Identification of risk factors for lower limb injuries in female athletes

Submitted by

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Statement of authorship and sources

This thesis contains no material published elsewhere or extracted in whole or in part from a thesis by which I have qualified for or been awarded another degree or diploma. No parts of this thesis have been submitted towards the award of any other degree or diploma in any other tertiary institution.

No other person's work has been used without due acknowledgment in the main text of the thesis. All research procedures reported in the thesis received the approval of the relevant Ethics/Safety Committees.

Sania Almousa **Date**

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Dedicated to my Sister

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Contents

List of conference presentations

1. 31st January-2nd February 2019: Sports Congress, Copenhagen, *Previous injury in female team sport athletes is associated with between limb strength imbalances*, Poster and Oral presentation.

2. 27th June 2018: Postgraduate research presentation day, University of South Wales. *Risk factors for anterior cruciate ligament injuries in female athletes: A systematic review*, Poster. -1st place award for the Poster presentation

3. 21st April 2017: Pan-Wales Postgraduate Conference in Sport and Exercise Sciences, Swansea University, Risk factors for anterior cruciate ligament injuries in National and International level female footballers in Wales, Poster and Oral presentation.

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Abstract

Sports-related injuries are commonly seen in the lower extremities and sometimes may affect an athlete's career in sports. Evidence suggests that the prevalence of certain injuries can be linked to sex. Specifically, female athletes have more acute ligament injuries, such as ACL injuries, while male athletes are more prone to muscle strain injuries. An improved understanding of sport-related injuries through identification of risk factors for lower limb injuries in female athletes could help advance the development of prevention strategies.

The aim of study 1 of this thesis was to systematically review studies investigating the risk factors associated with ACL injuries in female athletes. Electronic databases MEDLINE, EMBASE, CINAHL, and Cochrane Library were systematically searched to identify eligible studies. Findings suggest that small intercondylar notch width, and prior history of ACL injury feature as the main risk factors associated with ACL injury in female athletes. Limited and conflicted evidence was found for: knee hyperextension; family history; Body Mass Index; playing surface; tibial slope; muscular strength, flexibility and coordination; psychological factors; and sex hormones.

Chapter 2, novel normative data for female athletes obtained from field-based testing is presented. The measures include: eccentric knee flexor and isometric hip adduction and abduction muscle strength. In addition, the relationship between muscle strength measurements and anthropometrical data is also presented.

Chapter 3 investigated risk factors for lower limb injuries, evaluating muscle strength, life events, family history, menstrual cycle and oral contraception in female athletes. For this purpose, one hundred and thirty-five female athletes age 14-31 years completed a battery of pre-season questionnaires and assessments. The pre-season data were analysed and then all athletes were

followed for prospective injury. Findings indicate athletes who reported a high number of negative life events of the last 12 months, and displayed weak hip adductor strength, and between-limb adductor, and abductor strength imbalances at pre-season were associated with subsequent lower limb injury during the season.

Finally, in chapter 4, the effect of menstrual cycle phases on distress and muscle strength is presented in female soccer players. Specifically, menstrual distress and hip adductor strength were found to peak during the follicular phase.

Overall, it is anticipated that the findings by highlight potential avenues of research and development of more effective injury risk management practices while also taking into account the psychological risk factors in female athletes.

List of abbreviations and nomenclature

ACL	anterior cruciate ligament
cm	centimetres
d	Cohen’s *d* (effect size)
kg	kilograms of body mass
N	newtons of force
N/kg	newtons of force relative to body mass
Nm	newton metres of torque
Nm/kg	newton metres of torque relative to body mass
OR	odds ratio
RR	Relative Risk
SD	standard deviation
95% CI	95% confidence interval

Chapter 1

1.1 Introduction and overview

Over the past century, the presence of women taking part in sports has increased. However, the high intensity participation of women in sports also brought sport-related injuries and pathologies that are differentiated from those in male athletes.

One of the most common injuries in female athletes is a sprain or rupture of the anterior cruciate ligament (Joseph et al., 2013). It has been reported that female athletes are 2 to 3 times more likely to sustain an ACL injury than their male counterparts (Myklebust et al., 1998; Waldén et al., 2011a). As noncontact events account for over of 70% of ACL injuries, it is suggested that risk factors should be addressed in order to develop effective sport injury risk management strategies (Boden et al., 2000). For that, a broad spectrum of factors associated with greater risk of an ACL injury for females have been investigated, and thus, the aim of study 1 was to systematically review studies investigating the risk factors of ACL injuries in female athletes.

Although the aetiology for lower limb injuries in female athletes is not fully understood, suggestions for neuromuscular, biomechanical, anatomical, psychological, and hormonal factors have been put forth (Souryal and Freeman, 1993; Wojtys et al., 2002; Kosaka et al., 2016; Vacek et al., 2016). Risk factors are divided into internal (or intrinsic) and external (or extrinsic) risk factors as well as modifiable and non-modifiable. Internal risk factors are defined as those factors that act on the body to produce injury and cannot be changed, such as age, gender, previous injury; while external are those factors that act from outside of the body causing injury such as equipment, weather, training (Bahr and Holme, 2003; van Mechelen, Hlobil and Kemper, 1992). Modifiable risk factors are those factors that can be altered to reduce injury rates (e.g. muscular strength, flexibility); while non-modifiable risk factors include those which cannot be controlled and modified (e.g. anatomical structure) (Maffey and Emery, 2007).The role of lower extremity strength, as a modifiable risk factor to counterbalance poor knee joint stability has been proposed (Ireland et al., 2003). Muscular strength is defined as the ability of a muscle or a group of muscles to exert force on an external object or resistance; and the ability to produce controlled movement through coordinated muscle strength, endurance, muscle recruitment pattern, proprioceptive feedback, and reflex activity is called neuromuscular control (Huston and Wojtys, 1996; Hamilton and Luttgens, 2001; Zech et al., 2010; Maxey and Magnusson, 2013).

Muscle strength of lower limb may be critical to successfully stabilize the hip joint, protecting it from injuries and pathologies such as ACL injuries and patellofemoral pain (Cichanowski, 2007). Specifically, the hip muscles help control pelvic stability and in the case of strength insufficiency, leg malalignment may occur increasing the risk for injury (Shimokochi and Shultz, 2008). Also, if hamstring muscle co-contraction forces are insufficient, the ACL may undergo excessive load leading to sprain and possible rupture. For years, sports conditioning programs have included muscle strength, flexibility, endurance, and power training for injury risk management. However, more recently, an increased recognition of the need for functional joint stability through enhancement of neuromuscular control mechanisms has been identified (Griffin, 2003). Additionally, psychological factors have been proposed as a risk factor for injuries in athletes (Gunnoe, 2001), but are less often investigated.

The increase in participation of women in sports and associated injuries as a consequence has driven research interest into better understanding the physiological and metabolic responses that occur in women due to exercise; and the potential influence hormonal factors have on injuries. The examination of hormones and their impact on injury are a good starting point to investigate injuries that predominantly feature in female populations since it is these that differentiate between sex. During the menstrual cycle, hormones change between the phases; estrogen starts to rise in the later stages of the follicular phase reaching its peak before the ovulation phase and then estrogen and progesterone increase in the middle of the luteal phase before returning to baseline bringing about physiological effects (Frankovich and Lebrun, 2000; Draper et al., 2018). Thus, a variety of studies have investigated whether female hormones affect laxity, balance, muscle strength, and neuromuscular control which could lead to an increased risk of Anterior Cruciate Ligament (ACL) injuries (Dedrick et al., 2008; Lee and Yim, 2016; Yim, Petrofsky and Lee, 2018). So far, evidence is limited and available data is contradictory (Wojtys et al., 1998; Adachi et al., 2008).

Despite the increasing interest from sports professionals and researchers to identify the associated risk factors for lower limb injuries and the importance of muscle strength in an athlete’s performance, the assessment and evaluation of muscle strength often remains dependent on comparison with the uninjured leg. Functional impairment testing has been typically used in sports injury rehabilitation (Manske and Reiman, 2013); therefore, a frame of reference values is necessary for the interpretation of the correct evaluations in order to establish appropriate treatment goals, and to provide important prognostic parameters (Harbo, Brincks and Andersen, 2012; Benfica et al., 2018). Normative muscle strength data can be used by sports coaches, trainers, medicine physicians, physiotherapists, and others who are responsible for an athletes' health and specifically for return-to-play criteria. To date, no normative data is available for hip strength and knee flexor strength in female athletes. Given the gaps in the literature identified above, four studies were conducted during this PhD programme.

1.2 Risk factors for anterior cruciate ligament injuries in female athletes: A systematic review (Study 1)

For study 1, a systematic review was conducted regarding the risk factors of ACL injuries in female athletes. The abstract of the systematic review is presented below.

Abstract

Objectives: Anterior cruciate ligament (ACL) rupture is one of the most common knee injuries in sport. Female athletes are 2-3 times more likely to rupture their ACL than males. While a broad spectrum of risk factors has been proposed, identifying those athletes predisposed to ACL injury remains a significant challenge. Therefore, the objective was to systematically review studies investigating risk factors for ACL injuries in female athletes. It was proposed that equipped with a thorough understanding of risk factors, athlete screening and prevention strategies could be advanced.

Design: Systematic Review Methods: Electronic databases MEDLINE, EMBASE, CINAHL, and Cochrane Library were systematically searched to identify eligible studies. Study quality of those included were assessed, and data extracted.

Results: Small intercondylar notch width, and prior history of ACL injury featured as the main risk factors associated with ACL injury in female athletes. Limited and conflicted evidence was found for: knee hyperextension; family history; Body Mass Index; playing surface; tibial slope; muscular strength, flexibility and coordination; psychological factors; and sex hormones.

Conclusion: Currently, modifiable ACL risk factors for female athletes lack substantial support. Further research to: confirm current risk factors; and explore novel measures are warranted to better inform prevention strategies. Measures obtained from psychological questionnaires, strength and movement task screening may be such avenues worth exploring.

1.3 Introduction

Anterior cruciate ligament (ACL) rupture is among the most common injury in sports, accounting for 21% of all knee injuries at a rate of 6.5 per 100.000 athlete-Exposures hours (AEs) affecting athletes in the short and long term (Joseph et al., 2013). For female athletes, the chance of sustaining an ACL injury is approximately 2 to 3 times greater than their male counterparts (Myklebust et al., 1998; Waldén et al., 2011a; Prodromos, 2017). The cost of ACL injury is significant, and the impact may continue well into the athlete's lifetime. Reconstruction, is common, accounting for 76.6%, which alone places high economic burden on health care systems (Joseph et al., 2013). For example, in Australia, the estimated direct costs for primary ACL reconstruction in 2014-2015 were AUD$142 million. The overall cost increases further when physical therapy costs, which on average can range between US$1000-$3000 per case, are take into account (Prodromos, 2017; Zbrojkiewicz et al., 2018). ACL injury is likely to impair physical fitness as a result in knee instability and muscular strength loss, but may also affect the athlete psychologically, which consequently, impacts the ability of the athlete to return to sport (Lam et al., 2009; McCullough et al., 2012). Long-term, ACL injury increases risk of knee osteoarthritis. In a 12 year follow-up, 80% of female footballers who had had an ACL reconstruction were identified with radiographic knee osteoarthritis (Lohmander et al., 2004). As a consequence, knee osteoarthritis can constrain physical activity levels, thereby decreasing quality of life following retirement from sport.

Noncontact events account for 70% to 84% of ACL injuries for both sexes (Boden et al., 2000; Krosshaug et al., 2007; Steffen et al., 2017) suggesting that with improved movement patterns and fitness most were preventable. The success of reducing ACL injury, however, depends upon the efficacy of the risk factors selected for assessment and the subsequent intervention. Factors associated with injury proneness are typically classified into extrinsic and intrinsic risk factors. Intrinsic risk factors predispose the athlete to injury and include factors (Meeuwisse, 1994). Exposure to unfavourable extrinsic risk factors makes an already predisposed athlete even more susceptible to injury (Meeuwisse, 1994). In addition, risk factors can be further divided in terms of how they can be modified. Modifiable risk factors are those that can be altered and are the focus of prevention strategies that aim to reduce injury rates while non-modifiable risk factors cannot be altered.

While physical factors have dominated the literature, psychological factors influence both the risk for ACL injury, but also the progress of rehabilitation (Kosaka et al., 2016; Hsu et al., 2017). Psychological responses of an injured athlete such as anxiety, depression, decreased self-esteem and fear of re-injury can slow and affect the rehabilitation process and outcomes (Hsu et al., 2017). Consequently, psychological issues may: influence injury occurrence; further delaying progress; and prolonging absence from sport (Hsu et al., 2017).

While female athletes have a higher ACL injury prevalence than males, the underlying mechanisms that explain these gender differences remain unclear.

A broad spectrum of factors associated with greater risk of ACL for females have been investigated, the aim of this study was to systematically review studies investigating the risk factors of ACL injuries in female athletes to inform future prevention strategies with the aim to reduce ACL injuries. Accordingly, the following research question will be addressed: What risk factors are associated with the increased likelihood of anterior cruciate ligament injury in female athletes?

1.4 Methods

The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement was used (Moher et al., 2009).

Search strategy

Specific databases were used to ensure the identification of relevant studies regarding ACL injuries and sports. These databases were the following: MEDLINE (via PUDMED), CINAHL (via EBSCO), EMBASE (via OVID) and Cochrane library up to January 2018. Table 1.4a presents the search strategy of the systematic review. In addition, a manual search of the reference lists from the articles obtained and Google Scholar was conducted.

Table 1.4a: Search strategy for the systematic review.

