observed positive effects of plyometric training on the reactive H:Q co-activation ratios of athletes. Previous research has observed better symmetry of quadriceps and hamstrings activation of female athletes that had followed a twice weekly six week training programme (Chimera et al., 2004) and increased hamstring to quadriceps muscle peak torque ratio in the dominant (13%) and non-dominant (26%) limbs of female athletes which corrected previously established limb imbalances (Hewett et al., 1996). Thus, plyometric training has been observed to balance joint loads for effective dynamic stabilisation of the knee, and correct limb imbalances (Chimera et al., 2004; Hewett et al., 1996). The FIFA 11+ includes three plyometric exercises (squats with toe raise, vertical jumps, and Nordic hamstrings), which are advanced through three levels. In the current study, the participants of the experimental group did not advance past level 1 for any of the exercises. In previous research, plyometric training consisted of more advanced exercises (drop jumps, wall touches, lateral bounding), weighted exercises, and a greater quantity of plyometric exercises, which could have placed greater load on those participants performing the plyometric training and produced improved training effects on reactive H:Q co-activation ratios, in comparison to the FIFA 11+. Therefore, it could be suggested that the plyometric load of the FIFA 11+ is not enough to produce a positive training effect on immediate (reactive) neuromuscular control. Further to this, previous research on plyometric training utilised vertical jumps and drop-jump landings as testing protocols, which was trained in the intervention training to a greater degree than cutting manoeuvres are trained in the FIFA 11+. Thus, a lack of specific movement based training could have reduced the ability of the FIFA 11+ to develop learned responses to the testing protocol, and improve fatigue resistance of immediate feedback neuromuscular control.

5.5 PRACTICAL APPLICATIONS

From an ACL injury prevention perspective, the current study would suggest that the FIFA 11+ is beneficial in improving fatigue resistance of various kinetic and electromyographic variables of youth female footballers performing an unanticipated cutting manoeuvre. With the experimental group displaying a decrease in the effect of fatigue on peak apGRF in comparison to the control group, there is less load applied to the knee joint during the cutting manoeuvre. Therefore, the eight week training intervention ensured safer loads in the anterior-posterior direction. From study 2, it was clear that female footballers could benefit from enhanced ability to better tolerate impact from cutting to ensure they can safely tolerate larger loads over shorter periods of time experienced with fatigue. Although the training intervention lowered the load in the anterior-posterior direction, all other kinetic variables were unclear. Thus, changes to the FIFA 11+ that would improve the fatigue resistance of kinetic variables such as; lowering vGRF and increasing time to peak forces and GCT, would further benefit the female footballers to ensure lower loads are absorbed over longer periods of time following a simulated match-play protocol. Greater plyometric loads during the training intervention, a larger quantity of sport-specific movement based training aimed at reducing forces and improving technique of sidestep cutting, and performing the training intervention in a state of acute fatigue could produce greater beneficial effects of the FIFA 11+ on the fatigue resistance of kinetic variables.

Favourable effects of the FIFA 11+ on electromyographic variables were observed for feed-forward hamstrings control, specifically pre-activation of all three hamstring sites, ST activation during background muscle activity (0 - 30 ms), and H:Q co-activation ratios during pre-activation and background muscle activity (0 - 30 ms). Study 2 identified a protective activation of ST and SM during pre-activation and background muscle activity, and increases in H:Q co-activation ratios following a simulated match-play protocol. The eight week training intervention further enhanced the neuromuscular control of the hamstrings following a simulated match-play protocol. It is suspected that these changes occurred due to decreased force generating capacity of the hamstrings following the acute fatigue protocol (Kellis et al., 2010), the Nordic Hamstring exercise producing hamstrings fatigue during the intervention training and thus training a fatigue resistance of the hamstrings (Marshall et al., 2015), and plyometric training (Chimera et al., 2004; Hewett et al., 1996). From these findings, it could be suggested that injury prevention training that induces a certain level of neuromuscular fatigue, or performing intervention training when experiencing acute neuromuscular fatigue, could develop fatigue resistance of key neuromuscular risk factors for ACL injury.

5.6 LIMITATIONS

- *Coach supervision of FIFA 11+ trainin* - The current thesis required the coach to supervise and collect adherence data including; session participation, exercise participation (reps/sets) and level of difficulty for Part 2 of the FIFA 11+. The coach was asked to ensure the participants were using good technique throughout the FIFA 11+. The level of coach supervision was not monitored, but all resources were provided. Previous research has observed beneficial effects of neuromuscular training on biomechanical risk factors when auditory and verbal cues and feedback are delivered by coaches supervising the training (Padua & DiStefano, 2009). However these beneficial effects are not observed when neuromuscular training programmes are not supervised (Padua & DiStefano, 2009). Therefore, the coach supervision utilised in the current study would have provided greater potential for training effects to occur in the participants following the neuromuscular training programme.

- *Randomisation of control and experimental group.* Control and experimental groups were randomly selected after organising participants by playing position. There are further confounding factors that could have been considered when randomly assigning participants to control or experimental groups, and therefore could have had implications on the outcomes of the current study;
  - *High risk vs. low risk athletes* – Previous research has classified and grouped individuals by ACL injury risk using knee abduction moments. Myer et al. (2007) determined high and low risk participants as knee abduction moment of above and below 25.25Nm. The participants then participated in a 3x weekly 7 week neuromuscular training programme. The researchers observed that high risk female athletes decreased knee abduction moments following neuromuscular training, whereas the neuromuscular training had no effect on the low risk female athletes. Further to this, knee abduction moments of the high risk female athletes were not lowered to levels similar to the low risk group following training (Myer et al., 2007). The risk of ACL injury can affect the adaptations to neuromuscular training with high risk participants displaying greater adaptations to training than low risk participants. In the current study, it is possible that those who may have been classified as low risk participants in the FIFA11+ training group may not have developed as greater training

adaptations to the programme as those considered high risk participants. However, changes were calculated within-subject rather than group averages. Future research may want to consider level of risk as a factor when randomising groups into control and experimental, particularly when using between-group or between-subject analysis.

- *Sport specialisation vs. multi-sport athletes* – Sports specialisation in youth athletes can reduce motor skill development as young athletes are focused on only the motor skills they require for their specialised sport, and lack the array of motor skills that can be developed through multi-sport participation (Mostafavifar et al., 2012). However, with correct training and technique, those athletes specialising in a sport can develop more efficient and safe neuromuscular and biomechanical control and technique of the manoeuvres specific to their sport. For example; frequently training the unanticipated cutting manoeuvre commonly performed in football would develop learned responses to ACL injury situations and match-play situations (Besier et al., 2001). However, ensuring repetition of correct technique is vital, as frequent repetition of poor technique in training and competition can develop inefficient neuromuscular control patterns in youth athletes, which will be greater in those athlete specialising in one sport due to the quantity of training the same movement patterns compared to multi-sport athletes who perform a greater range of movement based activities (Cowley et al., 2006).

  Sports specialisation has contributed to increasing rates of sports-related injuries, thus those who do specialise in one sport may display greater neuromuscular and kinetic deficits than multi-sport athletes. Multi-sport participation alongside a neuromuscular training programme could help reduce the likelihood of sports-related injuries in youth athletes (Mostafavifar et al., 2012). Dalton (1992) identified that during periods of biological development (childhood and adolescence) excessive training in a specialised sport can produce excessive stress on joints and connective tissues which are already tight and inflexible due to muscles and tendons not increasing at the same rate as bones. This can create muscular imbalances making youth athletes susceptible to injury (Baker et al., 2009; Dalton, 1992). Although multi-sport participation can reduce the risk of injury, those that have sport specialised and therefore are at higher risk of injury, will display greater effects from the injury intervention, therefore future research may want to consider sport specialisation and multi-sport athletes when randomising control and experimental groups.

- *Years of physical activity/football experience* – Previous research has observed predictable age-related changes in skeletal muscle function with the typical adult losing muscle mass with age. However, the loss of cross-sectional area, fibre numbers and denervation of some fibres can be minimized or even reversed with training. Thus, those athletes that have participated in physical activity or training for a longer proportion of their life could have a greater quantity of Type II muscle fibres and greater muscle mass in comparison to someone of the same age who had not participated in as much training. Therefore, those participants who trained from a young age will produce greater force. The “muscle age” is not only dependent on the quantity of training throughout childhood and adolescence but also the type of training. Endurance training could improve the muscles aerobic capacity, and resistance training can improve muscle recruitment and activation, and increase muscle mass (Kirkendall et al., 1998). Sigward and Powers (2006) studied the effect of athletic experience on H:Q co-activation ratios during a preplanned sidestep cutting maneuvre performed by novice (five years or less experience) and experienced (more than five years experience) youth female athletes (14 - 16 years old). The researchers identified that novice female athletes display significantly greater H:Q co-activation during early deceleration of a sidestep cut (pre-activation) than experienced athletes, thus responding to the tak witht eh principles of skill acquisition (i.e. mass co-activation). The researchers also observed a negative relationship between the number of years experience and the H:Q co-activation ratio; suggesting that those females with greater years of experience performed the cutting task with less muscle co-activation. Russell et al. (2008) observed that adult participants (female and male) displayed larger H:Q co-activation ratios than children during the pre-activation phase of a two footed landing. These findings could indicate a learned feed-forward mechanism in adults (Ruseel et al., 2008).

5.7 KEY FINDINGS

1. Following the FIFA 11+ two to three times weekly for eight weeks could decrease peak apGRF in youth female footballers performing an unanticipated cutting manoeuvre following a simulated match-play protocol. Decreases in activation and deceleration power produced by the quadriceps muscles before initial contact could have contributed to the reduction in peak apGRF.

2. After the 8 week training intervention, fatigue resistance of feed-forward and immediate feedback responses of ST in youth female footballers performing an unanticipated cutting manoeuvre were improved; this could reduce the risk of valgus collapse on the knee.
3. The FIFA 11+ increased H:Q co-activation ratios during feed-forward mechanisms of the experimental group compared to the control group following a simulated match-play protocol, however the H:Q co-activation ratios during 31 - 60 ms displayed unclear between-group differences following a simulated match-play protocol.

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Chapter 6: Conclusion

6.1 OVERALL SUMMARY

The thesis enhances the knowledge of the effect of fatigue on kinetic and electromyographic variables of youth female footballers performing an unanticipated cutting manoeuvre, and the potential modification of these variables in the prevention of ACL injury risk after an eight week training intervention. There is existing research examining the kinetic and electromyographic variables of female footballers during various dynamic tasks. Research of the effect of fatigue on some of these variables is existing. However, the current research appears to be the first to examine the effect of the FIFA 11+ on the electromyographic and kinetic variables of youth female footballers performing an unanticipated cutting manoeuvre following a simulated match-play protocol, and consequently when female footballers are at a higher risk of injury (Krustrup et al., 2003; Mohr et al., 2005).

Combinations of modifiable kinetic and neuromuscular risk factors have been attributed to increased ACL injury risk in females, particularly youth females (Alentorn-Geli, 2009; Cowley, 2006; Griffin et al., 2000; Landry, 2007; Myer, 2004). Yet, previous research on ACL injury risk in females has not examined these risk factors simultaneously, or an unanticipated cutting manoeuvre as a dynamic task to collect data. Alternative reliability research has utilised either sEMG or kinetic data during anticipated dynamic tasks (Alenezi et al., 2014; Bolgla et al., 2010; Ferber et al, 2002; Fauth et al., 2010), but no previous research has utilised the two together with an unanticipated dynamic task. In Study 1, the combination of measures utilised throughout the current thesis were tested for test-retest reliability over multiple sessions. The study revealed that standards of reliability were met for a range of kinetic and electromyographic measures, and that these measures were acceptable to use for the consequent research.

The cutting manoeuvre has previously been identified as the most common mechanism of ACL injury in female football (Brophy et al., 2010), and in the game of football cutting is most commonly performed in an unanticipated manner (Young & Farrow, 2006). However, previous research studying the modifiable ACL injury risk factors present in female footballers has utilised a variety of dynamic tasks such as; vertical jump, drop-jump landings and pre-planned anticipated cutting manoeuvres. Furthermore the research on the effect of football specific fatigue on these risk factors is limited. Previous research has utilised general intermittent fatigue protocols, pre-planned anticipated dynamic tasks, and a limited number of outcome variables (Cortes et al., 2013; Gerlach et al., 2005; Kellis et al., 2011; Lucci et al.,2011; Smith et al., 2009; Weiss & Dickin, 2013; Zebis et al., 2011). In Study 2, it was revealed that youth female footballers displayed increases in GRF's , larger H:Q co-activation ratios displaying hamstring dominant strategies, and an ACL protective effect of ST and SM activation maintaining activation levels, following a simulated match-play protocol. The data suggested that following a simulated match-play protocol, the female footballers experienced greater force absorption but utilised a safer muscle recruitment strategy.

The prevention of ACL injury has previously been investigated with previous research observing a decrease in ACL injury risk in female footballers following neuromuscular training that was performed two-three times weekly, 15 - 20 minutes long, and implemented multi-component, sport-specific exercises (Grimm et al., 2015; Michaelidis

& Koumantakis, 2014; Yoo et al., 2010). The FIFA 11+ is a neuromuscular training programme that has been shown effective in lowering knee and overall injury incidence in youth female footballers (Owoeye et al., 2014; Soligard et al., 2008; Steffen et al., 2013). Owing to the majority of injuries in female footballers occurring in the last 30 minutes of each half of football match-play, when fatigue is present, and the findings of Study 2, it is important that injury prevention training improves the fatigue resistance of ACL injury risk factors. Study 3 examined the effects of the FIFA 11+ on the fatigue resistance of various kinetic and electromyographic variables. Favourable effects of the FIFA 11+ training were observed including; decreases in apGRF, increased feed-forward neuromuscular activation of the hamstrings, and improved H:Q co-activation ratios during feed-forward phases, following a simulated match-play protocol. Considering previous research (Palmieri-Smith et al., 2009), the combination of these favourable adaptations are likely to have reduced the risk of valgus collapse in the female footballers, a key ACL injury mechanism.

It is clear from the research that youth female footballers display kinetic variables during unanticipated cutting manoeuvres that may place them at risk of ACL injury, and this risk is further enhanced with fatigue (Cortes et al., 2011; Lucci et al., 2010). However, the FIFA 11+ can be beneficial in reducing this enhanced risk of ACL injury in youth female footballers by lowering apGRF during a cutting manoeuvre following a simulated match-play protocol. Electromyographic variables in the youth female footballers performing an unanticipated cutting manoeuvre were ACL protective with fatigue and fatigue resistance of these variables generally improved with FIFA 11+ training.

6.2 CONCLUSIONS AND RECOMMENDATIONS

The thesis involved a series of studies to examine the effect of neuromuscular training on the fatigue resistance of electromyographic and kinetic variables of youth female footballers performing an unanticipated cutting manoeuvre. The key findings derived from each study are outlined below:

6.2.1 Conclusions and Recommendations from Study 1: Reliability of Kinetic and Electromyographic Variables of Youth Female Footballers during an Unanticipated Cutting Manoeuvre

1. There were no significant differences in the mean score and large to nearly perfect ICC for all kinetic variables. The majority of kinetic variables displayed a CV% of less than 10%, with the exception of loading rates
2. The majority of electromyographic variables met standards of reliability. In comparison to previous research, electromyographic variables displayed a greater range of typical error.
3. For both electromyographic and kinetic variables, the typical error (CV%) could be utilised to determine if a meaningful change has occurred with an acute bout of exercise or injury prevention programme. If the change score of the participant is greater than the characteristics' typical error (CV%) then it could be determined that a meaningful change has occurred as a result of the acute bout of exercise or injury prevention programme, rather than the noise of measurement.

6.2.2 Conclusions and Recommendations from Study 2: The Effect of Fatigue on the Kinetic and Electromyographic Variables Associated with ACL Injury Risk in Youth Female Footballers during an Unanticipated Cutting Manoeuvre.