Database	Search strategy	Results
MEDLINE	(Anterior cruciate ligament OR ACL) AND (injur* OR tear* OR rupture* OR sprain*) AND athlet* OR sport*) AND (risk factor OR factor OR caus* OR etiolog*) Limits: Title/abstracts Filters: humans, gender	924
EMBASE	(Anterior cruciate ligament OR ACL) AND (injur* OR tear* OR rupture* OR sprain*) AND athlet* OR sport*) AND (risk factor OR factor OR caus* OR etiolog*) Limits: Keywords, abstract, title Filters: Female	353
CINAHL	(Anterior cruciate ligament OR ACL) AND (injur* OR tear* OR rupture* OR sprain*) AND athlet* OR sport*) AND (risk factor OR factor OR caus* OR etiolog*) Filters: female	680
Cochrane Library	(Anterior cruciate ligament OR ACL) AND (injur* OR tear* OR rupture* OR sprain*) AND athlet* OR sport*) AND (risk factor OR factor OR caus* OR etiolog*) No filters	228
Total		2185

Eligibility criteria

Eligibility criteria were established based on the concept of Population (female athletes), Exposure (risk factors), and Outcome (ACL injury) (PEO). All observational human studies investigating risk factors for ACL injury in female athletes were screened for eligibility. To ensure the studies used were relevant, specific criteria were applied. A study was included if: (1) the sample consisted of female athletes; (2) the risk factors were associated with ACL injuries, specifically, the study must report injury at the ACL and (3) it was an original primary study written in English, any other form or language was excluded. Studies reporting data that were not directly examined in relation to injury risk and the occurrence of ACL injury were excluded. In addition, studies with recreational athletes were excluded. Case series, case reports, ideas, opinions, editorials, reviews, systematic reviews and meta-analysis were excluded; however, their reference lists were checked for further relevant papers. Conferences abstracts were not reviewed because of their limited data in the electronic databases. Studies including mixed female and male athletes were included if ACL injuries in the female athletes were reported separately.

Study selection

Initially, the primary author screened the titles and abstracts. Duplicate articles removed, and reference lists of the identified primary studies checked for further relevant citations. In the second phase, full text copies were assessed for eligibility.

Data extraction and quality assessment

Data extraction was carried out using a predesigned and standardised form to record information and data (Appendix 1). Included studies were critically appraised using a modified National Heart, Lung, and Blood Institute (NHLBI, no date) assessment tool. The NHLBI is a quality assessment tool of risk of bias designed for observational studies including systematic reviews. It contains essential aspects to evaluate the internal and external validity. This tool includes 15 items and each item received 1 point based on the answer YES and 0 points for NO/Not Reported (NR). When there was insufficient information in the article to permit a judgment for an item, then the item was given a score of zero (0 points). Further details are given for each item to help guide assessment. The criteria were as follows: 1. Was the research question, hypothesis or objective in this paper clearly stated; 2. Was the study population clearly specified and defined; 3. Was the participation rate of eligible persons at least 80%;

4. Were all the subjects selected or recruited from the same or similar populations; 5. Were inclusion and exclusion criteria for being in the study prespecified and applied uniformly to all participants; 6. Was a sample size justification, power description, or variance and effect estimates provided; 7. Did the study use an acceptable case definition; 8. Was the timeframe sufficient so that one could reasonably expect to see an association between independent and dependent variables if it existed; 9. Were the independent variables clearly defined, valid, reliable, and implemented consistently across all study participants; 10. Did the study use the same method of data collection for all the participants; 11. Were the dependent variables clearly defined, valid, reliable, and implemented consistently across all study participants; 12. Were the outcome assessors blinded to the exposure status of participants; 13. Was loss to follow-up after baseline 20% or less; 14. Were key potential confounding variables measured and adjusted statistically for their impact on the relationship between independent and dependent variables; and 15. Did the study use appropriate statistical analysis. Any disagreements were resolved by discussion. The quality scores ranged from 0 to 15 points, where: poor quality studies scored ≤ 6; fair quality scored between 7 to 9, very good quality scored between 10 to 12, and high quality scored ≥ 13.

1.5 Results

Search results

Thirty-five studies identified from the initial 2185 results were included in this review (Figure 1.5a). Tables 1.5a, 1.5b and 1.5c show the characteristics of the included studies, the identified risk factors and the risk of bias across the studies.

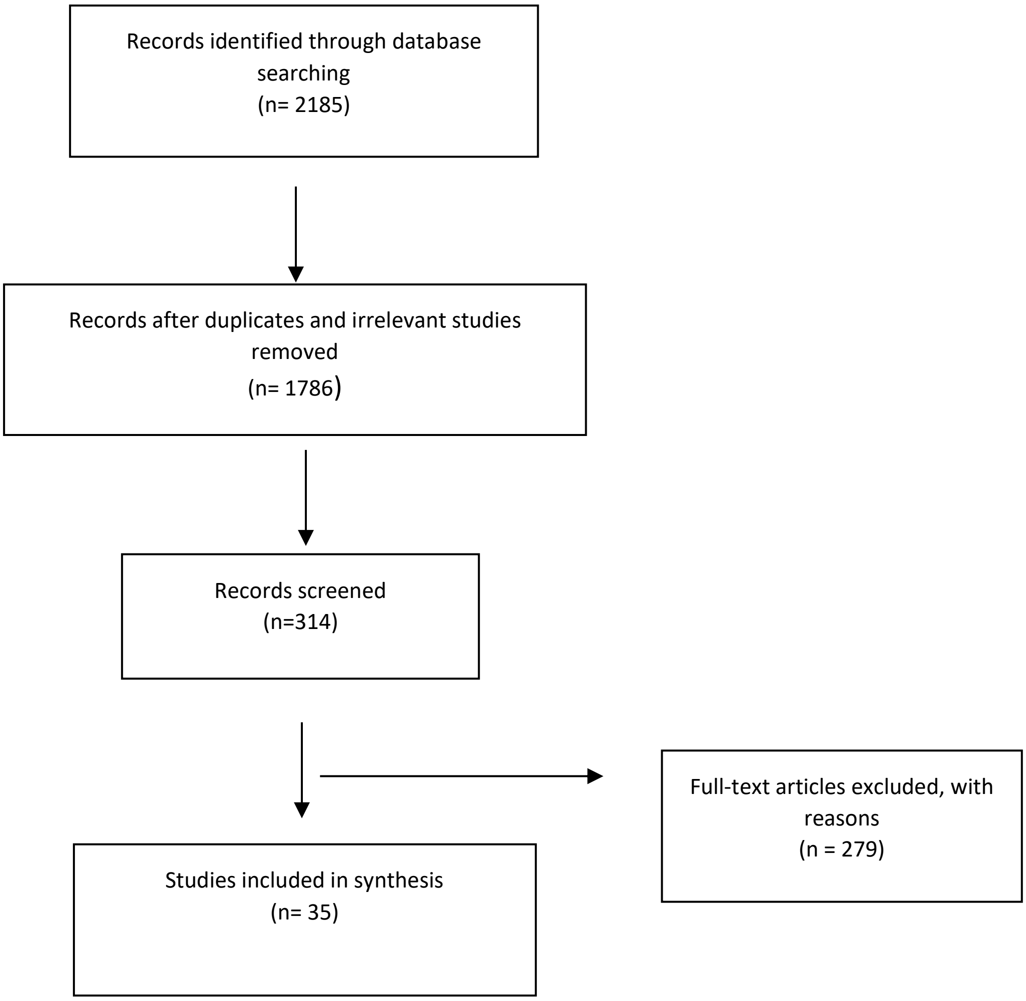


Figure 1.5a Flow diagram to show the process of study selection.

Table 1.5a Studies Included in the Systematic Review. CC: Case Control; CS: Case Series; NR: No Reported.

Study	N	Age	Sport	Positive findings	Risk factors	Quality
Miljko et al. (2012) CC	Cases: 24 Control: 27	21 (7) 17(5)	Handball	High inner angle of the lateral femoral condyle, narrow intercondylar notch width	Lateral femoral condyle angle, intercondylar notch width, Q angle, BMI	Poor
Hewett et al. (2005) Cohort	205	Injured: 15.8±1.0 Non injured: 16.1±1.7	Soccer Basketball Volleyball	Greater knee abduction	Kinematics, kinetics during a jump-landing task	Very Good

Hägglund and Waldén (2016) Cohort	4556	12-17	Soccer	Familial disposition	Familial disposition, playing surface	Very Good
Kramer et al. (2007) CC	Cases: 33 Control: 33	21 ±2.1 19.6 ±1.3	NR	Generalized laxity, genu recurvatum, Iliotibial flexibility, Q angle, tibial varum, pelvic tilt	Generalized laxity, genu recurvatum, Iliotibial flexibility, Q angle, tibial varum, navicular drop pelvic tilt	Poor
Souryal and Freeman, (1993) Cohort	783 *Mixed Female cases: 7	NR	Football Basketball Track Soccer	Narrow intercondylar notch	Intercondylar notch	Fair
Faude et al. (2006) Cohort	143	22.4 (5)	Soccer	Prior history of ACL injury	ACL tear history	Fair
Olsen et al. (2003) Cohort	NR Top 3 division *Mixed 1 elite division *Mixed Top 3 division women	Injured: 17-33	Handball	Artificial floor	Playing surface	Fair
Fuller et al. (2007) Cohort	Season 2005: 64 teams Season 2006: 72 teams	NR	Football	No positive findings	Playing surface	Very Good
Vacek et al. (2016) CC	Cases: 70 (only females) Control: 227 *Mixed	14-23 *Mixed	Lacrosse Basketball Soccer Field hockey Rugby Volleyball	Parent with ACL, joint laxity, BMI, genu recurvartum, strength (hip adduction & flexion, trunk flexion), reward dependence	Family ACL tear history, joint laxity, BMI, genu recurvartum, lower limb strength, trunk strength, personality characteristics	Fair
Arendt, Bershadsky and Agel, (2002) CS	Cases: 83	NR	NR Only for 1998-1999: basketball	Follicular phase	Menstrual cycle	Fair
Steffen et al. (2016) Cohort	867	20.9 (4.0)	Handball Football	Prior history of ACL injury, in- session training (h·wk)$^{-1}$	Prior history of ACL injury, , lower extremity strength, in- session training	Very Good

Dragoo et al. (2011) Cohort	128	NR	Basketball Field hockey Gymnastics Lacrosse Soccer Volleyball	Serum relaxin concentrations >6pg/mL	Serum relaxin concentrations >6pg/mL, BMI, hormonal contraception	Very Good
Zebis et al. (2009) Cohort	55	24 ±5	Handball Soccer	Lower preactivity of the semitendinosis, higher preactivity of the vastus lateralis	Knee flexor EMG preactivity, high knee extensor EMG preactivity during side cutting	Fair
Meyers (2013) Cohort	13 universities female teams	NR	Soccer	No positive findings	Playing surface	Very Good
Zazulak et al. (2007) Cohort	140 females *Mixed	19.4 ±1.0	NR	Greater trunk displacement	Trunk displacement	Very Good
Steffen et al. (2017) Cohort	838	21 ±4	Handball Football	Prior history of ACL injury	Prior history of ACL injury , postural control, ankle injury history	Very Good
Myer et al. (2008) CC	Cases: 19 Controls: 76	16.3 ±1.7 15.6 ±1.4	Soccer Basketball	Knee laxity, knee hyperextension	Knee laxity, knee hyperextension	Fair
Myer et al. (2009) CC	Cases: 22 Control: 88	NR	Soccer Basketball	No positive findings	Hamstring & quadriceps strength	Fair
Myer et al. (2015) Cohort	205	16.1	Volleyball Basketball Soccer	Knee abduction moment above 25.3 Nm	Strength testing, three-dimensional landing biomechanical analyses	Fair
Paterno et al. (2014) CC	Cases: 59 Control: 34	16.9 ±2.8 17.3 ±2.4	Soccer Basketball Volleyball Baseball Softball Football Rugby Other	Prior history of ACL injury	ACL tear history	Fair
Loudon, Jenkins and Loudon, (1996) CC	Cases: 20 Control: 20	16-41	NR	Genu recurvatum, excessive navicular drop, excessive subtalar joint position, hamstring length	Genu recurvatum, Q angle, excessive navicular drop, excessive subtalar joint position, hamstring length	Poor
Krosshaug et al. (2016) Cohort	710	21± (4)	Soccer Handball	Greater medial knee displacement, Prior history of ACL injury,	Knee displacement, ACL tear history	Fair
Raschner et al. (2012) Cohort	175 females *Mixed	14-19	Alpine ski racers	Core strength	Core strength	Very Good