1. Youth female footballers display a *very likely* increase in apGRF with fatigue, which would place greater stress on the ACL
2. Following the fatigue protocol, there were *very likely* increases in peak H:Q co-activation ratios, and H:Q co-activation ratios increased throughout the latency phases of an unanticipated cutting manoeuvre. However, during the first 30 ms following initial contact, when there is a high risk of ACL injury, the fatigue protocol produced quadriceps dominant H:Q co-activation ratios.
3. *Most likely* decreases in pre-activation of the quadriceps muscle group and *very likely decreases* in pre-activation of BF occurred with fatigue, however there were no substantial changes in pre-activation of SM and ST, which could be a protective mechanism to ACL injury

6.2.3 Conclusions and Recommendations from Study 3: The Extent of which the FIFA 11+ is Effective in Improving the Fatigue Resistance of the Kinetic and Electromyographic Variables of Youth Female Footballers Performing an Unanticipated Cutting Manoeuvre

1. Following the FIFA 11+ two to three times weekly for eight weeks, could decrease peak apGRF in youth female footballers performing an unanticipated cutting manoeuvre following a simulated match-play protocol. Decreases in activation and deceleration power produced by the quadriceps muscles before initial contact could have contributed to the reduction in peak apGRF.

2. After the eight week training intervention, fatigue resistance of feed-forward and immediate feedback responses of ST in youth female footballers performing an unanticipated cutting manoeuvre were improved, this could reduce the risk of valgus collapse on the knee.
3. The FIFA 11+ increased H:Q co-activation ratios during feed-forward mechanisms of the experimental group compared to the control group following a simulated match-play protocol, however the H:Q co-activation ratios during 31 - 60 ms displayed unclear between-group differences following an acute fatigue protocol.

6.3 FUTURE RESEARCH DIRECTIONS

The research examining ACL injury risk and prevention in females is extremely dense, however a lack of clear focus in youth female footballers and the common ACL injury mechanism in female football, the unanticipated cutting manoeuvre is sparse. Thus there currently exists scope for future research within the area. Whilst this thesis has enabled a better understanding of ACL injury risk factors and prevention in youth female footballers, there remain a number of unanswered questions within the current literature. Listed below are future research directions deemed important to investigate to advance the understanding of this particular research field.

- *Multiple skill levels and experience.* While the current study successfully studied effects of fatigue and the FIFA 11+ on the electromyographic and kinetic variables of youth female footballers performing an unanticipated cutting manoeuvre, future research is required to identify the effects of fatigue and intervention across multiple skill levels. The current study utilised participants performing at a similar level. Previous research has observed differences in H:Q co-activation level with experience, but the effect of fatigue and the FIFA 11+ on participants of differing skill levels and experience is yet to be elucidated (Sigward & Powers, 2006).

- *Limb differences.* The current study identified electromyographic and kinetic variables of the non-dominant limb, most commonly injured in female footballers (Brophy et al., 2010; Cowley et al., 2006; Landry et al., 2007; Silvers et al., 2007). However, previous research has observed limb differences in electromyographic and kinetic variables with dominance (Brophy et al., 2010; Cowley et al., 2006). Future research identifying the effect of fatigue and intervention on dominant and non-dominant limbs would identify any lack of training effects in the non-dominant limb and help to advance research to address limb dominance and reduce the weakness of the non-dominant limb in comparison to the dominant limb.

- *The impact of age, growth and maturation on the training effects of the FIFA 11+ and fatigue.* The current study furthers knowledge in the training effects of the FIFA 11+ and the effect of fatigue on 16 - 18 year old youth female footballers. As ACL injury commonly occurs in 16 - 18 year old females, it is important to understand the influence of fatigue and reduce the risk of ACL injury in this age group. However, previous research has observed important effects of neuromuscular training in pre-pubertal females which produce an artificial neuromuscular spurt to help reduce the neuromuscular differences between pre-pubertal/pubertal females and males (Myer et al.., 2011). Further to this, maturational and pubertal risk factors are vastly researched and it has been identified that the sex disparity in injury incidence is apparent from the onset of puberty (Wild et al., 2012). During puberty, females do not display improved muscle strength and the strength and activation of their hamstrings tends to be behind that of their quadriceps, and produce faulty mechanics characterised by erect posture and knee valgus (Wild et al., 2012). Therefore, combined hormonal effects produce a lack of strength and a more risky lower limb alignment in females during puberty, compared to males. It could be suggested that prevention training is best implemented during pre-pubertal years or early puberty.

- *Comparison of prevention programmes and their effects on electromyographic and kinetic variables of youth female footballers in a fatigued and non-fatigued state.* The current study utilised the FIFA 11+ and was the first known study to investigate the effects of the FIFA 11+ when youth female footballers are experiencing football specific fatigue mimicking the demands of match-play. However, previous research has found various neuromuscular training programmes are effective in reducing the incidence of injury, and Zebis et al. (2016) observed an evidence based prevention programme to produce electromyographic benefits in female handball and football athletes. The intervention utilised by Zebis et al. (2016) contained many more movement based sport-specific exercises, a larger total amount of exercises, cutting specific exercises, and equipment to further challenge the balance of athletes. Future research comparing the effectiveness of the FIFA 11+ and the prevention programme of Zebis et al. (2016) on female footballers experiencing fatigue could be beneficial.

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Chapter 7: Reflection

On reflection of the thesis there are key factors which may have influenced the study outcomes and could have been considered in more detail. These are:

The potential usefulness of video analysis

Previous research has related increasing medial to lateral hamstrings activation with higher knee abduction loads and dynamic valgus, thus placing stress on the ACL (Hanson et al., 2008; Palmieri-Smith et al., 2009). The amount of valgus observed during a sporting movement suggests poor muscular control of the GRF (Ford et al., 2003). Weinhandl et al. (2014) observed ACL loading during unanticipated cutting manoeuvres was largely due to the sagittal plane, and as such valgus forces alone could load the ACL sufficiently to rupture the ligament causing serious injury (Weinhandl et al., 2014). Therefore, video analysis of the cutting technique including the assessment of knee valgus could have been useful in identifying the risk of ACL injury through a valgus force. However, the current study was not a biomechanical study, rather investigating kinetic and electromyographic variables such as GRF's, loading rates, time to peak forces, and quadriceps and hamstrings muscular activation. Therefore, the inclusion of video analysis in the current study is beyond the scope of the research questions and objectives. There are also some concerns with the reliability and validity of video footage with the current study objectives, there are limitations with 2D video analysis such as; it's usage in measuring multiple planar motions particularly knee valgus which is a measure of femoral internal rotation, hip adduction, and tibial external rotation, thus may not be best represented by frontal plane motion, and conflicting research on the reliability and validity of 2D video analysis and relationship with 3D motion analysis (Maykut et al., 2015). The gold standard for performance analysis is 3D motion analysis. However, 3D video analysis requires significant financial, spatial and temporal costs (Maykut et al., 2015). Therefore, careful inclusion of video footage could be a useful future direction in the research area to understand the relationship between biomechanical, kinetic, and neuromuscular variables in the study population, the effect of fatigue and the effect of an 8 week neuromuscular training programme in any relationship between variables. As well as measuring other potential outcome variables, video analysis could have been useful as an additional checking system to ensure participants were performing the unanticipated cutting manoeuvre correctly and within the inclusion criteria (i.e. using the correct leg, cutting within the designated angle) to increase the validity and accuracy of the study. It could have taken the pressure off of the researcher in terms of the level of multi-tasking required to instruct the participants, start the EMG/force plate data collection and watch the performance of the cut closely. Consequently, no trials were removed from the current study due to error in performance of the dynamic task, the habituation session performed by all participants could have aided this, but video analysis could have been a useful tool to ensure this.

The extent to which the Study 2 protocol actually induces fatigue

The SAFT90 has been shown to be reliable and valid in mimicking the physiological responses of football match-play fatigue (Lovell et al., 2008). The SAFT90 is based on male footballers who generally cover the same overall distance as females, but more distance at high intensity running speeds and walking (Aslan et al., 2012; Andersen et al., 2012; Bradley et al., 2013). Greater distance covered in high intensity running and sprint profiles could be due to speed of movement being greater in males than females. Each participant of the current study, whether male or female, would have been performing the SAFT90 to their greatest capacity, thus the fatigue induced will be similar to that of match-play if not greater than match-play for each of the participants. If the FIFA 11+ can build some fatigue resistance to the level of fatigue induced during the SAFT90 (based on men's match-play data) then we can only assume that this fatigue resistance training would be more effective during female match-play when females are not performing as much high intensity running. For example, previous research has utilised the SAFT90 in studies with youth female footballers. These studies have observed fatigue-related changes in neuromuscular activation and leg stiffness (De Ste Croix et al., 2015). De Ste Croix et al. (2015) observed a 58.4% increase in EMD post-fatigue compared to pre-fatigue, and significant decreases in concentric (17%) and eccentric (26%) torque production using the SAFT90 protocol. These findings demonstrate a level of neuromuscular fatigue is experienced by youth female footballers performing the SAFT90 (De Ste Croix et al., 2015).

There were no outcomes put in place to measure the rate of fatigue in the participants of the current study. However, Lovell et al. (2008) observed the SAFT90 to be valid and reliable to mimic football match-play fatigue. Modifications to the SAFT90 were not tested for reliability, however they were included based on previous research on the activity profile of female footballers (Andersen et al., 2012). These modifications added technical elements to the protocol such as ball touches and headers, rather than intensity or workload which is already established and deemed a reliable replication of football match play fatigue (Lovell et al., 2008). Future research may want to perform physiological and metabolic monitoring (HR, blood lactate, etc.) or collect RPE data from participants to monitor the level of fatigue experienced. However, since the current study was completed, an adapted SAFT90 protocol for youth male footballers (YSAFT) has been developed and may be of greater relevance in the youth population in terms of modifications to the velocity and distance covered in locomotor categories, as well as duration of the profile aligning with match duration in the youth population (2 x 40 minute halves) (Barratt et al., 2013). No position specific or football specific activities i.e. cutting, heading, ball contacts, are included in the YSAFT. Thus although it may mimic the metabolic and physical demands of the average youth player, it does not account for positional variance or the technical demands of football match play (Barratt et al., 2013).

The implications of existing physiological status and physical fitness levels of players prior to testing on the study outcomes

There are several factors that could have been considered prior to each testing session which may have had implications on the study outcomes of studies 2 and 3. Factors such as physiological condition and current fitness levels.

Physiological match demands (%HRmax, % of maximum aerobic power) have been reported to be similar across gender and competition levels in football, with any differences reflecting a players' fitness level (Castagna et al., 2009). Particularly, the amount of high intensity running performed by a player during match play can be attributed to the players physical fitness level (Castagna et al., 2009). Thus, causing implications for the effect of the SAFT90 on better conditioned players compared to less conditioned players, with better conditioned players having a greater capacity to perform a larger quantity of high intensity running. Further to this, those players with a greater fitness level established by a high maximal aerobic power (VO2max) use their anaerobic energy system less which can subsequently reduce fatigue by saving glycogen and preventing a drop in the muscle pH (Balsom et al., 1994; Impellizzeri et al., 2006). Female footballers tend to experience fatigue in the last 30 minutes of match-play, when the majority of injuries are sustained. This phase of fatigue in female footballers is caused by depleted muscle glycogen stores decreasing the pH of the muscle (Krustrup et al., 2003). Those players with a higher VO2max will not experience the fatigue in the last 30 minutes of match-play to the degree of those with a lower VO2 max. Thus, this may have an effect on the outcomes of Study 2 as players with a greater VO2max will be fatigued to a lesser extent by the SAFT90 when compared to those with a lower VO2max (Balsom et al., 1994; Impellizzeri et al., 2006).

Girard et al. (2011) studied factors affecting fatigue with repeated sprinting in footballers. The researchers found that those players with a greater initial sprint performance experienced larger changes in muscle metabolite contributing to greater decrement in performance with a greater negative effect of fatigue, compared to those players with poorer initial sprint performance. The mechanism of this observation is reported by Mendez-Villanueva et al. (2008) as an over reliance on the anaerobic metabolism by those players with the greater initial sprint performance, thus showing a lower fatigue resistance to repeated sprint training. Other influencing factors discussed by Girard et al. (2011) include playing position and training status noting that those players who were aerobically trained and played a defensive or midfield position (Aziz et al., 2008) are typically able to resist fatigue to a greater extent than a more anaerobically trained individual (Girard et al., 2011). Therefore, in terms of the implications of these findings on the current research, those players who have a greater sprint performance, are anaerobically trained, or play in a forward position are more likely to experience greater decrements in fatigue with the SAFT90 than those players that are aerobically trained and play a defensive or midfield position (Aziz et al., 2008; Girard et al., 2011; Mendez-Villanueva et al., 2008). The experimental and control groups for study 3 were randomised with consideration of playing position which may reduce the implications of playing position on the study outcomes.

LaRoche (2009) studied the neuromuscular traits of females that produce successful or unsuccessful adaptations to resistance training. The researchers observed that following 8 weeks of explosive isokinetic resistance training those women who measured a higher muscle mass and contractility, with greater neural drive initially had a lower capacity for improvement with training than those women with lower initial performance levels (LaRoche, 2009). Therefore, in the current study those participants that have a smaller muscle mass and contractility, and lower levels of neural drive at the start of the 8 week injury prevention training intervention may produce greater neuromuscular adaptations than those with greater muscular performance levels (LaRoche, 2009). However, the current thesis investigates the within-subject differences from pre to post-intervention, rather than comparing between-subjects.

Research on football players has found that performance detriments such as; decreased knee extensor force, jump height and sprint performance, caused by match-play fatigue can take 1-3 days to recover to baseline levels (Raastad et al., 2002; Reilly & Rigby, 2002; Ronglan et al., 2006). Further research into team sports, specifically female handball players, observed that neuromuscular fatigue occurs with daily training and match-play, and recovery during competitive periods in which training and match-play occurs four out of five days is not sufficient to physiologically recover to baseline (Ronglan et al., 2006). The participants of the current study trained for their development academy or club team three to five times per week, and played in one to two matches per week. Therefore, the schedule of these players was congested and the recovery between training and match-play may not be sufficient enough to restore normal homeostasis and physiological condition (Dupont, 2015). From an injury viewpoint, those players that perform in two matches per week have an injury rate six times higher than those players that perform in one match per week. Therefore, recovery strategies are needed to reduce injury rates during congested times within the football season (Dupont, 2015). Football match-play fatigue occurs in three phases; immediately after an intense period of the game, immediately after the half time interval, and in the last 30 minutes of match-play (Krustrup et al., 2003). The fatigue that occurs in the last 30 minutes of match-play is caused by muscle glycogen depletion, and this coincides with the highest rate of injury within the 90 minutes of match-play. Researchers have found that muscle glycogen depletion after a football match will take two or three days to replenish when a specific nutrition plan is provided (Dupont, 2015). However, the participants in the current study were not following a specific nutrition plan or recovery strategy, thus muscle glycogen replenishment may take longer.

Although the participants in the current study did not perform vigorous exercise 48 hours prior to testing, previous research has identified that up to three days is needed to recover to baseline levels of performance and recovery strategies are integral in the ability of a player to recover baseline levels of physical condition (Dupont, 2015; Raastad et al., 2002; Reilly & Rigby, 2002; Ronglan et al., 2006). Specifically, the muscle glycogen depletion experienced in the last 30 minutes of match-play when most injuries occur may take more than three days to recover without the implementation of a nutrition plan or recovery strategies (Dupont, 2015). Therefore, the outcome measures from Study 2 and 3 may be negatively influenced by this showing poorer performance from the participants. However, with such a congested schedule, the players may not be in significantly different physiological condition during testing than they would be on a match-day or training session, thus physiological condition may not influence the application of the findings. Although physiological condition and recovery may have affected each participants outcomes, all of the participants performed similar amounts and types of training creating a homogenous group. Further to this, the testing sessions were carried out at the same time of day and day of the week, thus it would be expected that the participants physiological condition would be similar at each of the testing sessions.

Fatigue resistance can be developed through previous training. Previous research by Salvador et al. (2009) observed that an 8 week strength training programme improved strength and fatigue resistance in males and females. Training history can impact muscle fatigue (Bogdanis et al., 2012). It is known that power trained athletes are stronger and faster than endurance athletes and those who do not train. Further to this an endurance athlete has a slower rate of muscle power decline due to them being able to maintain performance. Thus those participants that have a greater training age/history may resist fatigue to a greater extent than those participants with a lesser training history due to muscle fibre composition, ionic regulation and muscle mass (Bogdanis et al., 2012). In Study 3, an activity log was collected to establish any other training the participants may have been performing away from their regular football training sessions. To minimise the implications of other training on the outcomes of the current studies, those players that were performing any injury prevention, plyometric or strength based training outside of their regular weekly football sessions were removed from analysis. None of the participants reported performing any type of training which could exclude them from the analysis. The participants reported the same amount and type of training, thus deeming the group homogenous and reducing the effect of implications on the study outcomes caused by physiological condition and fitness levels. Further to the activity log data collated by the researcher, the participants were instructed to attend the testing sessions in line with the inclusion criteria i.e. ii) drink alcohol in the final 24 hours before testing, iii) drink caffeine in the final 12 hours before testing.

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Chapter 8: Appendices

Appendix 2.1

EMG GUIDELINES PROVIDED BY SENIAM

Appendix 2.1 EMG Guidelines provided by SENIAM

http://www.seniam.org/

Appendix 2.2

FIFA 11+ PROGRAMME

Appendix 2.2 FIFA 11+ Programme

http://f-marc.com/11plus/downloads/

Appendix 3.1

UNIVERSITY OF GLOUCESTERSHIRE SPORT AND EXERCISE LABORATORIES
HEALTH QUESTIONNAIRE

Appendix 3.1 University of Gloucestershire Sport & Exercise Laboratories Health Questionnaire

About this questionnaire:

The purpose of this questionnaire is to gather information about your health and lifestyle. We will use this information to decide whether you are eligible to take part in the testing for which you have volunteered. It is important that you answer the questions truthfully. The information you give will be treated in confidence. Your completed form will be stored securely for 5 years and then destroyed.

Section 1, which has been completed by the tester, provides basic information about the testing for which you have volunteered. Sections 2 to 7 are for you to complete: please circle the appropriate response or write your answer in the space provided. Please also complete section 8. Sections 9 and 10 will be completed by the tester, after you have completed sections 2 to 8.

Section 1: The testing (completed by tester)

To complete the testing for which you have volunteered you will be required to undertake:

Moderate exercise (i.e., exercise that makes you breathe more heavily than you

do at rest but not so heavily that you are unable to maintain a conversation)

Vigorous exercise (i.e., exercise that makes you breath so heavily that you are

unable to maintain a conversation)

The testing involves:

Walking	☐	Generating or absorbing high forces through your arms	☐
Running	☐	Generating or absorbing high forces through your shoulders	☐
Cycling	☐	Generating or absorbing high forces through your trunk	☐
Rowing	☐	Generating or absorbing high forces through your hips	☐
Swimming	☐	Generating or absorbing high forces through your legs	☐
Jumping	☐		

Section 2: General information

Name: ....……....………….. Sex: M F Age: ....

Height (approx.): ....………..……….. Weight (approx.): ....

Section 3: Initial considerations

1. Do any of the following apply to you? No Yes

a) I have HIV, Hepatitis A, Hepatitis B or Hepatitis C

b) I am pregnant

c) I have a muscle or joint problem that could be aggravated by the testing described in section 1

d) I am feeling unwell today

e) I have had a fever in the last 7 days f) (If you have answered “Yes” to question 1, go straight to section 8)

Section 4: Habitual physical activity

2a. Do you typically perform moderate exercise (as defined in section 1) for 20 minutes or longer at least twice a week?

No Yes

2b. Have you performed this type of exercise within the last 10 days?

No Yes

3a. Do you typically perform vigorous exercise (as defined in section 1) at least once a week?

No Yes

3b. Have you performed this type of exercise within the last 10 days?

No Yes

Section 5: Known medical conditions

4. Do any of the following apply to you?

No Yes

a) I have had insulin-dependent diabetes for more than 15 years

b) I have insulin-dependent diabetes and am over 30 years old

c) I have non-insulin-dependent diabetes and am over 35 years old

5. Have you ever had a stroke?

No Yes

6. Has your doctor ever said you have heart trouble?

No Yes

7. Do both of the following apply to you?

No Yes

a) I take asthma medication

b) I have experienced shortness of breath or difficulty with breathing in the last 4 weeks?

8. Do you have any of the following: cancer, COPD, cystic fibrosis, other lung disease, liver disease, kidney disease, mental illness, osteoporosis, severe arthritis, a thyroid problem?

No Yes

(If you have answered “Yes” to any questions in section 5, go straight to section 8.)

Section 6: Signs and symptoms

9. Do you often have pains in your heart, chest, or the surrounding areas?

No Yes

10. Do you experience shortness of breath, either at rest or with mild exertion?

No Yes

11. Do you often feel faint or have spells of severe dizziness?

No Yes

12. Have you, in the last 12 months, experienced difficulty with breathing when lying down or been awakened at night by shortness of breath?

No Yes

13. Do you experience swelling or a build up of fluid in or around your ankles?

No Yes

14. Do you often get the feeling that your heart is racing or skipping beats, either at rest or during exercise?

No Yes

15. Do you regularly get pains in your calves and lower legs during exercise that are not due to soreness or stiffness?

No Yes

16. Has your doctor ever told you that you have a heart murmur?

No Yes

17. Do you experience unusual fatigue or shortness of breath during everyday activities?

No Yes

(If you have answered “Yes” to any questions in section 6, go straight to section 8.)

Section 7: Risk factors

18. Does either of the following apply to you?

No Yes

a) I smoke cigarettes on a daily basis

b) I stopped smoking cigarettes on a daily basis less than 6 months ago

c)

19. Has your doctor ever told you that you have high blood pressure?

No Yes

20. Has your doctor ever told you that you have high cholesterol?

No Yes

21. Has your father or any of your brothers had a heart attack, heart surgery, or a stroke before the age of 55?

No Yes

22. Has your mother or any of your sisters had a heart attack, heart surgery, or a stroke before the age of 65?

No Yes

23. Do any of the following apply to you?

No Yes

a) I have had insulin-dependent diabetes for less than 15 years

b) I have insulin-dependent diabetes and am 30 or younger

c) I have non-insulin-dependent diabetes and am 35 or younger

Section 8: Signatures

Participant: ………………………………………………….. Date: ....……….……........

Guardian*: ....…………………........ Date: ....………….…........

(*Required only if the participant is under 18 years of age.)

Section 9: Additional risk factors (to be completed by the tester if relevant)

24. Is the participant's body mass index >30 kg/m2?

No Yes

25. Has the participant answered no to questions 2a and 3a?

No Yes

Section 10: Eligibility (to be completed by the tester)

26. Is the participant eligible for the testing?

No Yes

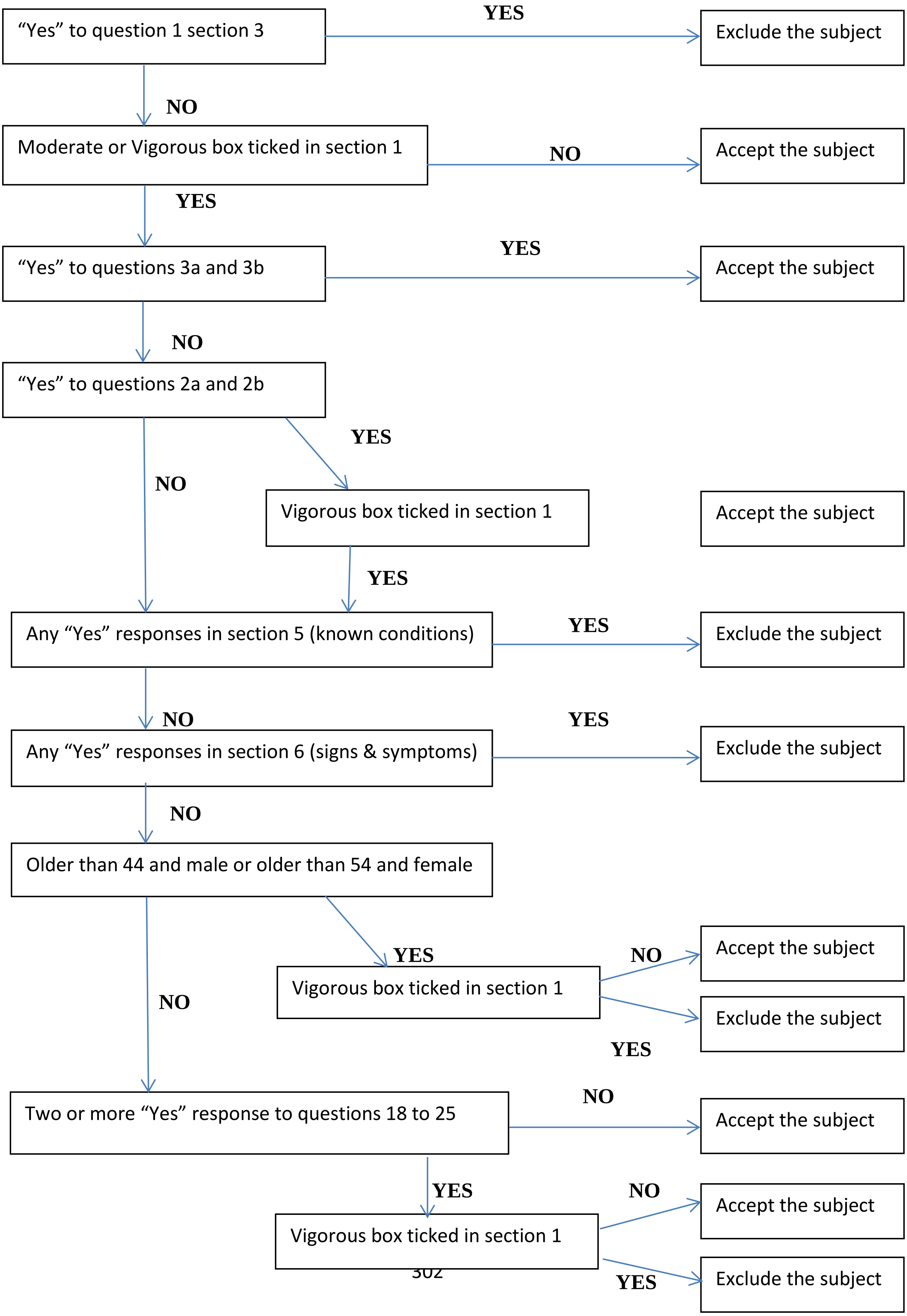
Name (of tester): ....……….............…………..

Signature: ………………………………………………… Date: ………....….……….…...

Appendix 3.2

UNIVERSITY OF GLOUCESTERSHIRE SPORT AND EXERCISE LABORATORIES
HEALTH QUESTIONNAIRE FLOW CHART

Appendix 3.2 University of Gloucestershire Sport & Exercise Laboratories Health Questionnaire Flow Chart



Appendix 3.3

PARTICIPANT INFORMATION SHEETS AND INFORMED CONSENT

Appendix 3.3 Participant Information Sheets and Informed Consent

<u>The effectiveness of neuromuscular training to resist fatigue in female footballers</u>

Dear Team member,

Thank you for your interest in taking part in this study. This information sheet will tell you a bit more about the study and what we would like you to do. Please read this carefully. If you decide not to take part it will not change your relationship with the research team, the University or your Club.

What is the project about?

We are interested in looking at the effect of football fatigue on the lower leg, particularly on the knee in female youth players. We are also looking at the effectiveness of prevention programmes, during pre-fatigue and post-fatigue states. This is a unique study investigating how well the prevention programmes work so that we can suggest improvements to reduce the risk of knee injury in female youth footballers.

About the study

This study is self-funded and will be run by a research team from the University of Gloucestershire. All researchers have experience working with athletes/children and have completed a full CRB check and Disclosure and Barring Service. The study has also been approved by the University Research Ethics Sub-Committee (RESC).

Who is taking part in the study?

Females aged 16 - 18 years who are participating in elite level women's football in the UK.

What will I be asked to do?

A researcher will visit your facility three times to do some testing.

On the first visit all tests will be explained to you and you will have a go at practicing the running components of the study. Other measurements such as height and weight will be taken.

On the second and third visits you will perform the actual tests. Initially, you will perform a standard ten-minute warm-up that is usually performed at your club before matches. This will include running and movements familiar to you. The researcher will then place some markers on to you, and you will perform a change of direction movement to measure joint angles, muscle contractions, and ground reaction forces i.e. the amount of force exerted from the ground through the leg during contact. Then you will perform some double footed hopping on a contact mat to measure leg stiffness.

The change of direction movement will consist of 15 metre runs, on one of the runs a light system will guide you in a direction to cut. Throughout the running and cutting you will be asked to maintain a certain speed and ensure your cut is within a taped area/angle. You will perform the cut multiple times in different trials, with rest between trials.

Following baseline testing, you will perform a modified version of the SAFT[90] exercise protocol. This protocol involves football specific movement around a sports hall for the same duration as your matches with a half-time interval, also the same as on a match day. Five minutes after finishing, you will repeat the testing.

If your club is selected as an intervention group, you will then perform a prevention programme for 8 weeks. You will perform the programme twice a week instead of your clubs usual warm up. The prevention programme will consist of running activities, plyometric, stretching, balance and core strengthening activities. You will receive access to the appropriate information sheets for your prevention programme which explains technique. Your coach will supervise your prevention programme to ensure you are using proper technique. If your club is not selected as an intervention group, you will train as normal for 8 weeks.

All participants will be asked to complete an activity log during week 1, week 4 and week 8 of the intervention period with basic questions on the amount and type of training you have been doing with your club and outside of your club.

After the 8 week intervention period is finished, you will return to the laboratory for your third visit to complete another testing session as described previously.

You are asked to provide your own water at each testing session in order to keep you hydrated throughout the testing session.

When will I do it?

Whenever your club and the appropriate facilities are available we will arrange a time for you to perform your testing. If you wish you may complete this as a group. Parents/guardians will be informed of the specific arrangements via written documentation.

Can I change my mind?

You can stop being a part of the study at any time, including anytime throughout data collection. All you have to do is let us know that you no longer want to take part. This will not affect your relationship with the research team, the University or your Club.

What will you do with the information?

All the information collected will be stored on a computer using ID codes and the results will only be seen by the research team. Your name will never be used. The data will be stored on password protected computers and in lockable filing cabinets for 5 years, then archived to build a data pool for future postgraduate researchers.

The tests we perform are nothing to do with performance and your coaches will not use the results to pick the team. The results can be used to make a specific individual program by your coaches in order to prevent future injury, therefore if you want your coaches to have access to your individual results in order to make changes to your training, you should fill in the Data consent form.

What if I have any questions?

If you have any questions then please feel free to ask either of the people below at any time.

What do I do next?

If you have read and understood everything that we want you to do and are happy to take part please sign the consent form that is attached to this sheet.

Miss George Reed

MPhil/PhD by Research Student

Applied Sport and Exercise Science
School of Sport and Exercise
University of Gloucestershire

e-mail: georginareed@connect.glos.ac.uk
Project mobile phone number: 07734452775

Prof Mark De Ste Croix

Faculty PostgraduateResearch Director
e-mail: mdestecroix@glos.ac.uk

UNIVERSITY OF GLOUCESTERSHIRE
at Cheltenham and Gloucester

The effectiveness of neuromuscular training to resist fatigue in female footballers

Sport & Exercise Laboratories

Participant informed consent form

I have had full details of the tests I am about to complete explained to me. I understand the risks and benefits involved, and that I am free to withdraw at any point. I confirm that I am in a fit condition to undertake the required exercise.

Participant

Name:………………………………………

Signed:…………………………………….. Date:………………...

Miss George Reed

MPhil/PhD by Research Student

Applied Sport and Exercise Science
School of Sport and Exercise
University of Gloucestershire

e-mail: georginareed@connect.glos.ac.uk
Project mobile phone number: 07734452775

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UNIVERSITY OF GLOUCESTERSHIRE
at Cheltenham and Gloucester

The effectiveness of neuromuscular training to resist fatigue in female footballers

Sport & Exercise Laboratories

Parent/ guardian informed consent form

I have had full details of the tests my child is about to complete explained to me. I understand the risks and benefits involved, and that she is free to withdraw at any point. I confirm that is in a fit condition to undertake the required exercise.