Leppänen et al. (2016) Cohort	171	12-21	Basketball Floorball	Lower peak knee flexion angle	Knee kinematics during a vertical drop jump task, BMI	Very Good
Leppänen et al. (2017) CC	Cases: 15 Control: 327	Basketball: 14.6 ±1.6 Floorball: 16.5 ±1.8	Basketball Floorball	Landing with less hip flexion, greater peak external knee flexion moment	Sagittal plane hip, knee, ankle biomechanics during vertical drop jump task	Very Good
Liederbach, Dilgen and Rose (2008) Cohort	183 females *Mixed	18-41 *Mixed	Ballet modern dance	No positive findings	Oral contraception, BMI, Q angle, knee hyperextension, hip rotation, manual muscle test score, navicular drop	Fair
Myklebust et al. (1998) Cohort	12 women's teams *Mixed	Injured 21.9±3.4	Handball	Late luteal phase	Menstrual cycle	Poor
Numata et al. (2018) CC	Case: 27 Control: 27	Mean: 15	Basketball Handball	Greater dynamic knee valgus	Dynamic knee valgus during single leg drop jump	Very Good
Wojtys et al. (2002) CS	Cases: 65	15-46	Ski Other sports	Ovulation phase	Menstrual cycle	Very Good
Hewett, Torg and Boden (2009) CC	Cases: 10 Control: 6	NR	Basketball	Less forward trunk lean, greater knee abduction	Forward trunk lean, knee abduction	Fair
Kosaka et al. (2016) Cohort	300	15	Handball Basketball	Patience, aggressiveness, volition for self-realization, volition for winning, judgement, cooperation	Diagnostic Inventory of Psychological Competitive Ability (DIPCA.3)	Very Good
Whitney et al. (2014) CC	Cases: 61 Control: 61 *Mixed	NR	NR	Thickness of the bony ridge at the anteromedial outlet of the femoral notch, notch width at the inlet, notch width at the interior attachment of the ACL to the, lateral femoral condyle, ACL volume, notch width at the middle of the ACL attachment, notch width at the outlet	ACL morphometric characteristics, femoral intercondylar notch	Fair
Beynnon et al. (2014a) CC	Cases: 61 Control: 61 *Mixed	13-21 12-22	Soccer Basketball Lacrosse Field hockey Rugby Volleyball	Increased lateral tibial plateau slope	Lateral tibial plateau slope	Very Good
Sturnick et al. (2014) CC	Cases: 61 Control: 61 *Mixed	NR	NR	No positive findings	Geometry of the tibial spine	Very Good

Beynnon et al. (2014b) CC	Cases: 54 Control: 54	13-21 12-22	NR	Surface geometry of the articular cartilage of the tibial plateau	Surface geometry of the articular cartilage of the tibial plateau	Fair

External risk factors

The association between playing surface and ACL injury was investigated in four studies (Olsen et al., 2003; Fuller et al., 2007; Meyers, 2013; Hägglund and Waldén, 2016). No relationship with grass or artificial floor and ACL injuries was reported in three studies (Fuller et al., 2007; Meyers, 2013; Hägglund and Waldén, 2016). Olsen et al. (2003) however, did find that ACL injuries were more common on an artificial playing surface for handball players compared to wooden floors.

Internal risk factors

Previous ACL injury was identified as a risk factor. Five studies (Faude et al., 2006; Paterno et al., 2014; Krosshaug et al., 2016; Steffen et al., 2016; Steffen et al., 2017) reported that female athletes who had previously sustained an ACL injury were more likely to reinjure compared to those with no history of ACL injury. The two studies by Steffen and associates (Steffen et al., 2016; Steffen et al., 2017) reported a 3.14 and 2.86-fold increased risk of sustaining a new injury compared to those who had no history of ACL injury. Paterno et al. (2014) reported the risk as for ACL reinjury as over four times for those with history of ACL, Faude et al. (2006) more than five times, while Krosshaug et al. (2016) found that the relative risk of sustaining a new ACL injury with previous ACL history was 3.8. Only one study (Leppänen et al., 2016) found no increased risk with prior history of ACL injury.

Hägglund and Waldén (2016) and Vacek et al. (2016) both identified an association between family history of ACL injury and ACL injury risk. Hägglund and Waldén (2016) found that female footballers who had a parent or a sibling with a history of ACL injury had more than three times higher ACL injury risk rate, while Vacek et al. (2016) found the risk was almost five times higher compared to those with no family history of ACL injury.

The bone morphology of the knee joint and ACL injury risk has received significant attention in the literature. Miljko et al. (2012) found injured handball players had higher inner angle of the lateral femoral condyle in the axial plane and narrower intercondylar notch width. Similarly, Souryal and Freeman (1993) found that the female athletes with ACL injuries had narrower intercondylar notch than non-injured. Whitney et al. (2014) reported that the risk for ACL injury is increased in females with a decreased femoral notch size.

Beynnon et al. (2014a, b) and Sturnick et al. (2014) measured the geometry of the subchondral bone portion (Beynnon et al., 2014b), the articular cartilage (Beynnon et al., 2014a), and the geometry of the tibial spine (Sturnick et al., 2014). Significant differences were found in the articular surface geometry of the medial and lateral compartments of the tibial plateau between the ACL injured and non-injured athletes (Beynnon et al., 2014a). The ACL injured females had a posterior–inferior directed orientation while the controls were more likely to have a posterior–superior directed orientation of the articular surface of the lateral compartment (Beynnon et al., 2014a). They also found that risk of ACL injury was associated with lateral tibial plateau slope and for every 1-degree rise in lateral tibial slope, the ACL injury risk increased by 31.9% (Beynnon et al., 2014b). However, Sturnick et al. (2014) found no difference between the ACL injured and non-injured in the geometry of the tibial spine.

Knee hyperextension, generalized and knee laxity were associated with the risk for ACL injury (Loudon, Jenkins and Loudon, 1996; Kramer et al., 2007; Myer et al., 2008; Vacek et al., 2016). Myer et al. (2008) reported that the magnitude of knee hyperextension more than doubled the risk for ACL injury; and knee laxity more than three times. Vacek et al. (2016) also found that female athletes with increased anterior-posterior knee laxity have greater risk for suffering an ACL injury. Kramer et al. (2007) found that athletes with ACL injury history had greater generalized laxity, but also tibial varum, inflexible iliotibial band and hamstrings, and anterior pelvic tilt. In contrast, Liederbach, Dilgen and Rose (2008) reported no association between ACL injury risk and knee hyperextension.

Using static assessments of posture, Loudon, Jenkins and Loudon (1996) found that ACL injured athletes had anterior pelvic tilt, and excessive navicular drop and subtalar joint pronation. Vacek et al. (2016) also found navicular drop to be associated with the ACL injury while Liederbach, Dilgen and Rose (2008) and Kramer et al. (2007) did not. Four studies (Loudon, Jenkins and Loudon, 1996; Kramer et al., 2007; Liederbach, Dilgen and Rose, 2008; Miljko et al., 2012) found no support to suggest that Q angle was associated with ACL injury. However, when Kramer et al. (2007) compared ACL injured and non-ACL injured athletes, group differences for Q angle were observed.

No support for BMI as an ACL injury risk factor was found in four studies (Liederbach, Dilgen and Rose, 2008; Dragoo et al., 2011; Miljko et al., 2012; Leppänen et al., 2016). However, Vacek et al. (2016) did find an association between BMI and ACL injury.

Studies examining the impact of menstruation cycle on ACL injury have reported mixed findings. Myklebust et al. (1998) found that the risk for ACL injury was increased during the late luteal phase while Arendt, Bershadsky and Agel (2002) found it was increased during the follicular phase. In further comparison, Wojtys et al. (2002) found an increased risk for ACL injury during the ovulatory phase. In Wojtys et al.'s (2002) study, further sub-group exploration of the sample suggested that ACL injury risk may be impacted by the use of oral contraception and that only the elevated risk during the ovulatory phase remained for the non-users of oral contraception. Liederbach, Dilgen and Rose (2008) and Dragoo et al. (2011) on the other hand found no connection between oral contraception use and ACL injury. Dragoo et al. (2011) found that ACL injured athletes had higher serum relaxin concentrations

(>6 pg/mL) during the mid-luteal phase of the menstrual cycle and as a result were 4 times more likely to sustain an ACL injury.

Investigations assessing a range of strength measures have been conducted. Steffen et al. (2016) and Myer et al. (2009) found no association between lower extremity strength (quadriceps, hamstring strength, hip abduction and functional lower strength) and ACL injury. Raschner et al. (2012) found greater trunk flexion and extension strength in non-injured female ski racers compared to those who had previously sustained an ACL injury. In contrast, Vacek et al. (2016) observed that increased trunk flexion strength was related to ACL injury in female athletes.

Mixed evidence for ACL injury risk factors was also found for measures derived from the performance of movement tasks. Zebis et al. (2009) found that ACL injured handball and soccer players had lower preactivity of the semitendinosus and higher preactivity of the vastus lateralis compared to the non-injured players during a side cutting maneuver. Zazulak et al. (2007) found trunk displacement was greater in the ACL injured athletes than the non-injured after a sudden force release in three directions of isometric trunk exertions. Krosshaug et al. (2016) found greater medial knee displacement during a drop jump landing in previously ACL injured female handball and soccer players. Leppänen et al. (2017); however, found no association between medial knee displacement and injury risk, but found that stiff landings with less hip and knee flexion during a vertical drop jump were associated with ACL injuries.

Hewett et al. (2005) measured neuromuscular control during a jump-landing task and observed that the ACL injured female athletes had 2.5 times greater knee abduction angle at landing and 20% higher ground reaction forces than the non-injured with 16% shorter stance time. More importantly, those female athletes that went on to ACL injury had 8.4°greater knee abduction angles at initial contact and 7.6° greater at maximum displacement than the non-injured during landing. Leppänen et al.

(2016) found that the smaller peak knee flexion angle and the higher vertical ground force obtained from an athlete performing a vertical drop jump increased ACL injury risk. Hewett, Torg and Boden (2009) found that ACL-injured athletes had less forward lean angle relative to vertical, and greater knee abduction during landing compared to non-injured participants. Myer et al. (2015) found that the risk for ACL injury increased by 6.8% when peak landing knee abduction movement during the drop vertical jump exceeded 25.3 Nm. Numata et al. (2018) found ACL injured female athletes had greater dynamic valgus during single leg landings when compared to non-injured athletes.

Studies that have explored psychological measures and their associations with ACL injury risk were limited to two. Vacek et al. (2016) evaluated the association between personality characteristics and ACL injury and found statistical significance only for the reward dependence subscale of the participants' temperament. Kosaka et al. (2016) found that injured athletes had significant high scores in six of psychological competitive ability scales (patience, aggressiveness, volition for self-realization, volition for winning, judgement, and cooperation) than the uninjured players.

Table 1.5b. Factors associated with ACL injuries in female athletes.

Variables	**Univariate analysis**			**Multivariate analysis**			**P value**[e]	**Binary Regression**	
	OR	95% CI	P value	OR	95%CI	P value		OR	P value
Playing surface									
Olsen et al. (2003)	2.35	1.09-5.07	0.03						
Intercondylar notch									
Miljko et al. (2012)							<0.001		
Souryal and Freeman (1993)							<0.001		
Whitney et al. (2014)									
a	1.66	1.10-2.50	<0.05	1.77	1.11-2.83	0.017			
b	0.85	0.71-1.0	<0.05						
c	0.69	0.54-0.88	<0.01	0.70	0.54-0.89	0.005			

d	0.82	0.67-1.0	<0.05				
e	0.69	0.56-0.86	<0.01				
Prior history of ACL injury							
Faude et al. (2006)	5.24	1.42-19.59	0.01				
Paterno et al. (2014)	4.51^{*}	1.5-18.2	0.0004				
Krosshaug et al. (2016)	3.8***	2.1-7.1					
Steffen et al. (2016)	3.14	1.61-6.12					
Steffen et al. (2017)	2.86	1.44-5.69					
Family history							
Hägglund and Waldén (2016)	3.57^{**}	1.48-8.62	0.005	3.82^{**}	1.56-9.39	0.003	
Vacek et al. (2016)				4.69	1.78-12.34	0.002	
Generalized laxity							
Kramer et al. (2007)							0.004
Navicular drop							
Vacek et al. (2016)				1.09	1.01-1.18	0.038	
Loudon, Jenkins and Loudon, (1996)			0.008			0.003	
Knee hyperextension							
Loudon, Jenkins and Loudon,(1996)			0.001			0.0001	
Kramer et al. (2007)							0.029
Myer et al. (2008)	2.34	0.82-6.72	0.11	4.78	1.24-18.4	0.02	
Vacek et al. (2016)	0.90	0.83-0.97	0.004				
Knee Laxity							
Myer et al. (2008)	3.23	1.47-7.08	<0.003	4.03	1.68-9.69	0.002	
Vacek et al. (2016)	1.27	1.12-1.45	<0.001	1.25	1.09-1.44	0.002	
Iliotibial band inflexibility							
Kramer et al. (2007)							0.01
Subtalar Joint position							
Loudon, Jenkins and Loudon, (1996)			0.004			0.044	

Anterior pelvic tilt											
Loudon, Jenkins and Loudon, (1996)			0.003								
Kramer et al. (2007)							0.03				
Previous acute knee injury											
BMI											
Vacek et al. (2016)	1.20	1.04-1.38	0.044	1.20	1.03-1.39	0.017					
Dynamic knee valgus											
Numata et al. (2018)											
-at the contact of the hallux with the ground								0.006			
-at the maximum knee valgus								0.007			
Tibial Varum											
Kramer et al. (2007)								0.01			
Trunk strength											
Raschner et al. (2012)	0.26	0.13-0.51	<0.001								
Trunk displacement											
Zazulak et al. (2007)											
-Extension displacement										1.85	0.014
-Flexion displacement										1.97	0.036
-Lateral displacement										2.53	0.099
Knee displacement											
Krosshaug et al. (2016)				1.40	1.12-1.74	<0.05					
Tibial slope											
Beynnon et al. (2014b)	1.21	1.07-1.39	0.003	1.32	1.11-1.57	0.002					
Tibial spine geometry											
Beynnon et al. (2014a)											
-Medial compartment									<0.001		
-Lateral compartment									<0.025		
Sturnick et al. (2014)											
Medial Volume	1.09	0.79-1.51	0.61	1.2	0.84-1.72	0.31					