Parent/ guardian

Name:………………………………………

Signed:…………………………………….. Date:………………...

Miss George Reed

MPhil/PhD by Research Student

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Project mobile phone number: 07734452775

Prof Mark De Ste Croix

Faculty PostgraduateResearch Director
e-mail: mdestecroix@glos.ac.uk

The effectiveness of neuromuscular training to resist fatigue in female footballers

(Information Sheet)

Dear Parent/Guardian,

The Participants for the research listed above will be required on the following date:

……………………..

Transport details are listed below:

……………………………………………………………………………………………………

……………………………………………………………………………………………………

Thank you again for your cooperation.

Miss George Reed

MPhil/PhD by Research Student

Applied Sport and Exercise Science
School of Sport and Exercise
University of Gloucestershire

e-mail: georginareed@connect.glos.ac.uk
Project mobile phone number: 07734452775

Prof Mark De Ste Croix

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e-mail: mdestecroix@glos.ac.uk

UNIVERSITY OF GLOUCESTERSHIRE
at Cheltenham and Gloucester

The effectiveness of neuromuscular training to resist fatigue in female footballers

(Data Consent Form)

Dear Participant,

The data gathered in this study will not be passed on to any other party and will remain anonymous if you so wish. However, the data may be beneficial for you if passed on to the relevant members of your club.

The data collected does not relate to actual performance, therefore your coaches will not use the data for team selection. It is purely to highlight any specific areas that could be improved through an individual training program in order to decrease your risk to injury.

If you wish for your data to be made available for your team management please sign below.

Participant

Name:…………………………………………..

Signed………………………………………….   Date:………………………………

Thank you again for your cooperation.

Miss George Reed

MPhil/PhD by Research Student

Applied Sport and Exercise Science
School of Sport and Exercise
University of Gloucestershire

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Project mobile phone number: 07734452775

Prof Mark De Ste Croix

Faculty PostgraduateResearch Director
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Appendix 3.4

SYNCHRONISATION OF THE BIOMETRICS EMG AND PASCO FORCE PLATE

Appendix 3.4 Synchronisation of the Biometrics EMG and PASCO force plate

Biometrics EMG START / STOP OTHER INSTRUMENTATION BY THE DATALOG (MASTER)

Synchronisation Cable type no. SYNC5

The MWX8 DataLOG may be used to Start/Stop another instrument which has the ability to be switched by a TTL signal, i.e. the ability to be switched by a signal line from logic 1 (+5 V) to logic 0 (+0 V) or visa versa. The 3rd party instrument is interfaced to the DataLOG using Synchronisation Cable type no. SYNC5. The silver plug is connected to either of the Digital Input Sockets of the DataLOG Figure 1 (1). At the other end of the cable are 2 wires coloured red and black.

□□□□□□□□□□□□□□□□□□□□□□□□□□□□□□□□□

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The output is configured using the Setup DataLOG Digital Inputs dialog (Record State Output) to one of the following actions:

□□ Uncheck *Active Low*, uncheck *pulse*

□□ Check *Active Low*, uncheck *pulse*

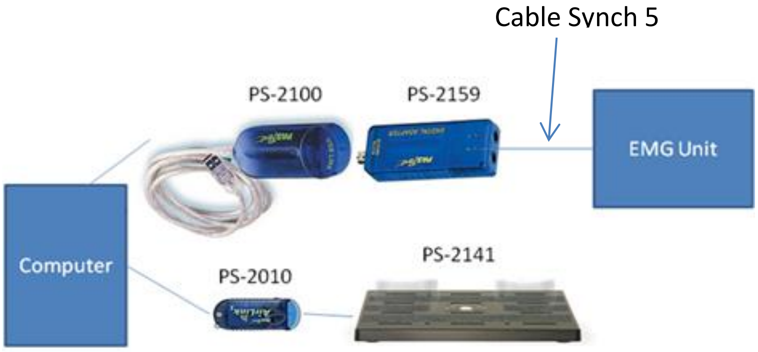
□□□□□□□□□□□□□□□□□□□□□□□□□□□□□□□□□□□□□□ high and back at the start and at the end of record. Uncheck *Active Low*, check *pulse*

□□□□□□□□□□□□□□□□□□□□□□□□□□□□□□□□□□□□□□□ low and back

at the start and at the end of

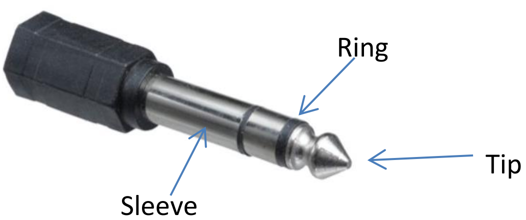
record. Check *Active Low*, check *pulse*

SparkVue Force Plate Connection Details:



A TRS (1/4” stereo phono plug) connector is required from the Digital adapter (Ps-2159) to the EMG unit. The pinout for all of the single-plug ScienceWorkshop digital sensors is as follows:

- **Sleeve:** Ground
- **Ring:** pulse (event = low)
- **Tip:** +5V Power



Biometrics Synch 5 Cable:

Connect Black wire to Sleeve (ground)

Connect Red Wire to Tip (+5v)

Appendix 4.1

DESCRIPTIVE STATISTICS FOR KINETIC AND NEUROMUSCULAR VARIABLES OF YOUTH FEMALE FOOTBALLERS (N=22) PERFORMING AN UNANTICIPATED CUTTING MANOEUVRE PRE AND POST-FATIGUE

Appendix 4.1 Descriptive statistics for kinetic and neuromuscular characteristics of youth female footballers (n = 22) performing an unanticipated cutting manoeuvre pre and post-fatigue

Variable	Latency Phase	Pre-fatigue (mean ± *sd*)	Post-fatigue (mean ± *sd*)
Peak vGRF (N)		1178 ± 152	1227 ± 256
Peak apGRF (N)		154 ± 37.20	210 ± 112
vGRF loading rate (N/s)		6851 ± 2181	5657 ± 3267
apGRF loading rate (N/s)		1978 ± 1088	1515 ± 996
Time to peak vGRF (s)		0.09 ± 0.03	0.07 ± 0.02
Time to peak apGRF (s)		0.06 ± 0.02	0.05 ± 0.01
GCT (s)		0.22 ± 0.03	0.19 ± 0.03
VM	Pre-activation (mV)	0.025 ± 0.022	0.01 ± 0.01
	0-30 ms (%)	19.81 ± 18.01	17.01 ± 5.81
	31-60 ms (%)	13.71 ± 4.97	15.10 ± 4.90
	61-90 ms (%)	12.80 ± 4.78	14.92 ± 4.44
	91-120 ms (%)	13.75 ± 3.54	14.76 ± 3.88
	GCT (mean) (mV)	0.04 ± 0.03	0.01 ± 0.01
	GCT (peak) (mV)	0.10 ± 0.07	0.02 ± 0.01
	Time to peak (s)	0.12 ± 0.05	0.11 ± 0.05
RF	Pre-activation (mV)	0.03 ± 0.03	0.01 ± 0.01
	0-30 ms (%)	20.09 ± 18.18	18.45 ± 7.77
	31-60 ms (%)	16.32 ± 6.37	17.54 ± 7.14
	61-90 ms (%)	14.83 ± 5.49	15.95 ± 4.46
	91-120 ms (%)	12.81 ± 5.15	15.03 ± 4.82
	GCT (mean) (mV)	0.05 ± 0.03	0.01 ± 0.01
	GCT (peak) (mV)	0.11 ± 0.07	0.02 ± 0.01
	Time to peak (s)	0.08 ± 0.04	0.11 ± 0.05
VL	Pre-activation (mV)	0.03 ± 0.03	0.01 ± 0.01
	0-30 ms (%)	17.24 ± 8.83	18.19 ± 6.08
	31-60 ms (%)	14.93 ± 4.24	17.50 ± 6.19
	61-90 ms (%)	12.42 ± 6.23	17.38 ± 2.12
	91-120 ms (%)	11.98 ± 4.96	15.19 ± 3.92
	GCT (mean) (mV)	0.04 ± 0.05	0.01 ± 0.01
	GCT (peak) (mV)	0.11 ± 0.07	0.02 ± 0.01
	Time to peak (s)	0.11 ± 0.05	0.09 ± 0.04
SM	Pre-activation (mV)	0.03 ± 0.06	0.03 ± 0.07
	0-30 ms (%)	13.73 ± 4.84	18.87 ± 10.06
	31-60 ms (%)	13.57 ± 5.05	17.19 ± 6.61
	61-90 ms (%)	13.92 ± 4.64	15.87 ± 5.09
	91-120 ms (%)	12.74 ± 7.49	13.67 ± 5.19
	GCT (mean) (mV)	0.03 ± 0.05	0.01 ± 0.01
	GCT (peak) (mV)	0.05 ± 0.08	0.02 ± 0.02
	Time to peak (s)	0.12 ± 0.05	0.10 ± 0.04
ST	Pre-activation (mV)	0.05 ± 0.06	0.05 ± 0.07
	0-30 ms (%)	15.13 ± 3.95	18.06 ± 6.09
	31-60 ms (%)	14.26 ± 3.17	16.50 ± 4.15
	61-90 ms (%)	14.37 ± 2.80	16.43 ± 2.90
	91-120 ms (%)	14.01 ± 3.17	14.70 ± 3.95
	GCT (mean) (mV)	0.09 ± 0.02	0.04 ± 0.03
	GCT (peak) (mV)	0.11 ± 0.06	0.05 ± 0.03
	Time to peak (s)	0.12 ± 0.07	0.11 ± 0.03
BF	Pre-activation (mV)	0.03 ± 0.03	0.01 ± 0.01
	0-30 ms (%)	15.14 ± 8.23	16.65 ± 5.48
	31-60 ms (%)	14.33 ± 5.60	15.80 ± 4.06
	61-90 ms (%)	13.44 ± 5.88	15.24 ± 4.44
	91-120 ms (%)	13.61 ± 5.44	14.08 ± 4.18
	GCT (mean) (mV)	0.04 ± 0.04	0.01 ± 0.00
	GCT (peak) (mV)	0.11 ± 0.08	0.02 ± 0.01
	Time to peak (s)	0.11 ± 0.06	0.11 ± 0.04
H:Q	Pre-activation (mV)	1.00 ± 0.06	1.00 ± 0.07
	0-30 ms (%)	0.78 ± 0.22	0.79 ± 0.23
	31-60 ms (%)	1.07 ± 0.28	1.14 ± 0.45
	61-90 ms (%)	1.11 ± 0.24	1.04 ± 0.27
	91-120 ms (%)	1.27 ± 0.46	1.08 ± 0.25
	GCT (mean) (mV)	2.14 ± 5.75	4.22 ± 5.98
	GCT (peak) (mV)	1.15 ± 0.78	4.35 ± 5.15

Appendix 5.1

COMPLIANCE LOG

Appendix 5.1 Compliance Log

DATE: __/__/__ TIME: __:__am/pm **GROUP**

WEEK ___ **FIFA 11+** ☐

SESSION ____

NO. OF PARTICIPANTS: ____

UNIVERSITY OF GLOUCESTERSHIRE
at Cheltenham and Gloucester

Exercise	Sets	Reps	Total No. of Participants Completing Exercise	Difficulty Level – Please display the no. of participants in each difficulty level (if applicable)		
				Easy	Intermediate	Hard

Notes/Comments/Reasons for Incompletion

Log Completed By

Name:_______________________________________ Role/Position: ______________________________

Appendix 5.2

ACTIVITY LOG

Appendix 5.2 Activity Log

WEEK 1 ACTIVITY LOG

Week commencing: ____/____/____

Number of football training sessions completed ☐

Average time (mins) of football training sessions ☐

Number of prevention sessions completed (If applicable) ☐

Number of competitive football matches completed ☐

Average time (mins) played in each match ☐

Number of non-football sessions completed ☐

Type of other training Completed

- ☐ Strength Training
- ☐ Plyometrics
- ☐ Cardiovascular Fitness Training/Running
- ☐ Other Sports - Please specify____

Please provide a brief description of the other training you have completed i.e. time (mins), type of exercise, sets/reps, distance, etc

RESEARCHERS USE ONLY	
FIFA 11+ ☐	CONTROL ☐
PARTICIPANT NO: ☐	

Appendix 5.3

RAW DATA OF KINETIC VARIABLES PRE AND POST-INTERVENTION FOR PRE AND POST-FATIGUE MEASURES

Appendix 5.3 Raw data of kinetic characteristics pre and post-intervention for pre and post-fatigue measures

P	Group	Condition	vGRF (N)		apGRF (N)		vGRF loading rate (N/s)		apGRF loading rate (N/s)		Time to peak vGRF (s)		Time to peak apGRF (s)		GCT (s)	
			Pre-intervention	Post-intervention	Pre-intervention	Post-intervention	Pre-intervention	Post-intervention	Pre-intervention	Post-intervention	Pre-intervention	Post-intervention	Pre-intervention	Post-intervention	Pre-intervention	Post-intervention
1	***E***	Pre-Fatigue	2116	1151	505	156	11945	26932	8077	3096	0.13	0.07	0.05	0.06	0.57	0.26
		Post-Fatigue	1064	1055	209	144	4602	4315	1107	1056	0.07	0.08	0.05	0.05	0.20	0.20
2	***E***	Pre-Fatigue	903	1151	204	121	32140	49305	18936	1590	0.06	0.05	0.04	0.06	0.22	0.28
		Post-Fatigue	1174	1121	331	224	10861	4909	6156	2797	0.10	0.10	0.05	0.07	0.22	0.22
3	***E***	Pre-Fatigue	1288	1018	120	139	29772	8943	758	5439	0.06	0.12	0.17	0.05	0.21	0.22
		Post-Fatigue	1351	998	360	197	10695	2966	1962	951	0.07	0.10	0.05	0.03	0.15	0.18
4	***E***	Pre-Fatigue	926	1349	152	214	5713	42538	2744	4457	0.10	0.06	0.07	0.05	0.22	0.25
		Post-Fatigue	1053	1065	352	110	7359	4635	2221	1075	0.03	0.05	0.03	0.03	0.15	0.15
5	***E***	Pre-Fatigue	1140	954	149	156	4607	9076	984	1298	0.05	0.05	0.03	0.03	0.18	0.15
		Post-Fatigue	1208	1080	269	132	7957	3505	503	1874	0.08	0.10	0.05	0.05	0.17	0.20
6	***E***	Pre-Fatigue	1463	2301	315	180	10667	18684	4249	2619	0.10	0.15	0.05	0.10	0.25	0.20
		Post-Fatigue	1488	2217	335	307	12786	17665	2694	4094	0.03	0.13	0.05	0.08	0.18	0.25
7	***E***	Pre-Fatigue	688	1079	147	212	1059	6854	1440	2817	0.05	0.07	0.05	0.05	0.20	0.17
		Post-Fatigue	1251	1212	501	214	16348	2793	7850	2847	0.05	0.08	0.05	0.05	0.18	0.20
8	***E***	Pre-Fatigue	1316	1105	167	220	8414	6505	3297	3522	0.08	0.07	0.05	0.07	0.20	0.18
		Post-Fatigue	1470	1259	299	173	6046	3174	1199	1414	0.05	0.08	0.05	0.03	0.17	0.22
9	***E***	Pre-Fatigue	1193	932	167	120	5421	5326	1595	944	0.08	0.10	0.07	0.07	0.20	0.23
		Post-Fatigue	1272	903	357	160	3888	3038	3739	842	0.10	0.07	0.05	0.05	0.20	0.22
10	***E***	Pre-Fatigue	1066	1826	200	243	9860	5920	1893	25.80	0.03	0.05	0.03	0.02	0.30	0.18
		Post-Fatigue	715	1155	242	268	197	3271	1648	1614	0.05	0.03	0.03	0.03	0.15	0.10
11	***E***	Pre-Fatigue	981	1049	105	186	5497	1539	708	929	0.05	0.05	0.03	0.00	0.20	0.15
		Post-Fatigue	828	1169	137	80.2	7564	2139	1648	1614	0.07	0.03	0.03	0.03	0.20	0.15
12	***C***	Pre-Fatigue	1089	973	92.65	108	6607	4549	1222	2173	0.12	0.10	0.07	0.03	0.22	0.20
		Post-Fatigue	1418	1480	110	215	6063	13295	2194	4288	0.08	0.10	0.05	0.08	0.23	0.20
13	***C***	Pre-Fatigue	1392	1311	197	73.12	7374	7940	2748	2225	0.10	0.07	0.05	0.03	0.25	0.17
		Post-Fatigue	1278	1357	180	122	8227	9901	932	1451	0.08	0.10	0.05	0.08	0.23	0.20
14	***C***	Pre-Fatigue	1027	14687	129	237	6233	7530	1255	3729	0.07	0.10	0.07	0.05	0.18	0.23
		Post-Fatigue	1081	1279	142	152	7337	4205	1729	950	0.08	0.05	0.05	0.05	0.18	0.18
15	***C***	Pre-Fatigue	1238	1550	146	251	5326	3741	1164	2346	0.12	1.22	0.07	1.18	0.22	0.20
		Post-Fatigue	1135	1400	139	218	8606	9263	1687	1332	0.10	0.08	0.07	0.05	0.22	0.20
16	***C***	Pre-Fatigue	1347	1183	97.14	177	7051	8235	164	1641	0.08	1.50	0.02	1.47	0.17	0.22
		Post-Fatigue	1514	1121	111	164	9262	10694	372	1401	0.97	0.08	0.90	0.08	0.25	0.23
17	***C***	Pre-Fatigue	1180	1218	88.16	212	8650	2491	3024	964	0.08	0.10	0.03	0.05	0.28	0.20
		Post-Fatigue	1555	1078	144	148	11817	7167	682	810	0.08	0.08	0.05	0.05	0.20	0.20
18	***C***	Pre-Fatigue	1313	1076	213	168	6543	1859	3594	2307	3.10	4.25	3.03	4.28	0.23	0.25
		Post-Fatigue	1278	1098	169	230	7070	9878	1559	2148	3.05	3.15	3.03	3.18	0.18	0.25
19	***C***	Pre-Fatigue	1362	1166	219	205	7577	5041	415	1879	0.05	0.05	0.03	0.03	0.18	0.23
		Post-Fatigue	1715	1178	121	248	36222	9513	97.00	4720	0.02	0.05	0.03	0.05	0.17	0.20
20	***C***	Pre-Fatigue	1120	1364	158	180	7767	20221	2556	997	0.10	0.08	0.08	0.03	0.23	-1.95
		Post-Fatigue	688	1457	83.46	162	4390	17797	333	1444	0.05	0.05	0.04	0.03	0.13	0.15
21	***C***	Pre-Fatigue	1095	1143	170	159	7248	6437	2871	2738	0.10	0.10	0.05	0.05	0.23	0.23
		Post-Fatigue	715	1075	102	171	825	5288	311	2349	0.08	0.08	0.03	0.03	0.20	0.20