Medial Height	1.17	0.83-1.66	0.38	1.15	0.81-1.63	0.43	
Medial Width	1.14	0.87-1.48	0.35	1.12	0.86-1.47	0.41	
Lateral Vol	1.04	0.83-1.29	0.75				
Lateral width	1.06	0.87-1.28	0.59				
Lateral length	1.01	0.94-1.09	0.74				
Body positioning							
Leppänen et al. (2016)							
-Peak knee flexion angle				0.55**	0.34-0.88	0.01	
-Increased ground force				1.26**	1.09-1.45	<0.01	
-Knee valgus angle at IC				1.79**	0.71-4.55	0.22	
-Knee flexion angle at IC				1.22**	0.63-2.00	0.70	
-Peak knee abduction moment				1.12**	0.91-1.39	0.27	
Leppänen et al. (2017)							
-Hip Flexion (for each 10° increase in hip ROM)				0.61**	0.38-0.99	<0.05	
-Peak external hip flexion moment				1.08**	0.98-1.18	0.14	
-Peak external knee flexion moment				1.21**	1.04-1.40	0.01	
-Hip flexion at IC				1.11**	0.95-1.07	0.73	
Hewett et al. (2005)							
-Knee abduction angle							<0.001
-Ground reaction forces							<0.05
-Stance time							<0.01
Hewett, Torg and Boden (2009)							
-Forward trunk lean							0.005
-Knee abduction							≤0.05
Muscle strength & recruitment							
Zebis et al. (2009)							
-Preactivity of Semitendinosis							<0.001
-Preactivity of Vastus lateralis							<0.01

Vacek et al. (2016)								
-Hip abduction	0.67	0.51-0.88	0.003					
-Hip flexion	1.38	1.12-1.70	0.003					
-Trunk flexion	1.28	1.08-1.51	0.004	1.26	1.07-1.48	0.005		
Hormonal								
Myklebust et al. (1998)							<0.01	
Dragoo et al. (2011)	4.4***		0.003					
Wojtys et al. (2002)							<0.001	
Psychology								
Vacek et al. (2016)								
Reward dependence				0.83	0.71-0.96	0.013		
Kosaka et al. (2016)								
-Patience	0.99	0.81-1.21	0.93					0.05[1]
-Aggressiveness	1.13	0.90-1.42	0.28					0.001[1]
-Volition for self-realization	0.99	0.78-1.26	0.95					0.046[1]
-Volition for winning	1.05	0.86-1.27	0.63					0.049[1]
-Judgement	1.19	0.97-1.45	0.09					0.004[1]
-Cooperation	1.12	0.89-1.41	0.33					0.019[1]

*IRR: Incidence rate ratio; **HR: Hazard Ratio; ***RR: Relative risk; a: thickness of the bony ridge at the anteromedial outlet of the femoral notch; b: notch width at the inlet; c: notch width at the interior attachment of the ACL to the lateral femoral condyle; d: notch width at the middle of the ACL attachment; e: notch width at the outlet. [e]: studies who provided only the p value. 1: comparison between injured and non-injured athletes.

Table 1.5c: Risk of bias across the studies.

Author, year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Total
Steffen et al., 2016	+	+	-	+	+	-	-	+	+	-	+	+	+	+	+	11
Olsen et al., 2003	+	+	-	+	+	-	-	+	+	+	+	-	-	-	+	9
Kosaka et al., 2016	+	+	-	+	+	-	-	+	+	+	+	-	+	-	+	10
Myer et al., 2009	+	+	-	-	-	-	-	+	+	+	+	-	+	-	+	8
Dragoo et al., 2011	+	+	-	+	+	+	-	+	+	+	+	-	+	-	+	11
Souryal and Freeman, 1993	+	+	-	+	+	-	-	+	-	+	+	-	+	-	+	9
Faude et al., 2006	+	+	-	+	-	-	-	+	+	+	+	-	-	-	+	8
Arendt, Bershadsky and Agel, 2002	+	+	-	+	+	-	-	+	-	+	+	-	-	-	+	8
Kramer et al., 2007	+	-	-	-	-	-	-	+	-	+	-	-	-	-	+	4
Miljko et al., 2012	+	+	-	+	-	-	-	-	-	+	+	-	-	-	+	6
Wojtys et al., 2002	+	+	-	+	+	+	-	-	-	+	+	+	+	+	+	11
Beynnon et al., 2014a	+	+	-	+	+	-	+	+	+	+	+	+	-	-	+	11
Hewett et al., 2005	+	-	-	+	-	-	+	+	+	+	+	+	+	+	+	11
Hewett, Torg and Boden, 2009	+	+	-	+	+	-	-	+	-	+	+	+	-	-	+	9
Myer et al., 2008	+	-	-	+	-	-	-	+	+	+	+	-	-	+	+	8
Meyers et al., 2013	+	+	-	+	+	-	-	+	+	+	+	+	-	-	+	10
Hägglund and Waldén, 2016	+	+	-	+	-	-	+	+	+	+	+	+	+	+	+	12
Steffen et al., 2017	+	+	-	+	+	-	-	+	-	+	+	+	+	+	+	11
Fuller et al., 2007	+	+	-	+	-	+	+	+	+	+	+	+	-	-	+	11
Zebis et al., 2009	+	+	-	+	+	-	-	+	+	+	-	+	-	-	+	9
Vacek et al., 2016	+	+	-	+	+	-	-	+	+	+	+	-	-	-	+	9
Myklebust et al., 1998	+	-	-	+	-	-	-	+	-	-	+	-	+	-	+	6
Liederbach, Dilgen and Rose, 2008	+	+	-	-	+	-	-	+	-	+	-	-	+	+	+	8

	Krosshaug et al., 2016	+	+	-	-	+	-	-	+	-	+	+	+	-	+	+	9
	Raschner et al., 2012	+	+	-	+	+	-	-	+	+	+	+	+	-	-	+	10
	Loudon, Jenkins and Loudon, 1996	+	-	-	-	-	-	-	-	-	+	+	-	+	-	+	5
	Paterno et al., 2014	+	+	-	-	+	-	-	+	+	+	+	-	+	-	+	9
	Whitney et al., 2014	+	-	-	-	+	-	-	+	+	+	+	-	-	+	+	8
	Sturnick et al., 2014	+	+	-	+	+	-	-	-	-	+	+	+	+	+	+	10
	Zazulak et al., 2007	+	+	-	-	+	-	-	+	-	+	+	+	+	+	+	10
	Leppänen et al., 2016	+	+	+	+	+	-	-	+	+	+	+	-	+	+	+	12
	Leppänen et al., 2017	+	+	+	+	+	-	-	+	+	+	+	-	+	+	+	12
	Myer et al., 2015	+	+	-	+	+	-	-	+	-	+	-	+	-	-	+	8
	Beynnon et al., 2014b	+	+	-	+	+	-	-	+	+	+	+	-	-	-	+	9
	Numata et al., 2018	+	+	-	+	+	-	-	+	+	+	+	+	-	-	+	10

1.6 Discussion

A review of the literature is included in this chapter. The review examines the risk factors of ACL injuries in female athletes, theories of ACL injury mechanisms and methodological issues related to risk factor measurements. The strongest evidence-based risk factors for ACL injury in female athletes based on this systematic review of the literature were previous ACL injury and a small intercondylar notch width. Previous ACL injury affects the anatomical structure of the knee that may bring about deficits in movement mechanics. Compensatory movement patterns could be adopted that may in the long-term lead to maladaptations and ACL re-injury (Souryal and Freeman, 1993). Poor physical rehabilitation, physical condition and reduced proprioception are further potential deficits that can contribute to this alteration. Adequate rehabilitation, in particular, the time to return to play presents significant challenges that demand attention. The mechanism to explain why a small femoral notch predisposes the ligament to greater injury risk is unclear. It may result in less robust structural properties, alternatively, it may produce a bony impingement against the small ACL, which predisposes the ligament to a higher risk of rupture (Simon et al., 2010). However, observation of the relationship between small intercondylar notch size and ACL injury must be interpreted with caution, since it is based on a small number of observations.

Conflicting and limited evidence was found for knee hyperextension, BMI, trunk strength, playing surface, family disposition, trunk displacement, tibial slope, generalized and knee laxity, lower extremity muscles' strength, flexibility and recruitment, biomechanical and neuromuscular, and sex hormones. Knee laxity has been proposed as a predisposing factor for ACL injury in females due to greater joint laxity compared to males (Boguszewski et al., 2015). Increased knee joint laxity could alter the dynamic lower extremity motions and may place the ACL at a higher risk of tearing. Rozzi et al. (1999) have suggested that excessive joint laxity impairs proprioception and knee sensitivity exposing the athlete to potential damaging forces increasing injury risk. However, evidence is minimal and the promising associations observed between knee laxity and ACL injuries requires confirmation using valid measures of passive and knee laxity. Although KT-1000 is widely accepted as a measurement tool for the knee laxity, the validity is questionable (Forster, Warren-Smith and Tew, 1989; Sernert et al., 2007). Knee arthrometers have been shown to provide accurate and reproducible knee laxity measurements with inter- and intra-rater reliability ranging from 0.41 to 0.92 and 0.83 to 0.97, respectively (Runer et al., 2021). Although each system exhibits features that have come to set the standard for measuring knee laxity, the same cannot be said for the reliability, which is affected by many factors such as experienced clinicians, device over-tightening, body positioning, inconsistent, force application, leg external/internal rotation, and knee effusions (Rohman and Macalena, 2016; Runer et al., 2021). Sex hormones are associated with joint laxity, and thus with the ACL injury. Whilst supported by some studies where knee laxity was found to increase during particular menstrual phases and anterior knee displacement using a KT-1000 was greater during the ovulation and luteal phase of the menstrual cycle (Zazulak et al., 2006; Hicks-Little et al., 2007). Dragoo et al. (2011) found that females who had sustained an ACL injury had higher serum relaxin concentration compared to those without an ACL injury during the mid-luteal phase. Long term exposure to high levels of serum relaxin may compromise the structural integrity of the female ACL. More specific, serum relaxin concentration raises the activation of the relaxin receptors on the ACL over time, which reduce the ACL integrity and increase the risk for a potential rupture (Dragoo et al., 2003). Besides the relaxin receptors, it has been demonstrated that human ACL cells have both estrogen and progesterone receptor sites (Liu et al., 1996; Dragoo et al., 2003). It is likely that sex hormones have an effect on ACL structure and composition, and this could explain the reason that women are more prone to the ACL injuries (Liu et al., 1996). Menstrual phase and associated sex hormones have been shown to impact ACL injury risk, however, conflicting evidence remains.

Four studies found no association between Q angle and ACL injuries in the female athletes. It has, however, been previously reported that women have higher Q angle than men (Horton and Hall, 1989; Guerra, Arnold and Gajdosik, 1994). Based on that difference, it was suggested that the higher Q angle alters the mechanics of the lower limb during high risk manoeuvres such as cutting and landing, placing the knee at a high risk for valgus stress and for an ACL injury (Arendt and Dick, 1995). However, height difference between men and women was unaccounted for (Merchant et al., 2008), and when Q angle was adjusted for height gender differences became trivial (Grelsamer, Dubey and Weinstein, 2005).

One external risk factor extensively studied is the impact of artificial playing surfaces, which have been associated with higher shoe-surface traction than natural grass, and as such could increase the risk for ACL injuries (Orchard, 2002). However, evidence for such an association between playing surface and ACL injury in this review was not conclusive. Similar inconclusive evidence linking playing surface and lower limb injuries has been reported for male athletes (Arendt and Dick, 1995). Such studies are difficult to interpret given the vast number of confounding factors. For example, factors such as: shoe type; weather and ground conditions; and speed of player movements all impact injury data leading to inconclusive findings. Dry weather increases the friction and torsional resistance from the shoe surface interface compared to wet or cold weather (Heidt et al., 1996; Orchard, 2002; Orchard and Powell, 2003). Similarly, shoe type can increase the surface traction. However, conclusions cannot be drawn and further studies are needed to investigate which surface is the safest.

Conclusive evidence for muscular strength as risk factor for ACL injury was not found. Therefore, maximal generating force capacity of muscle group(s) may not be important, but rather how it is applied during specific tasks and the coordination of muscle activation that is needed to determine ACL injury risk (Souryal and Freeman, 1993). For example, lower pre-activity of the semitendinosus was found in the ACL injured athletes by Zebis et al. (2009). This supports the theoretical importance of semitendinosus activity to stabilize the medial knee joint (Zebis et al., 2009). Well orchestrated muscle activity may limit dynamic valgus and external rotation of the knee joint thereby reducing the stress on the ACL and the possibility of injury (Zebis et al., 2009).

Away from the lower limbs, Zazulak et al. (2007) observed increased trunk displacement in the ACL injured athletes after a sudden force release. The increased trunk displacement suggests a potential neuromuscular control impairment of the body’s trunk, which in combination with the high ground-reaction forces may, compromise dynamic stability of the knee joint during sports movements (Zazulak et al., 2007).

The idea of familial predisposition towards ACL injury has led researchers to investigate genetic factors. Specific genes related to collagen with different polymorphism has been associated with ACL tears (Posthumus et al., 2009; Posthumus et al., 2010; John et al., 2016). In addition, gender differences between females and males in the expression of three genes (ACAN, FMOD, and WISP2) related with structure and integrity of ligaments have been found (Johnson et al., 2015). Further genetic investigation into familial susceptibility to ACL injuries is needed and should address the morphological characteristics and similarities between siblings and female athletes with ACL injuries. More research is also required to support the effect of the hormones on ACL and knee laxity, and whether oral contraception affects the knee laxity and risk of ACL injury.

In only two studies have psychological factors been suggested as predictors of ACL injuries among elite female athletes (Galambos et al., 2005). Yet, no consistent findings supporting psychological variables as risk factors for ACL injuries in female athletes were reported. The high levels of competitive ability found by Kosaka et al. (2016) to be associated with ACL injures in handball and basketball female players were suggested to be related to the athletes’ perfectionistic tendencies, leading to excessive forces and injuries. This could be explained by the fact that perfectionist athletes train harder and for longer periods than the non-perfectionist athletes, thereby increasing the risk for injury through exposure. However, the study failed to use a reliable and valid questionnaire to assess the psychological characteristics of the participants, and to record the exposure data, so could not accurately account for the exposure in the risk factor analyses. Therefore, since evidence is limited, further studies are needed to draw firm conclusions.

Although fatigue has been proposed as a risk factor for sports injuries (e.g., lateral ankle sprain (LAS), patellofemoral pain syndrome (PFPS) and hamstring injury) (Verschueren et al., 2020), no studies were found to support the relationship between fatigue and the occurrence of ACL injuries in female athletes. It has been shown that reduced knee and hip flexion, increased knee abduction angles and moments, and increased ground reaction forces during landing are risk factors for ACL injuries (Hewett et al., 2010). However, based on previous reviews, fatigue does not feature to have any consistent effect on lower limb kinetic and kinematic variables which increases the risk for ACL injury (Barber-Westin and Noyes, 2017; Bourne, Webster and Hewett, 2019; Benjaminse et al., 2019).

Several important methodological issues have arisen in this systematic review that require consideration. Some of the included studies analysed a small number of ACL injuries, and some of them contained both contact and non-contact in their analysis. Studies with small sample sizes are at increased risk of type II error and when combined with the lack of differentiation between contact and non-contact (mechanism of injury), it limited the relevance relative to the identification and measurement of injury risk. It would, therefore, be recommended to include in the analysis, only the non-contact ACL injuries in order to determine the risk factors correctly and to enable future studies to prevent them.

Given these methodological considerations, the analysis that was followed on study 3 was based on non-contact injuries to identify the potential risk factors. The limited evidence that was found in this systematic review regarding muscle strength of the lower limb contributed to the development of study 3, which aims to examine whether muscle strength is associated with lower limb injuries in female athletes.

Several studies used a case control study design to identify the risk factors of ACL injuries because it is a faster and inexpensive method. However, special consideration has to be given to the occurrence of potential biases, such as recall bias in information about the characteristics of the injuries (Schootman, Powell and Torner, 1994; Vanderlei et al., 2017).

Finally, the menstrual cycle is related to changes of hormonal levels based on the phase, which can have physiological effects on muscles, and ligaments and increase the risk of injury. Although studies in this systematic review evaluated the effect of menstrual phases on ACL injury, studies haven't examined the psychological effects that the menstrual cycle phases have on athletes, which may be associated with the different performance levels and thus, risk of injury such as ACL. Therefore, in our study 4, a distress questionnaire was used to evaluate the symptoms that players may have across the different menstrual cycle phases and if there is any association with differences in muscle strength.

Limitations

There are some potential limitations to this systematic review. This was not a statistical meta-analysis but a descriptive epidemiological summary of risk factors. In addition, studies not written in English were excluded as they could not be translated accurately to provide data essential for quality assessment.

Conclusion

Evidence to support most ACL risk factors in female athletes remains limited and further research is required to investigate those risk factors that can be modified in order to improve prevention strategies. Further work needs to be done on psychological risk factors and on strength and functional movement tasks screening which may contribute to the development of better injury risk management programmes.

Chapter 2: Normative hip adductors and abductors, and knee flexor strength values for female and healthy athletes (Study 2)

2.1 Abstract

Introduction: Hip and knee muscle strength performs an essential role in athletic performance, and impairment or weakness predisposes athletes to numerous pathologies requiring intervention (Prins and Van der Wurff, 2009; Thorborg et al., 2014; Suchomel, Nimphius and Stone, 2016). To date, normative values for female athlete populations are sparse. Considering the value of normative data to inform exercise and rehabilitation prescription, the aims of the present study were: 1) to establish normative values for eccentric knee flexor and isometric hip adduction and abduction muscle strength in healthy, female athletes; 2) to determine whether there is a relationship between muscle strength measurements and anthropometrical data in female athletes; 3) to evaluate the association between adduction and abduction variables at each position and between Nordbord testing positions.

Method: The database included tests performed between July 2017 to January 2020 for GroinBar; and from: January 2016 to January 2020 for NordBord. In seven different assessment protocols were captured including: isometric hip adduction and abduction at 45°, at 60°, at 90°, isometric knee flexor strength at prone position, and eccentric knee flexor strength (Nordic).

Results: At each testing position, strong positive correlations (range from 0.55 to 0.90) between adductors (ADD) and abductors (ABD) were obtained. The ADD:ABD ratios were found to range 1.18 to 1.23 depending on the testing angle. It found that body mass was correlated to eccentric knee flexor (r = 0.62; 95%CI: 0.54 to 0.69; p < 0.0001), and hip adductor (r = 0.64; 95%CI: 0.51 to 0.74; p < 0.0001) and abductor strength at 60° (r = 0.79; 95%CI: 0.70 to 0.85; p < 0.0001), suggesting the influence of muscle mass in the force-generating capacity of muscles. Hip adductor (r = 0.37; 95%CI: 0.16 to 0.54;

p < 0.0007) and abductor muscle strength at 60^{o} (r = 0.57; 95%CI: 0.40 to 0.70; p <0.0001) was also found to be associated with an athletes' stature suggesting that body size influences muscle strength.

Conclusions: These normative values can be applied in the clinical setting to estimate the degree of an athlete's weakness, to guide pre-season athletes' strength training at presentation relative to the predicted normal. Following the recovery progression of injured athletes, normative values will help in decision making and return to play.

2.2 Introduction

Muscle strength performs an essential role in sporting activities and is strongly correlated to superior jumping, sprinting, and other sport-specific performance (Suchomel, Nimphius and Stone, 2016). It is established as the most important predictor of function and is used as an outcome in rehabilitation following surgical interventions or injuries (Undheim et al., 2015).

In contrast, impaired muscle strength or weakness predisposes athletes to numerous pathologies requiring intervention (Prins and Van der Wurff, 2009; Thorborg et al., 2014). Muscle strength is task specific and the evaluation of muscle strength utilising a suite of assessments is becoming common practice in the sports domain. The knowledge gained from muscle strength assessments are proposed to help with decisions on training to improve physical function to advance sporting performance and address muscle strength deficits to reduce injury risk. Establishing normative data for newly developed (i.e., novel) muscle strength assessments is warranted to help guide practitioners in their evaluation and prescription. In particular, deficits can be identified, and quantified and the progression of interventions can be evaluated.

2.3 Muscle strength contraction

Muscular strength is defined as the ability of a muscle or a group of muscles to exert force on an external object or resistance, and it can be described as the peak force (in Newtons, N) or torque (in Newton-meters Nm). Muscle strength is task specific and can be measured under a variety of conditions such as isometric, isotonic, or isokinetic (Lord et al., 1992; Stone, 1993). Isometric muscle actions occur when force of the muscle's contraction and resistance force are equal and consequently, there is no motion and no change in joint angle (Muscolino, 2016; Mansfield and Neumann, 2013). Isotonic muscle actions can be either concentric (muscle shortens) or eccentric (muscle lengthens) (Hamilton and Luttgens, 2001). Concentric contraction occurs when a muscle contracts with a force that is greater than attachment's resistance force to moving, and as a result, the muscle moves the attachment and the muscle length shortening (Muscolino, 2016). Nevertheless, if a muscle contracts, attempting to pull in towards its centre, but the resistance force is greater than the muscle's contraction force, then the proximal and distal attachments of the muscle become farther apart, and as consequence, the muscle lengthens as it contracts, which is called eccentric muscle action (Muscolino, 2016; Mansfield and Neumann, 2013). Finally, isokinetic assessments are conducted with the use of special equipment where it is possible to have maximum muscle effort at a constant velocity throughout the entire range of motion of the related lever (Hamilton and Luttgens, 2001). The muscles response at maximum contraction to the device accommodating resistance, is called isokinetic.

Studies have highlighted the importance of muscle strength in sports competition, as stronger athletes are at higher levels of competition in a variety of sports in comparison to weaker athletes (Baker et al., 2001; Taber et al., 2016). Previous studies support lower extremity muscle strength as a predictive factor for future injuries (Prins and van der Wurff, 2009; Myer et al., 2009; Augustsson and Ageberg, 2017) for a broad range of reasons. Most importantly, leg strength is associated with function and performance, but also it is highly modifiable, making the evaluation of muscle strength a feasible method for early detection of deficits to identify those at risk and provide the information to prescribe intervention to address the deficits.

2.3.1 The importance of hip adductor and abductor strength

Hip strength is defined as the force production capability of the muscles that act around the hip joint (Neumann, 2009; Mansfield and Neumann, 2013). The 21 muscles that cross the hip contribute to provide forceful movements in 3 degrees of freedom: flexion/extension, abduction/adduction, and internal rotation/external rotation (Neumann, 2010; Holcomb, Miller and Rubley, 2012). Hip muscle strength ensures pelvis stability, allows a stable foundation for lower extremity kinetic chain movements preventing potential athletic injuries (Holcomb, Miller and Rubley, 2012).

The importance of measuring hip and groin strength has been demonstrated in clinical and research areas of sports. These include investigating relationships between muscle strength and injuries such as patellofemoral pain and ACL ruptures (Tyler et al., 2001; Souza and Powers, 2009; Thorborg et al., 2014; Khayambashi et al., 2016; Cibulka and Bennett, 2020).

Loss/low of hip muscle strength has been proposed as a contributing factor to pathologies in sports. Hip strength deficits have been linked with Patellofemoral pain (PFP). PFP is referred pain in the retropatellar and peripatellar regions and is a common complaint in young athletes who participate in jumping, cutting and pivoting sports (Halabchi et al., 2017). The PFP is more common in female athletes with an incidence of 1.09 per 1000 athletic exposures (Myer et al., 2010). It has been demonstrated that decreased hip abductor and external rotator strength may predispose to the development of PFP in female athletes (Ireland et al., 2003; Souza and Powers, 2009). Specifically, it seems that hip abductor deficits lead to increased knee valgus angles during sporting activities (e.g., running, weight bearing), increasing lateral patellar contact pressure, which over time results in pain (Powers, 2003; Ireland et al., 2003; Cichanowski et al., 2007; Prins and Van der Wurff, 2009).

Deficits in hip abductor muscle strength have been associated with the incidence of ACL injury and iliotibial band syndrome due to the knee abduction angle moments (Fredericson et al., 2000; Khayambashi et al., 2016). Specifically, weak hip abductor muscle strength has been linked to increased knee valgus angle results in greater iliotibial band tension, mainly during the early stance phase when maximal deceleration occurs to absorb ground reaction forces (Fredericson et al., 2000; Heinert et al., 2008). The underlying mechanism of ACL injuries due to deficits in hip abductors may be that hip abductor weakness predisposes athlete to greater hip adduction and internal rotation, causing increased knee valgus motion and knee abduction movements, resulting to ACL injury (Khayambashi et al., 2016).

Impaired adductor muscle strength has been associated with groin pain, but only in male athletes (Crow et al., 2010; Engebretsen et al., 2010; Thorborg et al., 2014; Bourne et al., 2020). Groin pain is a common pathology presenting in athletes who participate in sports that involve repetitive and forceful hip movements with sudden changes in direction and speed such as football and ice hockey (Hölmich et al., 2010; Mosler et al., 2017; Thorborg et al., 2018; Werner et al., 2019). Injury rates has been reported to be 53.06 per 100,000 athlete-exposures in athletes, resulting in significant time loss and subsequent impaired athletic performance (Werner et al., 2009; Kerbel et al., 2018). Epidemiological study found that the sports with the highest rates of injuries per 100,000 AEs are men’s soccer (110.84), men’s ice hockey (104.90), and women’s ice hockey (76.88) (Kerbel et al., 2018).

Imbalance between hip adductor and hip abductor muscle strength has also been linked to with groin pain compared with asymptomatic in male athletes (Thorborg et al., 2011; Tyler et al., 2011). When hip adductor muscle strength is expressed relative to hip abductor muscle strength and evaluated as a ratio, those with hip abduction imbalance favouring the preferred kicking limb had or developed hip/groin injury (Bourne et al., 2020).

Based on the research findings, hip strength assessment has been recommended for the evaluation of athletes for lower limb injuries (Ireland et al., 2003; Souza and Powers, 2009; Thorborg et al., 2014). Currently, there are a broad range of protocols available to practitioners for assessing hip strength using different types of equipment such as sphygmomanometer, hand-held dynamometry, and isokinetic dynamometry. A Sphygmomanometer is considered the most basic tool, and pressure produced against the device is captured to obtain measures. Protocols using Sphygmomanometer have been shown to be both valid and reliable for hip adduction strength testing, however, the assessment a recognised limitation is a ceiling effect when strong individuals are assessed (Delahunt et al., 2011; Toohey et al., 2018). Hand-held dynamometers (HHD) have been used to measure isometric torque at various joints by a variety of studies (e.g., shoulder, elbow, hip, knee, ankle) (Hébert et al., 2015; Achenbach et al., 2019; Pinheiro et al., 2019; Pontillo and Sennett, 2020). HHD is an inexpensive method for quantifying hip strength, requiring less time to set up and does not demand that the user have knowledge of machine-specific software; it has been found reliable but only when the same tester performs the measurements (intra-tester reliability) (Kelln et al., 2008; Thorborg et al., 2010). Despite the benefit of using the HHD to quantify muscle strength, the reliability of this device can be influenced by numerous factors, including technique, strength of assessor, and experience of the clinician. Finally, isokinetic dynamometry overcomes the limitations of both Sphygmomanometer and HHD by removing the influence of assessor strength, but with this comes barriers to its use in the field and with team sports. Isokinetic dynamometry is comparatively expensive, requires a large space, and considerable expertise to operate (O'Brien et al., 2019).