P = participant, E = experimental, C=control, vGRF = vertical ground reaction force, apGRF = anterior-posterior ground reaction force, GCT = ground contact time.

Appendix 5.4

RAW DATA OF NEUROMUSCULAR VARIABLES PRE AND POST-INTERVENTION FOR PRE AND POST-FATIGUE MEASURES

Appendix 5.4 Normalised data of neuromuscular variables pre and post-intervention for pre and post-fatigue measures

Pre-activation

P	Group	Condition	VM (mV)		RF (mV)		VL (mV)		SM (mV)		ST (mV)		BF (mV)		H:Q (%)	
			Pre-intervention	Post-intervention	Pre-intervention	Post-intervention	Pre-intervention	Post-intervention	Pre-intervention	Post-intervention	Pre-intervention	Post-intervention	Pre-intervention	Post-intervention	Pre-intervention	Post-intervention
1	***E***	Pre-Fatigue	1.338	4.300	0.028	0.003	0.046	0.003	0.026	0.001	0.058	0.034	0.032	0.011	1.338	4.300
		Post-Fatigue	0.007	0.020	0.009	0.012	0.041	0.007	0.001	0.001	0.034	0.034	0.006	0.006	2.347	1.315
2	***E***	Pre-Fatigue	1.410	4.146	0.028	0.005	0.045	0.005	0.061	0.001	0.064	0.034	0.053	0.015	1.410	4.146
		Post-Fatigue	0.003	0.005	0.004	0.018	0.014	0.002	0.001	0.001	0.034	0.034	0.026	0.002	2.956	2.225
3	***E***	Pre-Fatigue	0.986	0.578	0.003	0.023	0.010	0.021	0.003	0.002	0.005	0.034	0.002	0.005	0.986	0.578
		Post-Fatigue	0.008	0.006	0.003	0.004	0.007	0.005	0.001	0.001	0.036	0.034	0.015	0.004	3.993	4.077
4	***E***	Pre-Fatigue	1.225	0.721	0.031	0.027	0.027	0.039	0.061	0.001	0.030	0.035	0.016	0.047	1.225	0.720
		Post-Fatigue	0.009	0.009	0.017	0.008	0.018	0.004	0.001	0.001	0.034	0.034	0.005	0.005	1.346	4.115
5	***E***	Pre-Fatigue	2.332	1.888	0.031	0.009	0.017	0.027	0.050	0.001	0.087	0.034	0.086	0.031	2.332	1.888
		Post-Fatigue	0.007	0.004	0.004	0.008	0.007	0.002	0.006	0.002	0.034	0.034	0.005	0.005	4.415	3.467
6	***E***	Pre-Fatigue	0.705	1.989	0.080	0.006	0.064	0.008	0.065	0.001	0.063	0.035	0.047	0.011	0.705	1.989
		Post-Fatigue	0.003	0.022	0.034	0.019	0.011	0.021	0.001	0.001	0.034	0.035	0.012	0.025	2.251	1.179
7	***E***	Pre-Fatigue	1.823	1.811	0.008	0.006	0.004	0.006	0.013	0.001	0.019	0.034	0.029	0.005	1.823	1.811
		Post-Fatigue	0.040	0.018	0.035	0.006	0.044	0.007	0.009	0.001	0.016	0.034	0.007	0.009	0.427	2.528
8	***E***	Pre-Fatigue	0.739	1.940	0.016	0.028	0.011	0.003	0.004	0.001	0.020	0.034	0.005	0.004	0.739	1.940
		Post-Fatigue	0.009	0.011	0.015	0.027	0.013	0.015	0.008	0.002	0.008	0.034	0.008	0.008	0.671	1.401
9	***E***	Pre-Fatigue	3.956	1.582	0.061	0.013	0.056	0.005	0.300	0.001	0.300	0.034	0.029	0.008	3.956	1.582
		Post-Fatigue	0.003	0.016	0.003	0.015	0.003	0.013	0.011	0.001	0.008	0.034	0.003	0.008	2.340	1.229
10	***E***	Pre-Fatigue	1.235	1.380	0.011	0.003	0.017	0.002	0.001	0.001	0.034	0.034	0.011	0.005	1.235	1.380
		Post-Fatigue	0.008	0.005	0.010	0.030	0.019	0.006	0.007	0.001	0.008	0.034	0.004	0.009	0.517	1.219
11	***E***	Pre-Fatigue	0.003	0.003	0.013	0.004	0.013	0.004	0.001	0.001	0.034	0.034	0.021	0.007	2.228	1.214
		Post-Fatigue	0.008	0.006	0.004	0.020	0.003	0.043	0.005	0.001	0.005	0.034	0.004	0.018	1.445	0.951
12	***C***	Pre-Fatigue	0.536	0.189	0.058	0.017	0.031	0.013	0.001	0.010	0.034	0.016	0.005	0.006	0.536	0.189
		Post-Fatigue	0.006	0.008	0.007	0.013	0.005	0.005	0.001	0.004	0.034	0.002	0.003	0.003	2.318	0.328
13	***C***	Pre-Fatigue	1.529	0.249	0.167	0.013	0.043	0.009	0.001	0.012	0.034	0.026	0.002	0.005	1.529	0.249
		Post-Fatigue	0.002	0.007	0.006	0.007	0.003	0.005	0.001	0.006	0.034	0.007	0.001	0.004	6.217	0.916
14	***C***	Pre-Fatigue	0.496	0.584	0.710	0.075	0.002	0.049	0.001	0.048	0.034	0.057	0.002	0.053	0.496	0.584
		Post-Fatigue	0.004	0.009	0.007	0.017	0.002	0.014	0.173	0.011	0.184	0.007	0.002	0.004	2.720	0.589
15	***C***	Pre-Fatigue	1.387	0.306	0.270	0.050	0.003	0.025	0.001	0.025	0.034	0.031	0.002	0.007	1.387	0.306
		Post-Fatigue	0.004	0.018	0.005	0.026	0.002	0.047	0.036	0.011	0.063	0.007	0.003	0.008	1.085	0.299
16	***C***	Pre-Fatigue	3.865	1.068	0.041	0.028	0.011	0.031	0.001	0.029	0.034	0.031	0.005	0.094	3.865	1.068
		Post-Fatigue	0.001	0.007	0.001	0.017	0.001	0.011	0.004	0.005	0.003	0.007	0.001	0.007	6.426	0.589
17	***C***	Pre-Fatigue	2.631	1.399	0.211	0.020	0.022	0.019	0.012	0.031	0.040	0.019	0.026	0.082	2.631	1.399
		Post-Fatigue	0.006	0.002	0.010	0.018	0.004	0.006	0.006	0.008	0.003	0.010	0.003	0.007	2.245	1.449
18	***C***	Pre-Fatigue	1.500	1.111	0.183	0.024	0.061	0.047	0.001	0.066	0.034	0.047	0.027	0.029	1.500	1.112
		Post-Fatigue	0.004	0.018	0.004	0.028	0.003	0.017	0.266	0.021	0.267	0.018	0.005	0.015	3.803	0.790
19	***C***	Pre-Fatigue	0.910	1.565	0.199	0.021	0.102	0.038	0.001	0.095	0.034	0.035	0.051	0.017	0.909	1.565
		Post-Fatigue	0.012	0.021	0.013	0.208	0.014	0.018	0.175	0.025	0.187	0.018	0.011	0.017	2.878	1.018
20	***C***	Pre-Fatigue	0.559	4.023	0.737	0.004	0.035	0.003	0.001	0.030	0.035	0.014	0.016	0.059	0.559	4.023
		Post-Fatigue	0.003	0.011	0.002	0.011	0.004	0.016	0.005	0.012	0.012	0.007	0.011	0.029	3.554	1.295
21	***C***	Pre-Fatigue	0.936	6.507	0.848	0.010	0.020	0.013	0.006	0.039	0.038	0.059	0.092	0.051	0.936	6.507
		Post-Fatigue	0.002	0.010	0.001	0.012	0.004	0.005	0.007	0.016	0.111	0.007	0.010	0.013	4.237	2.715

P = participant, E = experimental, C = control, VM = vastus medialis, RF = rectus femoris, VL = vastus lateralis, SM = semimembranosis, ST = semitendonosis, BF = biceps femoris, H:Q = hamstring:quadriceps co-activation ratio

Background muscle activity (0 – 30 ms)

P	Group	Condition	VM (%)		RF (%)		VL (%)		SM (%)		ST (%)		BF (%)		H:Q (%)	
			Pre-intervention	Post-intervention	Pre-intervention	Post-intervention	Pre-intervention	Post-intervention	Pre-intervention	Post-intervention	Pre-intervention	Post-intervention	Pre-intervention	Post-intervention	Pre-intervention	Post-intervention
1	***E***	Pre-Fatigue	0.55	0.54	9.70	17.43	8.22	17.82	3.76	11.11	9.08	11.61	3.018	6.15	0.55	0.54
		Post-Fatigue	26.18	22.43	29.34	17.82	16.32	14.81	17.32	15.34	15.01	15.61	27.88	15.81	0.63	1.39
2	***E***	Pre-Fatigue	1.13	0.75	12.01	13.02	11.82	11.67	15.19	11.61	16.24	10.89	14.40	11.81	1.13	0.75
		Post-Fatigue	9.91	4.91	12.51	7.75	13.52	13.32	24.98	15.84	14.24	13.96	15.62	17.49	1.14	1.40
3	***E***	Pre-Fatigue	0.95	0.72	21.98	23.45	5.97	10.55	12.75	10.76	17.88	11.21	10.96	9.40	0.95	0.72
		Post-Fatigue	20.67	10.23	23.60	15.58	22.32	18.43	27.88	16.08	20.18	61.67	28.11	14.58	0.78	1.56
4	***E***	Pre-Fatigue	0.61	0.39	17.81	44.32	15.48	49.13	14.47	11.80	13.98	12.87	14.57	40.84	0.61	0.39
		Post-Fatigue	24.22	36.00	22.84	32.44	23.00	35.52	21.04	20.52	21.53	20.02	16.26	21.15	0.60	1.11
5	***E***	Pre-Fatigue	0.65	0.47	15.20	25.54	19.62	26.99	13.62	19.50	18.31	22.93	15.20	21.59	0.65	0.47
		Post-Fatigue	17.18	17.99	19.38	10.04	22.52	8.95	24.57	13.95	18.32	15.03	17.55	11.23	0.73	0.94
6	***E***	Pre-Fatigue	0.88	0.80	14.55	28.35	10.68	29.16	16.19	15.82	16.39	15.20	12.63	20.24	0.88	0.80
		Post-Fatigue	21.74	36.83	3.79	40.14	23.40	36.69	13.38	24.84	16.63	18.23	23.12	40.46	0.62	0.55
7	***E***	Pre-Fatigue	0.66	0.78	26.04	25.91	31.11	23.89	10.50	20.86	28.80	20.01	36.43	17.62	0.66	0.78
		Post-Fatigue	21.39	28.04	18.63	29.23	17.33	21.97	14.57	15.34	14.48	14.98	17.52	21.10	0.51	0.51
8	***E***	Pre-Fatigue	0.41	0.61	22.82	15.35	43.94	22.19	7.16	17.71	16.37	16.65	9.64	24.12	0.41	0.61
		Post-Fatigue	19.62	24.43	17.81	16.67	22.14	13.44	9.93	14.76	12.60	14.01	12.35	14.22	0.38	0.65
9	***E***	Pre-Fatigue	0.70	0.60	19.51	15.91	11.77	13.61	15.67	11.73	15.67	12.00	15.31	18.87	0.70	0.60
		Post-Fatigue	12.43	17.21	16.62	30.45	20.21	17.16	13.26	14.72	13.00	13.98	6.54	7.56	0.54	0.45
10	***E***	Pre-Fatigue	1.57	0.74	3.70	21.37	10.07	24.99	13.21	18.11	10.28	18.42	2.84	15.84	1.57	0.74
		Post-Fatigue	19.40	16.21	26.66	31.76	23.40	27.91	16.81	21.48	18.20	20.06	13.58	15.85	0.57	0.62
11	***E***	Pre-Fatigue	0.51	0.78	30.11	18.20	28.87	19.41	24.67	17.68	16.00	19.87	38.41	18.62	0.51	0.78
		Post-Fatigue	20.16	15.72	19.79	33.93	18.38	22.42	10.19	19.24	16.34	19.98	19.04	7.62	0.44	0.57
12	***C***	Pre-Fatigue	0.41	0.72	29.39	13.88	25.34	25.92	15.21	11.79	13.99	10.88	20.03	10.91	0.41	0.72
		Post-Fatigue	19.31	32.53	8.48	32.56	14.73	17.18	15.46	4.12	13.49	5.40	18.05	3.73	1.21	0.12
13	***C***	Pre-Fatigue	1.11	0.72	14.39	30.32	5.25	28.92	8.24	27.59	12.00	27.73	11.87	23.36	1.11	0.72
		Post-Fatigue	12.61	22.75	22.98	26.46	19.40	18.66	13.47	5.41	12.99	5.04	12.52	6.21	0.41	0.15
14	***C***	Pre-Fatigue	0.75	0.80	18.04	18.47	22.17	16.66	19.33	17.72	19.02	22.30	14.53	19.77	0.75	0.80
		Post-Fatigue	16.39	21.38	18.83	27.55	14.50	28.35	34.24	6.41	28.53	23.04	15.95	11.13	2.47	0.53
15	***C***	Pre-Fatigue	0.90	0.47	14.72	32.40	13.70	31.54	14.42	20.65	13.98	16.65	15.30	25.53	0.90	0.47
		Post-Fatigue	7.46	29.01	11.03	21.82	5.48	10.99	6.28	32.24	11.85	12.19	7.53	23.60	1.28	0.83
16	***C***	Pre-Fatigue	1.01	0.64	11.74	31.31	16.59	23.63	9.19	24.32	11.49	16.27	8.80	13.12	1.01	0.64
		Post-Fatigue	7.70	33.62	5.43	13.81	5.86	32.13	12.86	13.42	10.53	6.80	7.77	23.70	2.37	0.27
17	***C***	Pre-Fatigue	0.66	0.50	13.09	12.33	16.69	26.25	12.55	10.49	11.00	16.17	11.35	17.05	0.66	0.50
		Post-Fatigue	26.19	12.76	30.67	19.83	25.63	18.71	18.25	18.80	13.84	25.93	17.33	17.44	0.44	1.07
18	***C***	Pre-Fatigue	0.84	0.63	13.44	18.28	18.48	18.40	11.45	12.48	13.64	19.30	17.00	7.23	0.84	0.63
		Post-Fatigue	7.83	7.91	9.52	16.16	8.67	16.33	53.30	16.83	29.40	21.17	14.96	16.80	2.90	0.74
19	***C***	Pre-Fatigue	0.68	0.46	19.74	67.26	18.26	44.58	18.23	23.52	17.54	41.09	16.33	25.03	0.68	0.46
		Post-Fatigue	19.60	18.48	17.95	20.73	20.48	19.78	17.15	17.31	17.05	19.17	18.12	20.87	0.78	0.60
20	***C***	Pre-Fatigue	0.88	0.41	11.06	23.73	19.92	16.84	11.75	10.56	13.66	10.92	14.93	13.29	0.88	0.41
		Post-Fatigue	17.41	38.55	27.70	37.17	14.86	50.74	10.89	26.93	25.13	31.26	21.63	38.84	0.60	0.46
21	***C***	Pre-Fatigue	0.89	0.79	17.05	7.95	14.39	10.92	23.91	12.12	13.58	7.05	19.67	5.98	0.89	0.79
		Post-Fatigue	8.20	12.77	12.12	4.32	17.61	5.75	12.52	11.13	20.14	11.53	15.33	18.07	1.51	0.99