Recently, a novel field-testing device (The ForceFrame, VALD Performance, Australia) has been developed to assess strength of hip adductors and abductors of both limbs simultaneously, as well as the hip adduction/abduction strength ratio (O' Brien et al., 2019). It is a transportable assessment system, does not require any extensive training or expertise, enhances measure standardization and reduces the variability related to examiner strength and testing technique (Desmyttere, Gaudet and Begon, 2019). In addition, this device easily estimates the hip adduction/abduction strength ratio.

An advantage of the GroinBar is that hip muscle strength testing can be conducted in different positions that are commonly used in the assessment of adductor related groin pain (Hölmich et al., 2004). The adductor longus has been described to be the most common injured adductor muscle due to its anatomical position. Prior EMG study in male athletes with a history of groin pain have proposed that adductor longus strength needs to be assessed in multiple clinical positions (Lovell, Blanch and Barnes, 2012). However, different testing positions also provide evaluation of other primary hip adductors. For example, Pectineus muscle has its greatest activation at 90^{o} hip flexion with Adductor brevis, Gracilis at 45^{o}, and adductor Magnus at 0^{o} (knee) (Lovell, Blanch and Barnes, 2012). Therefore, GroinBar is capable to test different muscles in different angles. The device has been shown to have excellent reliability for adductor strength testing (ICC=0.94) (Ryan et al., 2019).

2.3.2 The importance of eccentric knee flexor strength

Hamstring strains are one of the most prevalent injuries in sports that involve high-speed running, jumping, and kicking. In track and field, soccer, Australian football, rugby, and American football, hamstring strain injury rate is 3.05 per 10,000 athlete-exposures (Chumanov et al., 2007; Yu et al., 2008; Dalto et al., 2015). It has been reported that a typical 25-player squad in football can expect about 7 hamstring strain injuries each season (Ekstrand, Hägglund and Waldén, 2011). Hamstring strain injury occurs during the late stance and late swing phase of the running gait cycle when a muscle is eccentrically overstretched (Chumanov et al., 2007; Yu et al., 2008).

Although hamstring injury risk management programmes are applied, hamstring strain injuries still occur (Brooks et al., 2006; Ekstrand, Hägglund and Waldén, 2011; Ekstrand et al., 2013; Orchard et al., 2013). Additionally, reinjury incidence after acute hamstring injuries are reported to range from 13.9 to 63.3% within the same playing season or up to 2 years after the initial injury (De Visser et al., 2012).

Deficits in eccentric knee flexor strength has been linked to future hamstring injuries, especially with re-injury indicating the importance of assessment to reduce the injury risk (Sugiura et al., 2008; Opar et al., 2013; Opar et al., 2015).

The Nordbord (Vald Performance, Qld Australia), is a novel field testing device recently developed for the assessment of hamstring eccentric strength, and based on the Nordic hamstring exercise used in large random controlled trials that showed positive outcomes in reducing the incidence of HSI (Al Attar et al., 2016). The device is designed specifically to obtain objective measurements of eccentric knee flexor strength (Opar et al., 2013). Nordbord has been shown to be a reliable device and can record bilateral peak force and torque of eccentric knee flexor strength, average force and torque whilst calculating between-limb force imbalance (Opar et al., 2013).

2.4 Reference values

Functional impairment testing has been typically used in sports injury rehabilitation (Manske and Reiman, 2013); therefore, a frame of reference values is necessary for the interpretation of the correct evaluations for establishing appropriate treatment goals, for providing important prognostic parameters, and for motivating the athlete during the rehabilitation process (Harbo, Brincks and Andersen, 2012; Benfica et al., 2018). Finally, normative data provide a baseline comparison of an individual's values to their peers providing a better understanding of normal variation within sport. ’Athletic performance is the result of a complex combination of factors including constitution-disposition, coordination, muscle strength, endurance, nutrition, cognition, and tactics but also genetic components and anthropometric features (Bourgois et al., 2000; Tucker and Collins, 2012). Anthropometric and body type characteristics have been reported to influence sports performance and as a consequence, may impact on a player’s progression up to the highest levels of their sport (Slater et al., 2005; Sánchez-Muñoz et al., 2020). The muscle strength of lower limb muscles are important determinants of sporting performance in relation to sprinting, jumping, throwing and changing direction rapidly. However, literature is quite limited and reports in relation to the effect of anthropometrical factors on muscle strength are mainly focused on male athletes and specific sports such as rugby. Given that sports performance requires muscle strength, the identification of whether anthropometrical features are associated with muscle strength may allow to development of an anthropometric and physiological profile in female athletes in the future.

Normative muscle strength data can be useful for sports coaches, trainers, medicine physicians, physiotherapists, and others who are responsible for an athletes' health and specifically for return-to-play criteria. To date, no data on normative values have been published for the hip strength and knee flexor strength in female athletes.

Therefore, the aims of the present study are: 1) to establish normative values for eccentric knee flexor and isometric hip adduction and abduction muscle strength in healthy, female athletes; 2) to determine whether there is a relationship between muscle strength measurements and anthropometrical data in female athletes; 3) to evaluate the association between adduction and abduction variables at each position and between Nordbord testing positions. Accordingly, the following research questions were addressed:

1. What are the normative values for eccentric and isometric knee flexor strength, isometric hip adduction and abduction muscle strength (tested at 45°, 60°, 90°, supine (knee), and supine (ankle) positions in healthy female athletes?
2. Is there a relationship between the (eccentric knee flexor, isometric hip adductor and abductor muscle) strength measures and anthropometrical data (body mass, stature, age) in female athletes?
3. Is there an association between hip isometric adductors and abductors strength measures obtained from a range of body positions (i.e., 45°, 60°, 90°, supine (ankle), and supine (knee))?
4. Is there an association between eccentric and isometric knee flexor strength?

2.5 Methods

This study is a secondary analysis of the VALD performance database that at the time consisted of 3888 tests obtained from female athletes.

2.5.1 Database

The database includes tests performed between July 2017 to January 2020 for GroinBar; and from: January 2016 to January 2020 for NordBord. The athletes were from a variety of sports: triathlon, skating, martial arts, bowling, cycling, bobsled/driver, basketball, swimming, volleyball, Gaelic football, soccer, American football, softball, handball, beach volley, track and field, surfing, dance, tennis, fire-fighting, field hockey, Australian rules football, netball, weightlifting, lacrosse, golf, skiing from elite clubs, Olympic and NCAA, and university students were included. Body mass (kg), stature (cm) and age (years) were also provided.

2.5.2 Strength Measures

Data was obtained from seven assessment protocols: isometric hip adduction and abduction at 45°, at 60°, at 90°, supine neutral at knee, supine neutral at ankle; isometric knee flexor strength at prone position, and eccentric knee flexor strength (Nordic).

Isometric hip adductor and abductor strength

Hip and groin adduction and abduction strength was assessed by using the GroinBar Strength Testing System (Vald Performance, Queensland, Australia). Hip adduction (ADD) and abduction (ABD) isometric strength were evaluated at five test positions: 45°, 60°, 90°, supine (knee), and supine (ankle). The 60° and 90° positions have been described in the cohort study 3.

Isometric hip ADD and ABD strength tests at 45° were obtained with the participants adopting a standardised supine position beneath the GroinBar (Vald Performance Albion, Australia) with their knee joint at an angle of 45° as described by Ryan et al. (2019). For the isometric hip ADD strength test, the femoral and tibial condyles were positioned central to the force pads and the isometric hip ABD test lateral femoral condyle and head of the fibula were central to the outer force pads (O'Brian et al., 2019).

For the testing of isometric hip ADD and ABD strength at Supine Neutral (Ankle), participants were required to lie beneath the GroinBar (Vald Performance Albion, Australia) in a standardise supine position, with their knee joint at an angle of neutral position (lying), and arms by side. For the isometric hip ADD strength test, the medial malleoli (inner ankles) were positioned central to the force pads and the isometric hip ABD test lateral malleoli (outer ankles) were central to the outer force pads.

For the testing of isometric hip ADD and ABD strength at Supine Neutral (knee), participants were required to lie beneath the GroinBar (Vald Performance Albion, Australia) in a standardise supine position, with their knee joint at an angle of neutral position (lying), and arms by side. For the isometric hip ADD strength test, the medial femoral condyle (inner knee) was positioned central to the force pads and the isometric hip ABD test lateral femoral condyle (outer knee) were central to the outer force pads.

Strength measures

Force data for the right and left ADD and ABD exercises was measured from force transducers sampling at 50Hz. Isometric hip strength was determined for each leg from the peak force during the best of three repetitions of 5 s of ADD and ABD (Ryan et al., 2019).

The highest peak forces from the attempts for abductors and for adductors were used in the analysis. The peak force for both limbs, and for both positions was determined automatically through the Scoreboard software and expressed as absolute (N), and percentage imbalance between limbs was also provided based on the following equation: IF(Left Limb<Right Limb,1-MIN(Left Limb: Right Limb)/MAX(Left Limb: Right Limb),-1+MIN(Left Limb: Right Limb)/MAX(Left Limb: Right Limb) x 100). Negative percentage imbalances indicate that the left limb's score was greater than the right limb. The force data were uploaded to a personalized account and exported into a customized Microsoft Excel spreadsheet (Microsoft, Redmond, USA) for analysis. The mean strength from both limbs was used for analysis.

Nordic hamstring exercise strength

The assessment of hamstring strength was conducted using the NordBord device (VALD Performance, Brisbane, Australia) to measure eccentric and isometric knee flexor strength.

The eccentric knee flexor strength measurement has been described at the cohort study 3.

For the isometric prone, the participants kneeled on the device, with the ankles secured immediately superior to the lateral malleolus by individual ankle hooks. Participants were required to bend to prone or "bridge" position, with 0° of knee and hip flexion with the elbows flexed 90^0 stabilized on the ground. Participants holding stable their elbows on the ground, keeping the trunk and hips in a neutral position, applied pressure down with both limbs.

Force data were captured from each limb and transferred to a personal computer at 100 Hz through a USB cable and forces recorded to the Scorebord data collection app. The maximum scores of left and right limbs of the three repetitions were used for further data analysis. Eccentric and isometric hamstring strength was recorded in absolute force in Newtons (N) for each limb and the data was presented as a mean from both limbs. The limbs asymmetry was calculated as the difference between limbs using the following equation: IF(Left Limb<Right Limb,1-MIN(Left Limb: Right Limb)/MAX(Left Limb: Right Limb),-1+MIN(Left Limb: Right Limb)/MAX(Left Limb: Right Limb)), and was expressed as percentage. Where negative percentage imbalances indicate that the left limb's score was greater than the right limb.

2.6 Data analysis

All statistical analyses were performed using JMP 14.1 (SAS Institute, Inc) and IBM statistics Spss 26. To describe data: mean and standard deviations (SD) were used. The highest peak forces from attempts for abductors and for adductors were used in the analysis. The ratio of adduction to abduction strength (ADD divided by ABD) was also calculated.

Pearson correlation coefficients (r) were generated to explore the bivariate relationships between 'strength' measures and anthropometric factors (i.e., age, posture, and body mass). Pearson product moment correlation matrix for the strength dependent variables were assessed between hip adductors and abductors at 45° (N), at 60^{o} (N), at 90^{o} (N), at supine neutral (knee) (N), and at supine neutral (ankle) (N), and between, eccentric and isometric knee-flexor strength.

The magnitude of the correlations was rated as <0.1 trivial; 0.1-0.3 small; 0.3-0.5 moderate; 0.5-0.7 large; 0.7-0.9 very large; and 0.9-1.0 almost perfect (Hopkins et al., 2009). All associations $p<0.05$ were considered significant.

2.7 Results

In total, 1916 Nordbord tests were obtained from 592 female athletes (Age: 28 (5) years; Stature: 171 (10) cm; Body mass: 69 (14) kg), and 1972 GroinBar tests from 498 female athletes (Age: 28 (5) years; Stature: 172 (10) cm; Body mass: 71 (16) kg) tested on the GroinBar were analysed using the range of protocols as shown in Table 2.7a.

Table 2.7a: Demographic characteristics of the study athletes.
SD, standard deviation; N, newtons; cm, centimetres; kg, kilograms.

	Body mass (kg) Mean (SD)	**Body mass (kg) Range**	**Stature (cm) Mean (SD)**	**Stature (cm) Range**	**Age (years) Mean (SD)**	**Age Range (years)**
Nordic	69.9 (15)	40-122	171 (10.5)	140-2.02	27.8 (5.2)	15-44
Iso Prone	63 (6.3)	52-87	170 (7.6)	157-191	27.3 (5.8)	18-51
GroinBar 45^{o}	65.4 (10.3)	50-110	169.2 (7.1)	152-183	28.5 (4.9)	18-44
GroinBar 60^{o}	77.1 (17.8)	40-122	175.8 (12.6)	152-2.02	26 (6.2)	15-51
GroinBar 90^{o}	67.2 (9.0)	55-87	171 (7.0)	160-186	30.6 (3.0)	20-38
Supine (ankle)	75.5 (20.0)	49-122	168.9 (7.0)	167-171	27.2 (5).0	18-36
Supine (knee)	64 (8.8)	41-110	170.2 (8.4)	147-191	29.6 (5.1)	15-51

2.7.1 Normative values

The normative data for the isometric hip adductor and abductor strength and the between-limb imbalances for the testing positions of 45^{o}, 60^{o}, 90^{o}, supine (ankle) and supine (knee), and their hip adductor-to-abductor ratios are presented in Table 2.7.1a and 2.7.1b. For the GroinBar, the highest force output was observed at the 60^{o} position, and the lowest force output was observed at the supine (ankle). ADD: ABD was consistent across all testing positions ranging between 1.18 to 1.23. Normative values for eccentric and isometric knee flexor strength are presented in Table 2.7.1c. Eccentric knee flexor strength was greater, and less imbalanced between-limbs than the isometric testing at prone position.

Table 2.7.1a: Normative data of GroinBar strength, and between-limb imbalance for female athletes by testing position**.** N, newtons; SD, standard deviation; 95%CI, 95% confidence interval.

Testing Positions	Isometric hip abductor strength Mean (SD) (N)	95%CI	Isometric hip abductor strength Imbalance Mean (SD) (%)	95%CI	Isometric hip adductor strength Mean (SD) (N)	95%CI	Isometric hip adductor strength Imbalance Mean (SD) (%)	95%CI
45^{o} N=176	302 (53)	294 to 310	4.7 (3.7)	4.2 to 5.3	305 (61)	296 to 314	4.8 (3.6)	4.3 to 5.4
60^{o} N=657	307 (78)	301 to 313	6.5 (7.2)	5.9 to 7.0	324 (86)	317 to 330	4.7 (3.9)	4.4 to 5.0
90^{o} N=354	287 (82)	278 to 295	7.4 (6.4)	6.7 to 8.1	322 (75)	314 to 329	4.3 (3.9)	3.9 to 4.7
Supine (ankle) N=371	166 (73)	159 to 174	5.9 (5)	5.4 to 6.4	168 (82)	159 to 176	4.6 (4.3)	4.2 to 5.1
Supine (knee) N=414	293 (71)	286 to 300	5.9 (9.1)	5.1 to 6.8	298 (86)	290 to 306	5.1 (4.7)	4.6 to 5.5

Table 2.7.1b: Adduction (ADD)-abduction (ABD) ratio by testing position. N, newtons; SD, standard deviation; 95% confidence interval.

Forceplace	N	ADD:ABD Mean (SD)	95% CI
45^{o} (N)	176	1.21 (0.03)	1.21 to 122
60^{o} (N)	657	1.22 (0.04)	1.22 to 1.23
90^{o} (N)	354	1.23 (0.05)	1.23 to 1.24
Supine (Ankle) (N)	371	1.18 (0.04)	1.17 to 1.18
Supine (Knee) (N)	414	1.21 (0.05)	1.21 to 1.22

Table 2.7.1c: Normative data of Nordbord strength (Mean, SD), and between-limb imbalance for female athletes by testing position**.** N, newtons; SD, standard deviation; 95%CI, 95% confidence interval.

Positions Nordbord	**Mean (SD) (N)**	**95%CI**	**Imbalance Mean (SD) (%)**	**95%CI**
ISO prone N=158	270 (68)	260 to 281	10.0 (7.2)	8.9 to 11.1
Nordic N=1758	282 (71)	279 to 286	8.3 (6.9)	8.0 to 8.6

2.7.2 Correlations between strength variables

The correlation matrix between the isometric hip adductors and abductors of the female athletes is represented in Table 2.7.2a. The strongest correlation was demonstrated between adductors and abductors in supine (ankle) position. There was significant moderate to good associations between the adductors at 45°, 60°, 90°, and supine (knee) to their abductors at same degrees. These results indicate that as the adductors strength increases, so does the abductors strength. Fair inverse correlation was found between abductor strength at supine position (Ankle) and abductor strength at 90° suggesting that as the abductor strength at supine (ankle) position increase, the abductor strength at 90 decreases. No correlation was found between the eccentric and isometric knee flexor strength and between-limb imbalances (Table 2.7.2b).

Table 2.7.2a: Correlation Matrix for adduction and abduction strength variable **Correlation is significant at the 0.01 level (2-tailed), *Correlation is significant at the 0.05 level (2-tailed). N, newtons.

Position	**Mean abduction at 45° (N)**	**Mean adduction at 45° (N)**	**Mean abduction at 60° (N)**	**Mean adduction at 60° (N)**	**Mean abduction at 90° (N)**	**Mean adduction at 90° (N)**	**Mean abduction Supine (Ankle) (N)**	**Mean adduction Supine (Ankle) (N)**	**Mean abduction Supine (knee) (N)**	**Mean adduction Supine (knee) (N)**
Mean abduction at 45° (N)	1.00	0.55**	-0.09	-0.08	0.02	-0.09	-0.05	-0.03	0.00	0.00
Mean adduction at 45° (N)	0.55**	1.00	-0.19	-0.22	0.17	0.12	-0.04	-0.07	0.01	-0.08
Mean abduction at 60° (N)	-0.09	-0.19	1.00	0.71**	0.02	-0.07	-0.22	-0.19	-0.07	-0.01
Mean adduction at 60° (N)	-0.08	-0.22	0.71**	1.00	-0.03	-0.09	-0.14	-0.10	-0.10	-0.06
Mean abduction at 90° (N)	0.02	0.17	0.02	-0.03	1.00	0.64**	-0.27**	-0.24	0.18	0.03
Mean adduction at 90° (N)	-0.09	0.12	-0.07	-0.09	0.64**	1.00	-0.04	-0.01	0.14	0.12
Mean abduction Supine (Ankle) (N)	-0.05	-0.04	-0.22	-0.14	-0.27**	-0.04	1.00	0.90**	0.15	0.24
Mean adduction Supine (Ankle) (N)	-0.03	-0.07	-0.19	-0.10	-0.24	-0.01	0.90**	1.00	0.14	0.22
Mean abduction Supine (Knee) (N)	0.00	0.01	-0.07	-0.10	0.18	0.14	0.15	0.14	1.00	0.65**
Mean adduction Supine (Knee) (N)	0.00	-0.08	-0.01	-0.06	0.03	0.12	0.24	0.22	0.65**	1.00

Table 2.7.2b: Correlation between strength values (Nordbord) between Nordic and ISO prone testing positions. **Correlation is significant at the 0.01 level (2-tailed), *Correlation is significant at the 0.05 level (2-tailed).

Nordic	N	Mean (SD)	Mean Nordbord-Nordic	
			R	p
Imbalance Nordbord-Nordic (%)	1758	8.3 (6.9)	-0.16	0.01**
Mean ISO Prone (N)	158	270 (68)	-0.18	0.05*
Imbalance-ISO Prone (%)	158	10.0 (7.2)	-0.16	0.05*

2.7.3 Correlation between muscle strength and body mass, stature, and age

As shown in Tables 2.7.3a-c below, body mass, stature, and age showed statistically significant correlations with some strength measures. The results revealed a significantly moderate to good positive correlation between the body mass and eccentric knee flexor strength, and isometric adductor strength at 60^o (r=0.62 to 0.64; p<0.0001). The strongest Pearson's correlation coefficient showed between body mass and isometric hip abductors strength at 60^o (Table 2.7.3a; Figure 2.7.3a). This result indicates that as the body mass increases, so does the abductors strength at 60^o. No correlation was found for isometric hip adductors and abductors strength and between-limb imbalance at supine (knee) position, and for between-limb imbalances of eccentric knee flexor strength, and of adductors and abductors at 60^o.

The results revealed a significantly moderate to good positive correlation between stature and isometric hip abductor strength at 60^o, and fair correlation with isometric hip adductors at 60^o, but no relationship with their between -limb imbalance was found (Table 2.7.3b; Figure 2.7.3b). No correlation was found between stature and eccentric knee flexor strength, isometric hip adductors and abductors strength at supine (knee) position, and their between-limb imbalances.

Table 2.7.3a: Pearson r correlation coefficients, p values, and ± 95 % confidence intervals (CI) for each comparison of Forceplace strength, between limb imbalances and Body Mass (Mean, SD Kg); **Correlation is significant at the 0.01 level (2-tailed), *Correlation is significant at the 0.05 level (2-tailed). N, newtons; SD, standard deviation; 95%CI, 95% confidence interval.

	N	**Mean (SD)**	**Body Mass (kg) Mean (SD)**	**r (95%CI)**	**p value**
Mean Nordbord-Nordic (N)	272	296 (83)	70 (15)	0.62 (0.54 to 0.69)	<.0001**
Between-limb Imbalance-Nordic (%)	272	10 (8.5)		-0.11 (-0.23 to 0.009)	0.07
Mean abduction Force at 60° (N)	106	339 (101)	77.1 (17.8)	0.79 (0.70 to 0.85)	<.0001**
Between-limb imbalance abduction Force at 60° (%)	106	5 (3.8)		-0.14 (-0.33 to 0.05)	0.14
Mean adduction Force at 60° (N)	106	346 (116)		0.64 (0.51 to 0.74)	<.0001**
Between-limb imbalance-adduction Force at 60° (%)	106	5.2 (4.2)		0.10 (-0.09 to 0.29)	0.30
Mean abduction at supine (knee) (N)	70	270 (75)	64 (8.8)	0.09 (-0.15 to 0.32)	0.47
Between-limb imbalance-abduction supine (knee) (%)	70	10 (17)		0.10 (-0.13 to 0.33)	0.39
Mean adduction Supine (knee) (N)	70	285 (67)		0.23 (-0.007 to 0.44)	0.06
Between-limb imbalance-adduction at Supine (knee) (%)	70	5.4 (5.3)		-0.11 (-0.33 to 0.13)	0.37

Fair inverse correlation between age and between-limb imbalance of isometric hip abductors at supine (ankle) position, and positive fair correlation to isometric hip abductors strength at supine (knee) position (Table 2.7.3b; Figure 2.7.3c). Therefore, these results indicate that as the age increases, the between-limb imbalance of isometric hip abductors at supine (ankle) position decreases, and the isometric hip abductors strength at supine (knee) position increases.

Table 2.7.3b: Pearson r correlation coefficients, p value, and ± 95 % confidence intervals for each comparison of Forceplace strength, between limb imbalances and Stature (Mean, SD cm); **Correlation is significant at the 0.01 level (2-tailed), *Correlation is significant at the 0.05 level (2-tailed). N, newtons; SD, standard deviation; 95%CI, 95% confidence interval.

	N	**Mean (SD)**	**Stature (cm) Mean (SD)**	**r (95%CI)**	**p value**
Mean Nordbord-Nordic (N)	246	278 (63)	174.8	0.16 (0.03 τo 0.28)	0.0128*
Between-limb imbalance Nordic (%)	246	9.9 (8.2)		-0.10 (-0.23 to 0.02)	0.11
Mean abduction Force at 60° (N)	81	302 (75)	175.8 (12.6)	0.57 (0.40 τo 0.70)	<.0001**
Between-limb imbalance-abduction Force at 60° (%)	81	5.5 (4.2)		-0.20 (-0.40 to 0.02)	0.0806
Mean adduction Force at 60° (N)	81	306 (92)		0.37 (0.16 τo 0.54)	0.0007**
Between-limb imbalance-adduction Force at 60° (%)	81	5.1 (3.8)		0.07 (-0.15 to 0.29)	0.53
Mean abduction at Supine (knee) (N)	76	268 (69)	170.3 (8.1)	0.01 (-0.21 to 0.24)	0.92
Between-limb imbalance-abduction Supine (knee) (%)	76	9.6 (16)		-0.02 (-0.24 to 0.21)	0.87
Mean supine (knee) adduction (N)	76	278 (61)		-0.10 (-0.32 to 0.13)	0.40
Between-limb imbalance-adduction Supine (knee) (%)	76	5.2 (4.9)		0.10 (-0.14 to 0.31)	0.44

Table 2.7.3c: Pearson r correlation coefficients, p value, and ±95% confidence intervals for each comparison of Forceplace strength, between limb imbalances and age (mean, SD years). **Correlation is significant at the 0.01 level (2-tailed), *Correlation is significant at the 0.05 level (2-tailed). N, newtons; SD, standard deviation; 95%CI, 95% confidence interval.