P = participant, E = experimental, C = control, VM = vastus medialis, RF = rectus femoris, VL = vastus lateralis, SM = semimembranosis, ST = semitendonosis, BF = biceps femoris, H:Q = hamstring:quadriceps co-activation ratio

31 – 60 ms

P	Group	Condition	VM (mV)		RF (mV)		VL (mV)		SM (mV)		ST (mV)		BF (mV)		H:Q (%)	
			Pre-intervention	Post-intervention	Pre-intervention	Post-intervention	Pre-intervention	Post-intervention	Pre-intervention	Post-intervention	Pre-intervention	Post-intervention	Pre-intervention	Post-intervention	Pre-intervention	Post-intervention
1	***E***	Pre-Fatigue	6.66	20.71	10.17	21.67	10.91	20.83	4.95	11.99	10.76	11.59	2.90	6.37	0.65	0.48
		Post-Fatigue	15.18	5.27	17.02	9.17	15.90	10.18	17.21	15.17	15.01	15.64	16.87	11.24	1.20	2.09
2	***E***	Pre-Fatigue	10.29	23.62	14.15	25.36	18.52	24.46	22.75	14.16	24.04	10.89	17.02	11.34	1.44	0.50
		Post-Fatigue	14.07	17.83	17.79	9.03	13.72	9.44	15.79	14.44	14.02	13.97	15.87	19.58	1.25	1.71
3	***E***	Pre-Fatigue	16.92	7.10	20.96	13.61	16.73	13.11	16.39	12.25	13.41	11.21	20.36	10.04	1.18	1.00
		Post-Fatigue	28.48	15.85	33.93	24.35	30.49	19.63	28.53	16.67	20.07	61.63	21.97	9.63	0.78	1.48
4	***E***	Pre-Fatigue	7.85	16.43	11.13	21.30	11.95	24.33	10.49	18.12	8.55	12.43	9.53	17.60	1.01	0.85
		Post-Fatigue	23.13	18.61	23.40	14.20	22.49	14.99	23.98	18.97	21.67	20.02	18.04	17.62	0.92	1.28
5	***E***	Pre-Fatigue	21.20	18.20	22.99	17.57	22.46	16.92	13.91	28.85	21.41	22.31	19.40	13.62	0.86	1.64
		Post-Fatigue	13.72	17.84	11.65	8.93	19.12	14.03	22.12	15.00	18.31	15.00	14.18	15.54	1.24	1.21
6	***E***	Pre-Fatigue	12.55	13.41	18.30	13.32	17.78	13.99	15.83	22.62	18.12	14.38	15.79	14.01	1.02	1.89
		Post-Fatigue	19.99	26.69	5.75	23.45	21.44	20.20	16.75	17.67	16.70	18.22	18.68	25.63	1.19	0.88
7	***E***	Pre-Fatigue	17.90	14.04	26.98	14.82	18.66	19.00	13.50	20.04	17.89	20.00	18.53	15.02	0.90	1.46
		Post-Fatigue	10.54	23.54	18.93	27.98	11.52	27.96	19.48	17.93	18.64	14.99	14.87	16.43	1.31	0.63
8	***E***	Pre-Fatigue	16.21	20.75	20.67	15.30	19.49	18.16	9.44	16.20	15.60	16.67	8.43	23.28	0.79	1.04
		Post-Fatigue	19.12	45.46	19.14	19.03	20.20	17.21	11.11	12.68	16.36	13.99	15.59	14.34	0.74	0.66
9	***E***	Pre-Fatigue	17.24	10.63	17.56	10.20	16.59	7.63	15.67	12.00	15.67	11.98	12.82	17.72	0.90	1.50
		Post-Fatigue	15.79	7.95	18.83	11.78	17.78	4.78	14.78	13.39	15.31	13.99	8.73	7.67	0.76	1.62
10	***E***	Pre-Fatigue	1.41	16.59	4.32	18.85	10.26	20.93	11.22	18.48	10.20	18.30	4.27	12.27	1.66	0.90
		Post-Fatigue	19.21	23.90	18.07	22.09	29.49	23.86	18.32	20.01	20.63	19.93	18.13	15.89	0.95	0.83
11	***E***	Pre-Fatigue	27.91	18.31	22.76	27.66	18.51	32.56	21.14	19.45	15.26	19.82	24.85	13.91	0.89	0.84
		Post-Fatigue	22.25	28.28	22.30	29.79	15.81	25.31	12.62	16.70	11.96	19.96	18.19	8.44	0.69	0.64
12	***C***	Pre-Fatigue	23.04	14.60	18.51	9.95	18.31	13.53	20.52	13.34	14.00	17.36	20.69	8.70	0.97	1.03
		Post-Fatigue	12.04	22.21	10.62	16.95	11.96	17.56	13.70	11.43	13.33	9.85	20.16	12.62	0.88	0.66
13	***C***	Pre-Fatigue	10.35	20.75	15.50	24.39	6.59	26.95	12.17	30.28	12.02	28.84	11.80	24.37	1.01	0.73
		Post-Fatigue	14.42	21.24	15.90	21.41	19.05	14.73	15.08	5.34	12.97	5.30	12.87	6.99	1.94	1.82
14	***C***	Pre-Fatigue	20.58	12.93	20.86	20.38	19.09	11.96	19.83	17.16	19.02	18.39	21.55	22.70	1.02	1.11
		Post-Fatigue	12.97	20.52	19.35	18.57	12.92	17.74	32.78	9.84	27.18	19.04	20.42	13.97	1.76	1.53
15	***C***	Pre-Fatigue	14.21	14.47	21.34	19.26	15.63	26.30	15.32	9.28	14.00	15.04	17.09	16.71	1.24	0.83
		Post-Fatigue	7.00	13.48	5.65	12.95	5.29	11.00	7.84	25.19	13.27	19.25	7.98	17.98	0.60	0.55
16	***C***	Pre-Fatigue	13.13	11.32	10.45	15.95	9.79	23.30	6.63	22.43	11.52	18.58	8.52	13.94	1.00	0.79
		Post-Fatigue	10.32	18.05	7.33	11.65	10.58	21.72	10.91	22.73	10.90	14.93	10.01	25.21	0.93	1.11
17	***C***	Pre-Fatigue	16.23	18.08	9.06	11.40	12.55	11.80	11.65	13.38	11.00	13.66	11.57	11.49	1.24	0.91
		Post-Fatigue	17.46	31.05	23.85	26.76	16.63	31.41	15.76	33.50	15.85	29.54	15.72	34.20	0.60	1.14
18	***C***	Pre-Fatigue	10.78	11.75	12.89	17.62	6.27	10.74	5.76	10.78	13.04	12.40	14.04	11.08	1.21	0.83
		Post-Fatigue	8.33	8.61	9.02	15.30	9.73	8.97	21.56	7.81	22.12	8.82	15.99	4.67	3.03	0.55
19	***C***	Pre-Fatigue	13.91	10.92	28.47	16.49	17.04	13.20	19.01	21.73	16.69	12.09	17.31	23.06	1.00	1.36
		Post-Fatigue	14.97	15.26	18.19	37.91	17.99	25.66	10.26	28.23	10.98	28.23	21.40	39.43	0.93	1.18
20	***C***	Pre-Fatigue	12.10	12.66	6.93	25.07	14.05	20.13	10.33	9.91	13.18	12.89	13.88	16.60	2.78	0.79
		Post-Fatigue	10.34	22.08	27.70	17.03	17.82	19.57	6.55	23.47	12.69	19.18	7.92	22.79	0.50	1.11
21	***C***	Pre-Fatigue	13.42	7.08	15.40	11.96	14.92	11.70	7.54	15.22	13.95	13.59	16.66	11.76	1.68	1.39
		Post-Fatigue	13.76	9.84	14.50	7.77	17.09	6.41	37.45	14.75	40.77	15.95	15.49	20.19	2.26	2.42

P = participant, E = experimental, C = control, VM = vastus medialis, RF = rectus femoris, VL = vastus lateralis, SM = semimembranosis, ST = semitendonosis, BF = biceps femoris, H:Q = hamstring:quadriceps co-activation ratio

61 – 90 ms

P	Group	Condition	VM (mV)		RF (mV)		VL (mV)		SM (mV)		ST (mV)		BF (mV)		H:Q (%)	
			Pre-intervention	Post-intervention	Pre-intervention	Post-intervention	Pre-intervention	Post-intervention	Pre-intervention	Post-intervention	Pre-intervention	Post-intervention	Pre-intervention	Post-intervention	Pre-intervention	Post-intervention
1	***E***	Pre-Fatigue	8.78	18.52	12.06	21.96	8.66	22.74	9.25	12.06	11.46	11.53	4.14	23.20	0.82	0.94
		Post-Fatigue	9.09	6.68	12.08	11.18	15.92	10.54	15.77	14.89	4.98	15.75	10.80	12.35	1.12	1.79
2	***E***	Pre-Fatigue	19.82	23.53	22.59	24.47	13.06	24.85	18.36	14.14	19.61	10.86	21.22	17.64	1.06	0.60
		Post-Fatigue	13.71	29.70	14.49	12.85	19.67	8.80	10.21	12.54	13.93	14.05	10.37	9.07	0.87	0.79
3	***E***	Pre-Fatigue	15.34	13.85	10.11	9.06	18.10	12.50	24.53	14.92	14.90	11.44	32.89	15.49	1.36	1.22
		Post-Fatigue	24.18	18.14	22.40	20.89	20.54	14.72	19.43	16.53	20.05	61.66	16.43	14.19	0.85	1.65
4	***E***	Pre-Fatigue	8.34	16.40	13.30	8.01	9.82	7.83	8.46	15.75	4.27	12.62	7.91	7.59	0.95	1.15
		Post-Fatigue	19.56	17.94	19.72	19.64	19.89	17.72	21.92	20.51	21.78	20.00	23.55	29.29	1.10	1.58
5	***E***	Pre-Fatigue	15.06	17.31	18.71	21.77	16.90	15.02	15.34	27.00	17.76	22.47	17.77	25.36	0.98	1.45
		Post-Fatigue	15.88	22.26	21.75	16.65	16.34	20.00	18.94	15.00	18.33	14.96	13.44	19.12	0.97	1.09
6	***E***	Pre-Fatigue	13.63	12.49	19.52	7.68	21.63	7.68	16.55	14.70	19.13	14.00	17.26	9.52	0.98	1.36
		Post-Fatigue	18.23	18.23	11.03	9.10	18.11	13.03	15.67	15.42	16.73	18.74	18.47	14.52	1.16	1.52
7	***E***	Pre-Fatigue	14.60	24.13	25.14	15.38	14.52	19.36	16.85	19.94	12.09	20.05	12.65	27.62	0.87	1.25
		Post-Fatigue	8.11	18.43	12.01	19.32	14.86	19.11	18.09	15.92	17.57	15.01	11.64	15.34	1.47	1.13
8	***E***	Pre-Fatigue	15.31	15.59	12.61	17.38	18.98	16.48	11.52	17.56	12.13	16.70	13.56	20.08	0.81	1.12
		Post-Fatigue	20.49	12.23	21.97	20.89	16.08	25.41	19.21	14.78	22.15	13.99	18.53	13.52	1.08	0.76
9	***E***	Pre-Fatigue	17.41	10.49	19.35	7.40	22.67	7.74	15.67	12.00	15.67	12.00	26.60	16.02	1.00	1.60
		Post-Fatigue	20.08	15.28	12.38	5.73	17.24	6.67	14.80	13.67	16.64	14.00	13.26	12.21	0.92	1.59
10	***E***	Pre-Fatigue	1.35	16.88	2.79	17.47	6.31	17.47	7.47	18.75	10.19	18.22	3.39	17.80	0.98	0.88
		Post-Fatigue	15.02	29.37	16.14	18.70	18.65	15.06	15.98	19.60	19.35	20.03	20.02	16.52	0.72	1.01
11	***E***	Pre-Fatigue	16.16	19.63	17.36	24.16	15.66	25.73	16.64	20.63	15.46	19.89	12.43	12.92	0.92	0.88
		Post-Fatigue	20.35	17.25	24.89	20.29	18.43	22.71	13.33	26.03	14.58	20.09	14.90	20.94	0.84	1.01
12	***C***	Pre-Fatigue	12.99	15.56	15.60	13.79	20.27	8.66	17.93	15.33	13.99	20.49	18.05	14.44	0.92	1.33
		Post-Fatigue	8.22	14.14	14.33	11.61	7.20	10.72	11.30	20.30	13.76	19.74	19.58	19.36	0.84	1.67
13	***C***	Pre-Fatigue	8.69	18.68	10.97	12.97	8.90	14.36	12.92	16.48	12.01	20.47	10.66	18.17	1.03	1.32
		Post-Fatigue	13.58	15.02	12.27	19.22	15.16	15.82	12.46	4.74	13.00	4.91	12.34	10.70	1.50	0.41
14	***C***	Pre-Fatigue	20.90	12.80	20.48	15.92	14.63	12.57	17.66	14.15	19.00	14.81	17.33	17.58	1.71	1.16
		Post-Fatigue	16.32	21.90	16.70	21.10	15.34	15.12	25.58	14.11	21.12	12.88	19.79	10.13	0.81	0.60
15	***C***	Pre-Fatigue	13.62	15.17	16.65	12.22	15.03	18.42	15.19	10.73	13.99	22.19	14.71	14.60	0.98	1.03
		Post-Fatigue	8.26	8.01	7.82	15.38	6.44	18.51	29.04	15.15	19.66	18.12	11.51	11.63	1.51	1.12
16	***C***	Pre-Fatigue	10.66	13.80	11.41	13.86	4.69	16.61	6.17	15.21	11.53	16.87	6.82	14.33	1.20	1.09
		Post-Fatigue	13.18	15.87	12.55	10.54	18.85	11.52	9.23	18.72	12.68	19.65	13.93	12.82	1.30	1.95
17	***C***	Pre-Fatigue	10.36	24.21	5.47	15.59	6.05	8.82	10.47	15.88	10.99	14.06	12.99	14.09	1.37	0.68
		Post-Fatigue	11.72	16.09	13.97	9.92	14.95	16.98	13.00	10.91	15.88	11.71	11.92	11.06	0.59	0.57
18	***C***	Pre-Fatigue	3.99	11.50	7.28	14.73	3.25	9.58	7.01	8.86	13.02	7.14	5.59	10.53	1.47	0.64
		Post-Fatigue	13.84	9.44	13.42	11.37	14.42	8.27	9.23	5.88	15.02	7.47	19.83	4.74	1.12	1.41
19	***C***	Pre-Fatigue	12.15	6.34	19.46	5.15	16.60	5.47	19.17	20.44	18.02	9.70	21.89	27.45	1.32	1.33
		Post-Fatigue	16.08	11.77	17.72	16.32	17.38	10.96	17.95	13.27	17.86	12.28	20.58	15.91	0.60	1.75
20	***C***	Pre-Fatigue	19.85	20.83	18.44	27.54	2.95	20.57	16.24	12.46	13.65	13.73	14.46	13.50	2.78	0.64
		Post-Fatigue	10.08	11.58	13.74	12.18	18.42	11.00	9.76	18.01	11.17	13.39	5.47	17.55	0.60	1.41
21	***C***	Pre-Fatigue	9.47	8.88	12.03	18.22	5.18	11.34	8.56	21.02	13.09	15.58	9.40	14.65	1.68	1.33
		Post-Fatigue	18.49	14.72	16.60	22.13	15.21	15.09	11.72	17.18	16.89	19.79	12.06	21.54	1.14	1.75

P = participant, E = experimental, C = control, VM = vastus medialis, RF = rectus femoris, VL = vastus lateralis, SM = semimembranosis, ST = semitendonosis, BF = biceps femoris, H:Q = hamstring:quadriceps co-activation ratio

91 – 120 ms

P	Group	Condition	VM (mV)		RF (mV)		VL (mV)		SM (mV)		ST (mV)		BF (mV)		H:Q (%)	
			Pre-intervention	Post-intervention	Pre-intervention	Post-intervention	Pre-intervention	Post-intervention	Pre-intervention	Post-intervention	Pre-intervention	Post-intervention	Pre-intervention	Post-intervention	Pre-intervention	Post-intervention
1	***E***	Pre-Fatigue	10.25	12.34	9.44	14.24	4.37	16.78	6.18	11.68	7.73	11.61	7.24	22.29	1.07	1.25
		Post-Fatigue	11.72	9.85	9.80	13.05	12.96	10.87	15.49	14.67	15.00	15.73	8.33	10.28	1.20	1.23
2	***E***	Pre-Fatigue	26.56	14.37	22.90	15.97	9.25	18.46	15.88	9.90	14.99	10.86	20.00	15.57	0.95	0.80
		Post-Fatigue	11.79	15.69	13.61	13.60	18.35	5.94	12.64	13.23	13.91	14.00	7.86	6.08	1.04	0.95
3	***E***	Pre-Fatigue	16.39	15.41	14.30	12.99	10.59	14.73	3.23	11.76	20.86	11.26	19.53	17.21	1.00	0.93
		Post-Fatigue	17.31	34.56	10.96	11.89	17.17	10.87	17.88	16.27	20.01	61.77	18.06	19.49	1.45	2.25
4	***E***	Pre-Fatigue	11.13	22.27	16.43	4.76	11.94	5.58	20.66	13.06	8.76	12.73	9.31	9.64	1.18	1.10
		Post-Fatigue	21.88	17.16	22.68	18.92	24.19	18.74	23.26	20.47	21.55	19.98	32.54	21.27	1.11	1.95
5	***E***	Pre-Fatigue	19.04	46.30	17.36	32.30	16.65	49.14	57.57	20.25	15.23	22.58	18.61	41.83	1.45	0.79
		Post-Fatigue	20.78	22.90	23.84	30.12	18.71	31.56	15.77	16.48	18.35	15.02	21.42	20.16	0.88	1.06
6	***E***	Pre-Fatigue	14.01	12.04	15.82	12.53	17.43	12.33	20.56	6.91	17.76	14.96	16.73	12.94	1.16	1.06
		Post-Fatigue	15.24	8.57	21.07	12.31	12.59	12.60	15.05	15.38	16.64	18.68	15.48	8.64	0.99	1.72
7	***E***	Pre-Fatigue	15.70	19.72	9.20	20.19	13.48	16.79	22.26	20.39	15.84	19.94	14.15	27.92	1.26	1.21
		Post-Fatigue	9.93	12.21	8.93	10.14	13.42	10.04	10.94	14.71	12.68	15.04	10.29	12.94	1.18	1.89
8	***E***	Pre-Fatigue	13.45	15.90	10.91	17.90	13.58	13.55	9.50	17.00	11.32	16.67	18.01	9.51	1.08	0.94
		Post-Fatigue	17.81	9.99	16.17	13.20	19.12	17.42	17.93	15.57	19.85	13.98	20.67	15.81	1.06	1.14
9	***E***	Pre-Fatigue	14.13	11.25	16.21	6.96	22.14	8.54	12.27	12.00	15.67	11.98	23.00	12.70	3.00	1.52
		Post-Fatigue	18.40	9.25	17.61	6.69	16.94	11.57	12.41	14.61	14.98	14.03	15.53	16.09	0.82	1.93
10	***E***	Pre-Fatigue	1.30	17.92	1.27	19.38	6.18	14.95	0.38	19.12	10.21	18.23	2.36	21.58	1.48	1.27
		Post-Fatigue	18.33	12.62	18.94	16.10	11.72	16.58	20.81	19.70	18.39	20.02	21.17	22.21	1.39	1.71
11	***E***	Pre-Fatigue	11.90	21.38	12.54	25.85	11.80	26.95	0.44	21.18	15.77	19.96	5.93	17.87	0.96	0.96
		Post-Fatigue	13.95	29.82	17.77	11.32	16.56	20.47	8.69	20.87	13.47	20.04	10.88	32.54	0.80	1.43
12	***C***	Pre-Fatigue	15.82	13.92	10.30	22.82	14.65	13.28	14.51	16.49	14.01	19.14	13.81	20.08	1.10	1.03
		Post-Fatigue	7.66	9.73	8.62	11.17	6.76	9.21	9.23	24.29	13.45	26.27	13.56	22.29	1.60	0.71
13	***C***	Pre-Fatigue	7.37	19.91	7.50	20.00	11.61	16.55	11.73	12.54	12.00	15.26	6.61	13.94	1.26	1.03
		Post-Fatigue	12.12	13.12	10.40	15.83	8.30	16.18	12.93	9.94	12.94	9.86	12.25	12.21	1.19	0.94
14	***C***	Pre-Fatigue	15.51	13.81	17.01	10.80	17.18	10.70	19.41	42.25	18.97	11.11	19.76	10.60	1.15	1.37
		Post-Fatigue	16.41	21.21	17.32	14.84	16.69	15.12	5.66	19.49	9.65	9.71	19.07	17.37	0.78	0.73
15	***C***	Pre-Fatigue	10.26	15.12	9.84	14.46	12.79	10.09	13.38	20.38	14.05	17.67	11.28	15.05	1.20	1.49
		Post-Fatigue	9.50	11.73	10.39	13.55	11.21	18.51	18.18	6.80	15.73	12.22	13.45	7.98	1.01	1.81
16	***C***	Pre-Fatigue	13.40	12.63	9.33	11.39	4.28	13.52	7.46	15.71	11.42	24.85	6.91	14.31	1.23	0.60
		Post-Fatigue	14.48	9.33	16.42	13.36	15.80	14.05	9.80	16.75	13.80	26.82	15.77	16.16	1.15	1.35
17	***C***	Pre-Fatigue	7.17	15.90	4.25	16.20	4.11	13.01	10.11	20.05	10.97	13.72	13.04	13.87	1.88	1.13
		Post-Fatigue	9.63	11.57	9.59	7.50	12.40	13.57	14.36	5.38	13.87	6.17	13.87	8.06	1.33	0.76
18	***C***	Pre-Fatigue	11.48	10.10	10.67	16.44	11.43	16.00	21.43	17.70	14.12	14.91	9.09	9.95	1.63	1.02
		Post-Fatigue	18.31	17.29	16.85	9.08	19.94	7.40	3.61	11.64	10.84	5.40	11.77	5.23	0.83	0.68
19	***C***	Pre-Fatigue	17.39	6.40	13.17	2.46	16.36	3.69	16.86	16.80	17.73	9.33	14.64	19.11	1.23	4.06
		Post-Fatigue	15.06	15.83	22.76	4.86	17.89	4.99	20.98	6.60	20.67	5.70	15.33	3.85	1.15	0.73
20	***C***	Pre-Fatigue	24.56	27.33	21.28	37.32	4.34	27.07	23.00	13.38	13.50	22.85	16.25	14.40	1.17	0.60
		Post-Fatigue	11.31	8.90	9.50	15.31	13.44	8.10	15.08	13.79	11.13	18.32	7.72	10.75	0.95	1.35
21	***C***	Pre-Fatigue	20.75	11.25	12.86	18.41	10.60	11.58	17.28	20.33	13.22	15.27	12.28	12.57	1.06	1.18
		Post-Fatigue	12.92	14.92	12.04	17.47	14.16	13.59	6.94	14.77	4.73	17.17	9.25	15.44	0.63	1.02

P = participant, E = experimental, C = control, VM = vastus medialis, RF = rectus femoris, VL = vastus lateralis, SM = semimembranosis, ST = semitendonosis, BF = biceps femoris, H:Q = hamstring:quadriceps co-activation ratio

GCT

P	Group	Condition	VM (mV)		RF (mV)		VL (mV)		SM (mV)		ST (mV)		BF (mV)		H:Q (%)	
			Pre-intervention	Post-intervention	Pre-intervention	Post-intervention	Pre-intervention	Post-intervention	Pre-intervention	Post-intervention	Pre-intervention	Post-intervention	Pre-intervention	Post-intervention	Pre-intervention	Post-intervention
1	***E***	Pre-Fatigue	0.281	0.027	0.174	0.026	0.228	0.032	0.238	0.003	0.265	0.089	0.221	0.052	1.135	1.694
		Post-Fatigue	0.007	0.020	0.009	0.022	0.071	0.012	0.001	0.002	0.068	0.068	0.006	0.014	0.862	1.556
2	***E***	Pre-Fatigue	0.066	0.043	0.058	0.032	0.095	0.044	0.099	0.003	0.096	0.095	0.070	0.032	1.504	0.079
		Post-Fatigue	0.009	0.018	0.013	0.074	0.056	0.007	0.003	0.002	0.075	0.074	0.064	0.011	0.342	0.144
3	***E***	Pre-Fatigue	0.008	0.101	0.006	0.025	0.013	0.061	0.002	0.003	0.003	0.092	0.003	0.014	0.897	0.059
		Post-Fatigue	0.005	0.007	0.004	0.006	0.005	0.003	0.001	0.002	0.053	0.042	0.009	0.006	0.073	0.435
4	***E***	Pre-Fatigue	0.032	0.149	0.042	0.057	0.042	0.040	0.089	0.003	0.067	0.084	0.042	0.062	3.818	0.031
		Post-Fatigue	0.010	0.013	0.014	0.015	0.014	0.008	0.001	0.003	0.051	0.051	0.008	0.009	0.066	0.302
5	***E***	Pre-Fatigue	0.072	0.028	0.058	0.024	0.033	0.023	0.085	0.002	0.136	0.051	0.111	0.052	1.182	0.493
		Post-Fatigue	0.004	0.026	0.004	0.052	0.005	0.015	0.008	0.002	0.057	0.068	0.006	0.013	3.119	0.186
6	***E***	Pre-Fatigue	0.225	0.053	0.121	0.019	0.096	0.029	0.148	0.004	0.098	0.073	0.094	0.026	0.662	0.116
		Post-Fatigue	0.003	0.028	0.125	0.039	0.010	0.057	0.001	0.002	0.063	0.058	0.014	0.016	0.263	0.122
7	***E***	Pre-Fatigue	0.016	0.023	0.007	0.012	0.004	0.010	0.006	0.002	0.013	0.057	0.053	0.010	0.514	0.072
		Post-Fatigue	0.035	0.016	0.079	0.015	0.059	0.016	0.008	0.003	0.053	0.068	0.007	0.014	1.381	0.164
8	***E***	Pre-Fatigue	0.014	0.009	0.016	0.015	0.019	0.006	0.011	0.002	0.077	0.063	0.013	0.012	0.803	0.224
		Post-Fatigue	0.008	0.008	0.013	0.050	0.007	0.015	0.014	0.003	0.013	0.074	0.012	0.024	1.640	0.374
9	***E***	Pre-Fatigue	0.046	0.024	0.077	0.009	0.080	0.006	0.600	0.003	0.600	0.086	0.045	0.014	24.116	0.136
		Post-Fatigue	0.007	0.019	0.009	0.017	0.006	0.012	0.011	0.003	0.008	0.074	0.007	0.011	1.842	0.153
10	***E***	Pre-Fatigue	0.138	0.033	0.057	0.008	0.027	0.006	0.001	0.002	0.103	0.057	0.069	0.014	0.014	0.050
		Post-Fatigue	0.012	0.010	0.010	0.025	0.058	0.007	0.011	0.002	0.010	0.051	0.007	0.016	1.221	0.252
11	***E***	Pre-Fatigue	0.018	0.029	0.028	0.011	0.018	0.009	0.001	0.002	0.068	0.051	0.031	0.016	0.049	0.063
		Post-Fatigue	0.006	0.014	0.013	0.011	0.006	0.057	0.011	0.002	0.012	0.051	0.008	0.032	1.835	0.178
12	***C***	Pre-Fatigue	0.079	0.292	0.020	0.056	0.062	0.057	0.002	0.057	0.080	0.111	0.010	0.032	0.571	5.850
		Post-Fatigue	0.013	0.007	0.029	0.006	0.014	0.006	0.002	0.053	0.077	0.025	0.006	0.020	1.518	5.158
13	***C***	Pre-Fatigue	0.017	0.235	0.023	0.017	0.086	0.007	0.002	0.014	0.085	0.056	0.009	0.007	0.175	0.062
		Post-Fatigue	0.009	0.014	0.007	0.016	0.007	0.008	0.001	0.031	0.080	0.013	0.007	0.012	0.213	2.268
14	***C***	Pre-Fatigue	0.019	0.298	0.112	0.062	0.013	0.084	0.001	0.066	0.063	0.111	0.010	0.057	0.132	0.228
		Post-Fatigue	0.010	0.010	0.016	0.010	0.006	0.005	0.161	0.007	0.193	0.007	0.010	0.004	18.506	0.942
15	***C***	Pre-Fatigue	0.022	0.254	0.055	0.038	0.012	0.027	0.002	0.017	0.074	0.035	0.011	0.009	0.105	0.065
		Post-Fatigue	0.016	0.009	0.014	0.071	0.009	0.091	0.169	0.011	0.216	0.008	0.008	0.003	15.697	1.876
16	***C***	Pre-Fatigue	0.010	0.137	0.036	0.035	0.045	0.048	0.008	0.107	0.093	0.076	0.053	0.191	0.696	0.752
		Post-Fatigue	0.005	0.013	0.008	0.032	0.004	0.015	0.011	0.016	0.011	0.024	0.010	0.017	2.651	1.229
17	***C***	Pre-Fatigue	0.010	0.093	0.013	0.032	0.015	0.030	0.003	0.079	0.094	0.047	0.013	0.127	0.404	0.849
		Post-Fatigue	0.005	0.025	0.007	0.040	0.004	0.035	0.011	0.027	0.007	0.029	0.005	0.028	2.227	1.100
18	***C***	Pre-Fatigue	0.063	0.110	0.077	0.035	0.100	0.054	0.008	0.094	0.080	0.060	0.076	0.114	0.214	0.854
		Post-Fatigue	0.012	0.038	0.009	0.033	0.007	0.031	0.187	0.034	0.219	0.027	0.012	0.023	14.966	0.669
19	***C***	Pre-Fatigue	0.006	0.070	0.012	0.021	0.170	0.039	0.001	0.127	0.060	0.043	0.076	0.044	0.223	2.139
		Post-Fatigue	0.015	0.040	0.018	0.063	0.016	0.075	0.465	0.074	0.467	0.072	0.017	0.054	52.561	2.227
20	***C***	Pre-Fatigue	0.046	0.069	0.101	0.010	0.025	0.013	0.002	0.046	0.078	0.032	0.026	0.141	0.108	0.669
		Post-Fatigue	0.003	0.010	0.001	0.009	0.002	0.010	0.008	0.020	0.009	0.010	0.007	0.029	2.940	1.963
21	***C***	Pre-Fatigue	0.062	0.041	0.196	0.049	0.035	0.057	0.004	0.097	0.078	0.110	0.184	0.161	0.075	2.581
		Post-Fatigue	0.008	0.022	0.007	0.034	0.010	0.032	0.034	0.033	0.036	0.019	0.019	0.018	4.858	1.721

P = participant, E = experimental, C = control, VM = vastus medialis, RF = rectus femoris, VL = vastus lateralis, SM = semimembranosis, ST = semitendonosis, BF = biceps femoris, H:Q = hamstring:quadriceps co-activation ratio

Peak

P	Group	Condition	VM (mV)		RF (mV)		VL (mV)		SM (mV)		ST (mV)		BF (mV)		H:Q (%)	
			Pre-intervention	Post-intervention	Pre-intervention	Post-intervention	Pre-intervention	Post-intervention	Pre-intervention	Post-intervention	Pre-intervention	Post-intervention	Pre-intervention	Post-intervention	Pre-intervention	Post-intervention
1	***E***	Pre-Fatigue	0.735	0.064	0.441	0.064	0.583	0.086	0.525	0.005	0.570	0.090	0.640	0.124	0.987	1.028
		Post-Fatigue	0.021	0.061	0.033	0.050	0.085	0.033	0.002	0.003	0.069	0.069	0.018	0.033	0.645	0.729
2	***E***	Pre-Fatigue	0.127	0.111	0.102	0.089	0.208	0.125	0.182	0.005	0.198	0.096	0.144	0.064	1.247	0.512
		Post-Fatigue	0.034	0.050	0.029	0.125	0.136	0.020	0.010	0.003	0.077	0.075	0.133	0.020	1.081	0.834
3	***E***	Pre-Fatigue	0.011	0.225	0.010	0.064	0.026	0.112	0.004	0.005	0.005	0.093	0.006	0.029	0.789	0.461
		Post-Fatigue	0.008	0.021	0.008	0.013	0.011	0.008	0.001	0.003	0.055	0.063	0.014	0.012	3.338	2.285
4	***E***	Pre-Fatigue	0.094	0.320	0.091	0.219	0.115	0.183	0.175	0.004	0.141	0.091	0.106	0.269	1.429	0.489
		Post-Fatigue	0.012	0.028	0.019	0.034	0.024	0.018	0.001	0.003	0.052	0.052	0.015	0.015	1.310	1.338
5	***E***	Pre-Fatigue	0.165	0.048	0.091	0.047	0.050	0.054	0.152	0.003	0.211	0.054	0.161	0.087	1.713	3.628
		Post-Fatigue	0.006	0.048	0.006	0.114	0.008	0.034	0.011	0.004	0.057	0.069	0.012	0.020	4.078	0.778
6	***E***	Pre-Fatigue	0.297	0.140	0.215	0.056	0.184	0.086	0.228	0.013	0.208	0.086	0.160	0.058	0.859	1.733
		Post-Fatigue	0.005	0.068	0.221	0.075	0.010	0.094	0.001	0.002	0.063	0.061	0.022	0.054	0.354	0.905
7	***E***	Pre-Fatigue	0.037	0.041	0.019	0.023	0.010	0.015	0.009	0.002	0.027	0.058	0.134	0.019	1.730	1.205
		Post-Fatigue	0.070	0.046	0.121	0.043	0.136	0.038	0.013	0.003	0.073	0.069	0.012	0.027	0.438	0.929
8	***E***	Pre-Fatigue	0.027	0.015	0.032	0.022	0.030	0.010	0.021	0.002	0.133	0.063	0.025	0.024	2.085	1.879
		Post-Fatigue	0.012	0.022	0.022	0.109	0.011	0.037	0.037	0.004	0.026	0.075	0.021	0.038	1.828	1.051
9	***E***	Pre-Fatigue	0.102	0.042	0.132	0.027	0.147	0.017	0.600	0.004	0.600	0.086	0.108	0.033	3.971	1.675
		Post-Fatigue	0.010	0.039	0.017	0.047	0.010	0.049	0.019	0.003	0.014	0.075	0.016	0.024	1.380	0.764
10	***E***	Pre-Fatigue	0.148	0.047	0.149	0.016	0.059	0.012	0.002	0.002	0.109	0.058	0.177	0.028	0.810	1.184
		Post-Fatigue	0.024	0.028	0.021	0.039	0.105	0.013	0.023	0.002	0.014	0.052	0.012	0.035	0.321	1.328
11	***E***	Pre-Fatigue	0.052	0.034	0.081	0.018	0.072	0.013	0.002	0.002	0.070	0.052	0.095	0.029	1.090	1.302
		Post-Fatigue	0.012	0.032	0.027	0.024	0.010	0.086	0.047	0.003	0.031	0.052	0.020	0.061	2.009	1.021
12	***C***	Pre-Fatigue	0.177	0.406	0.052	0.125	0.168	0.142	0.003	0.114	0.080	0.193	0.019	0.063	2.576	1.644
		Post-Fatigue	0.036	0.017	0.053	0.020	0.036	0.018	0.003	0.094	0.079	0.046	0.012	0.035	0.746	0.319
13	***C***	Pre-Fatigue	0.068	0.305	0.095	0.033	0.221	0.015	0.004	0.029	0.086	0.115	0.018	0.012	0.392	0.457
		Post-Fatigue	0.027	0.023	0.017	0.031	0.021	0.013	0.002	0.082	0.082	0.048	0.014	0.030	2.780	2.458
14	***C***	Pre-Fatigue	0.034	0.361	0.160	0.126	0.026	0.175	0.002	0.150	0.063	0.204	0.018	0.118	0.429	0.703
		Post-Fatigue	0.022	0.019	0.031	0.028	0.015	0.010	0.439	0.015	0.440	0.016	0.014	0.008	12.992	0.681
15	***C***	Pre-Fatigue	0.062	0.280	0.104	0.105	0.032	0.075	0.003	0.051	0.075	0.083	0.031	0.019	0.702	0.332
		Post-Fatigue	0.043	0.031	0.033	0.134	0.023	0.094	0.407	0.032	0.416	0.016	0.022	0.006	10.203	0.222
16	***C***	Pre-Fatigue	0.022	0.229	0.093	0.094	0.146	0.099	0.024	0.240	0.101	0.163	0.160	0.201	1.123	1.456
		Post-Fatigue	0.012	0.042	0.024	0.064	0.012	0.040	0.027	0.032	0.023	0.067	0.016	0.031	1.488	0.891
17	***C***	Pre-Fatigue	0.026	0.162	0.025	0.063	0.112	0.056	0.004	0.135	0.095	0.055	0.028	0.132	1.080	1.201
		Post-Fatigue	0.016	0.080	0.027	0.106	0.013	0.113	0.023	0.091	0.018	0.096	0.011	0.089	1.277	0.873
18	***C***	Pre-Fatigue	0.145	0.240	0.159	0.064	0.259	0.208	0.031	0.233	0.095	0.158	0.159	0.141	0.694	1.032
		Post-Fatigue	0.028	0.114	0.025	0.131	0.016	0.103	0.436	0.189	0.438	0.119	0.021	0.115	15.091	1.715
19	***C***	Pre-Fatigue	0.012	0.178	0.022	0.130	0.202	0.160	0.002	0.260	0.063	0.161	0.158	0.143	0.860	1.186
		Post-Fatigue	0.026	0.085	0.034	0.181	0.032	0.167	0.525	0.174	0.525	0.170	0.026	0.167	17.846	1.190
20	***C***	Pre-Fatigue	0.121	0.142	0.209	0.036	0.106	0.029	0.006	0.059	0.082	0.070	0.078	0.200	0.537	1.685
		Post-Fatigue	0.007	0.025	0.004	0.024	0.004	0.035	0.010	0.030	0.022	0.016	0.020	0.075	3.916	1.494
21	***C***	Pre-Fatigue	0.121	0.112	0.307	0.123	0.082	0.129	0.010	0.219	0.089	0.200	0.295	0.233	0.695	1.813
		Post-Fatigue	0.020	0.033	0.017	0.097	0.023	0.089	0.142	0.062	0.143	0.035	0.033	0.042	4.774	0.699

P = participant, E = experimental, C = control, VM = vastus medialis, RF = rectus femoris, VL = vastus lateralis, SM = semimembranosis, ST = semitendonosis, BF = biceps femoris, H:Q = hamstring:quadriceps co-activation ratio

Time to Peak

P	Group	Condition	VM (s)		RF (s)		VL (s)		SM (s)		ST (s)		BF (s)	
			Pre-intervention	Post-intervention	Pre-intervention	Post-intervention	Pre-intervention	Post-intervention	Pre-intervention	Post-intervention	Pre-intervention	Post-intervention	Pre-intervention	Post-intervention
1	***E***	Pre-Fatigue	0.28	0.05	0.05	0.04	0.09	0.05	0.54	0.15	0.47	0.10	0.52	0.09
		Post-Fatigue	0.13	0.14	0.07	0.13	0.09	0.13	0.11	0.11	0.06	0.09	0.13	0.13
2	***E***	Pre-Fatigue	0.09	0.06	0.09	0.05	0.09	0.06	0.09	0.07	0.11	0.02	0.12	0.09
		Post-Fatigue	0.12	0.06	0.13	0.12	0.14	0.20	0.13	0.16	0.11	0.12	1.11	0.09
3	***E***	Pre-Fatigue	0.17	0.13	0.02	0.00	0.17	0.14	0.18	0.11	0.18	0.15	0.07	0.11
		Post-Fatigue	0.06	0.09	0.05	0.10	0.06	0.09	0.03	0.08	1.04	0.07	0.06	0.09
4	***E***	Pre-Fatigue	0.17	0.11	0.07	0.03	0.13	0.07	0.17	0.04	0.17	-0.01	0.13	-0.01
		Post-Fatigue	0.03	0.02	0.12	0.05	0.05	0.05	0.08	0.05	0.13	0.06	0.10	0.04
5	***E***	Pre-Fatigue	0.09	0.05	0.08	2.28	0.07	2.36	0.07	2.05	0.07	2.34	0.16	2.00
		Post-Fatigue	0.12	0.10	0.12	0.11	0.08	0.10	0.08	0.10	0.10	0.06	0.11	0.11
6	***E***	Pre-Fatigue	0.11	0.07	0.08	2.37	0.07	2.43	0.07	2.42	0.09	2.54	0.08	2.19
		Post-Fatigue	0.16	0.02	0.16	0.04	0.08	0.06	0.09	0.00	0.07	0.07	0.07	-0.04
7	***E***	Pre-Fatigue	0.01	0.10	0.01	0.06	0.01	0.07	0.20	0.07	0.02	0.06	0.01	0.11
		Post-Fatigue	-0.08	0.04	0.14	0.04	0.14	0.03	0.10	0.04	0.11	0.11	0.13	0.04
8	***E***	Pre-Fatigue	0.06	0.04	0.06	0.08	0.09	0.10	0.16	0.10	0.12	0.07	0.17	0.09
		Post-Fatigue	0.07	0.14	0.13	0.10	0.08	0.06	0.14	0.06	0.15	0.14	0.15	0.06
9	***E***	Pre-Fatigue	0.10	0.08	0.06	0.10	0.08	0.16	0.11	0.19	0.10	0.04	0.11	0.14
		Post-Fatigue	0.08	0.17	0.09	0.15	0.03	0.20	0.11	0.90	0.08	0.86	0.13	0.96
10	***E***	Pre-Fatigue	0.24	0.09	0.20	0.08	0.26	0.11	0.14	0.07	0.27	0.05	0.24	0.12
		Post-Fatigue	0.11	0.11	0.08	0.04	0.08	0.05	0.11	0.05	0.13	0.07	0.13	0.09
11	***E***	Pre-Fatigue	0.04	0.51	0.09	0.51	0.10	0.53	0.04	0.49	0.01	0.45	0.09	0.53
		Post-Fatigue	0.11	0.07	0.05	0.02	0.06	0.03	0.17	0.12	0.15	0.07	0.16	0.13
12	***C***	Pre-Fatigue	0.05	0.09	0.02	0.06	0.04	0.10	0.06	0.11	0.04	0.12	0.04	0.09
		Post-Fatigue	0.09	0.02	0.19	0.13	0.11	0.20	0.09	0.11	0.12	0.11	0.05	0.10
13	***C***	Pre-Fatigue	0.17	0.03	0.11	0.04	0.20	0.03	0.20	0.03	0.11	0.05	0.13	0.03
		Post-Fatigue	0.12	0.03	0.08	0.05	0.11	0.13	0.10	0.19	0.12	0.19	0.20	0.19
14	***C***	Pre-Fatigue	0.09	0.02	0.09	0.03	0.07	0.14	0.06	0.10	0.12	0.10	0.15	0.10
		Post-Fatigue	0.10	0.07	0.11	0.11	0.11	0.09	0.06	0.17	0.05	0.17	0.05	0.15
15	***C***	Pre-Fatigue	0.15	0.04	0.10	0.04	0.13	0.05	-0.59	0.11	0.16	0.07	0.13	0.04
		Post-Fatigue	0.17	0.05	0.17	0.07	0.17	0.07	0.11	0.10	0.09	0.12	0.18	0.10
16	***C***	Pre-Fatigue	0.09	0.03	0.17	0.03	0.15	0.05	0.18	0.06	0.21	0.08	0.16	0.11
		Post-Fatigue	0.15	0.08	0.16	0.15	0.15	0.02	0.19	0.05	0.17	0.09	0.14	0.07
17	***C***	Pre-Fatigue	0.12	0.08	0.20	0.14	0.25	0.16	0.13	0.16	0.20	0.08	0.16	0.07
		Post-Fatigue	0.05	0.09	0.04	0.10	0.04	0.07	0.09	0.12	0.11	0.10	0.08	0.10
18	***C***	Pre-Fatigue	0.15	0.15	0.09	0.02	0.12	0.15	0.17	0.17	0.06	0.21	0.09	0.16
		Post-Fatigue	0.15	0.15	0.15	0.14	0.15	0.14	0.04	0.17	0.04	0.18	0.09	0.19
19	***C***	Pre-Fatigue	0.10	0.01	0.04	0.01	0.08	0.03	0.05	0.02	0.05	0.03	0.03	0.03
		Post-Fatigue	0.10	0.10	0.05	0.13	0.11	0.12	0.10	0.13	0.09	0.12	0.07	0.13
20	***C***	Pre-Fatigue	0.12	0.09	0.11	0.08	0.11	0.07	0.14	0.09	0.14	0.13	0.12	0.06
		Post-Fatigue	0.22	0.22	0.03	0.00	0.09	0.02	0.17	0.02	0.10	0.01	0.16	0.01
21	***C***	Pre-Fatigue	0.19	0.16	0.05	0.11	0.14	0.16	0.06	0.16	0.09	0.10	0.03	0.09
		Post-Fatigue	0.14	0.14	0.13	0.13	0.10	0.13	0.13	0.10	0.13	0.15	0.13	0.09

P = participant, E = experimental, C = control, VM = vastus medialis, RF = rectus femoris, VL = vastus lateralis, SM = semimembranosis, ST = semitendonosis, BF = biceps femoris, H:Q = hamstring:quadriceps co-activation ratio