	N	Mean (SD)	Age (years) Mean (SD)	r (95%CI)	p value
Mean Nordbord-Nordic (N)	404	279 (65)	27.8 (5.2)	0.04 (0.06 to 0.14)	0.40
Between-limb Imbalance-Nordic (%)	404	8.8 (7.1)		-0.08 (-0.18 to 0.01)	0.09
Mean abduction Force at 45° (N)	94	302 (49)	28.5 (4.9)	-0.05 (-0.25 τo 0.16)	0.66
Between-limb Imbalance-abduction at 45° (%)	94	4.7 (3.6)		0.12 (-0.09 τo 0.31)	0.27
Mean adduction Force at 45° (N)	94	306 (62)		-0.10 (-0.3 to 0.1)	0.32
Between-limb Imbalance-adduction at 45° (%)	94	5.2 (3.9)		-0.23 (-0.42 to -0.032)	0.0239*
Mean abduction Force at 60° (N)	110	295 (67)	26 (6.2)	0.05 (-0.14 to 0.23)	0.63
Between-limb Imbalance-abduction at 60° (%)	110	12.3 (13.3)		0.17 (-0.016 to 0.35)	0.07
Mean adduction Force at 60° (N)	110	331 (76)		0.19 (-0.002 to 0.36)	0.0482*
Between-limb Imbalance-adduction 60° (%)	110	4.3 (4)		-0.16 (-0.33 to 0.03)	0.10
Mean abduction Force at 90° (N)	87	323 (70)	30.6 (3.0)	-0.08 (-0.29 to 0.13)	0.45
Between-limb Imbalance-abduction Force at 90° (%)	87	7.1 (6)		-0.20 (-0.40 to 0.009)	0.06
Mean adduction Force at 90° (N)	87	343 (74)		-0.23 (-0.42 to -0.02)	0.0303*
Between-limb Imbalance-adduction Force at 90 (%)	87	5.3 (5.2)		0.05 (-0.16 to 0.26)	0.62
Mean abduction Supine (ankle) (N)	63	148 (24)	27.2 (5)	-0.21 (-0.43 to 0.04)	0.10
Between-limb Imbalance-abduction Supine (ankle) (%)	63	4.1 (3.6)		-0.26 (-0.47 to -0.01)	0.0419*
Mean adduction Supine (ankle) (N)	63	142 (24)		-0.08 (-0.32 to 0.17)	0.53
Between-limb Imbalance-adduction supine (ankle) (%)	63	6.4 (5.5)		-0.06 (-0.30 to 0.19)	0.65
Mean abduction Force (knee) (N)	135	295 (68)	29.6 (5.1)	0.25 (0.08 to 0.40)	0.0038**

Between-limb Imbalance-abduction supine (knee) (%)	135	8 (14.4)		-0.15 (-0.30 to 0.02)	0.09
Mean adduction Supine (knee) (N)	135	288 (67)		0.17 (0.0009 to 0.33)	0.0489*
Between-limb Imbalance-adduction Supine (knee) (%)	135	5.4 (4.4)		-0.06 (-0.22 to 0.11)	0.52

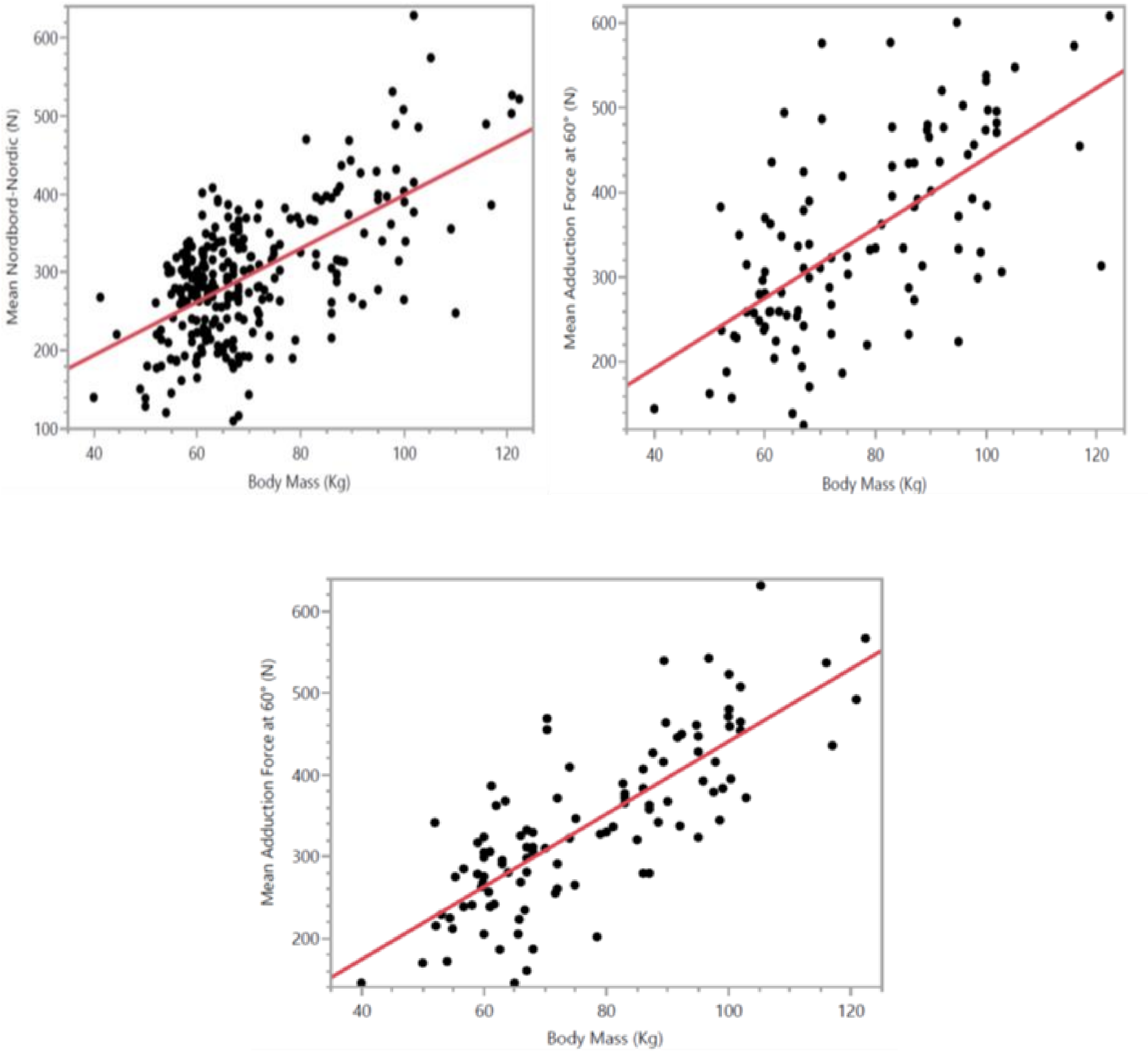


Figure 2.7.3a: The relationship between body mass and mean Nordbord ($r=0.62$; $p<0.0001$), hip abductors ($r=0.79$; $p<0.0001$) and adductors ($r=0.64$; $p<0.0001$) strength at 60^{0}.

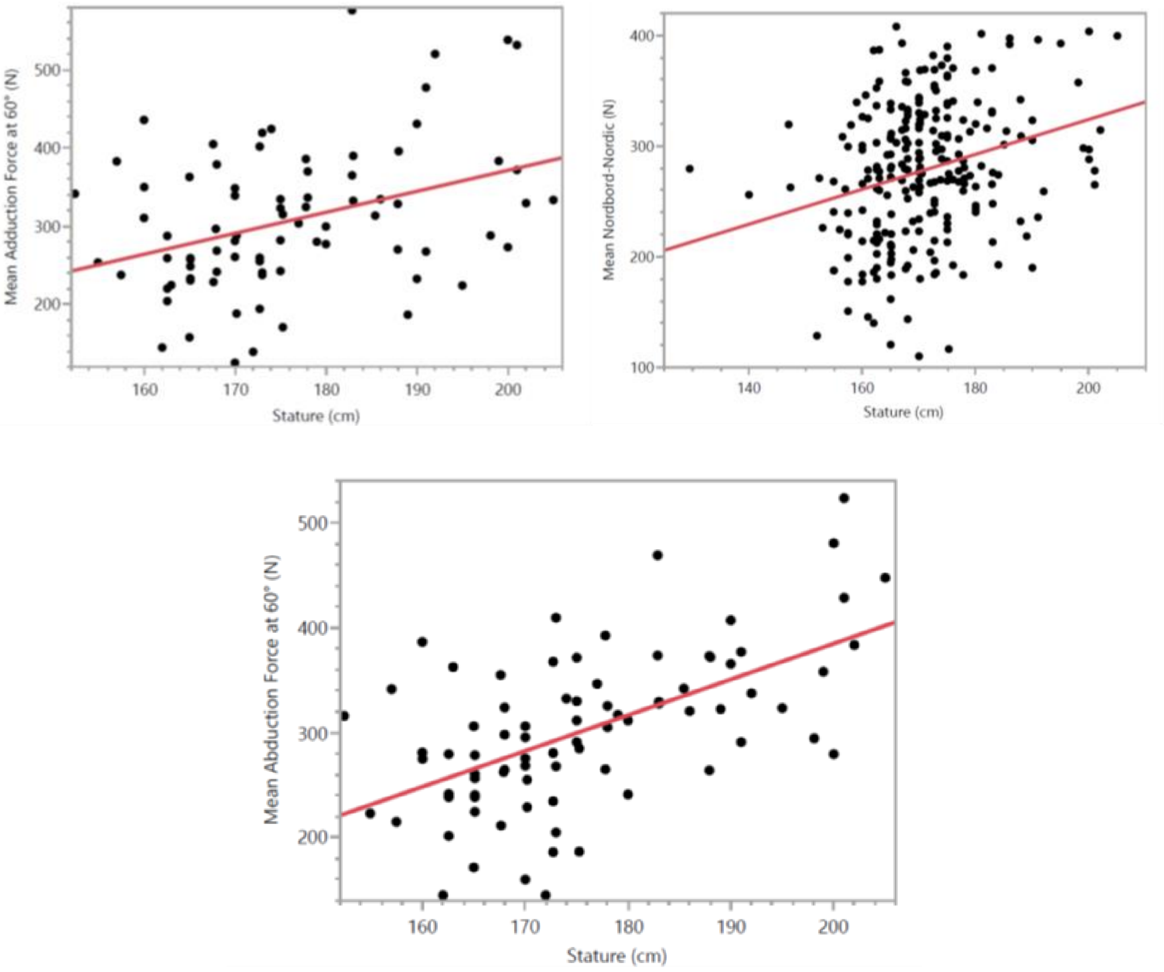


Figure 2.7.3b: The relationship between stature and mean Nordbord (r=0.16; p=0.01), hip abductors (r=0.57; p<0.0001) and adductors strength (r=0.30; p<0.0007) at 60^{o}.

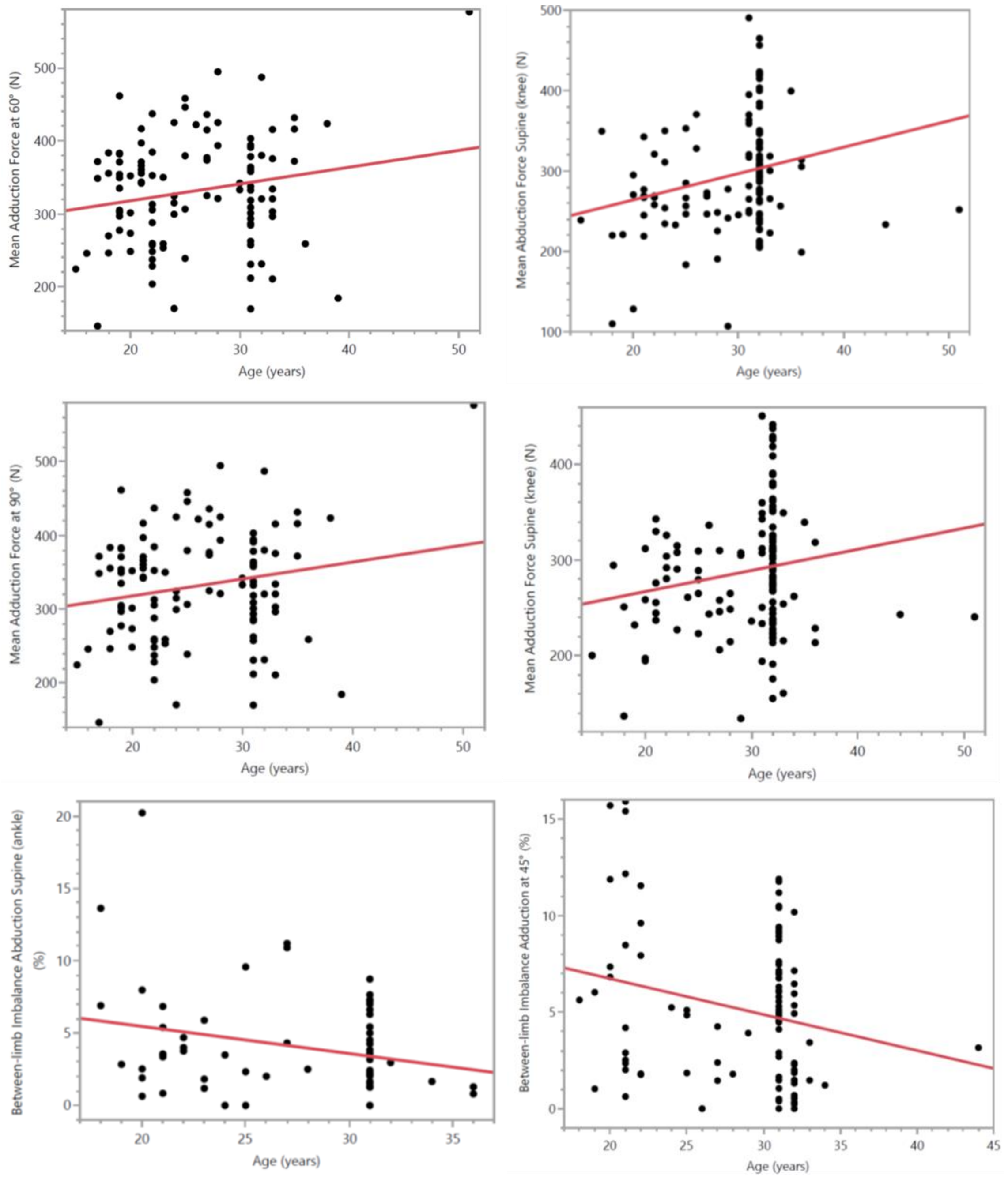


Figure 2.7.3c: The relationship between age and hip adductors strength at 60^{o} (r=0.19; p=0.048), 90^{o} (r=-0.23; p=0.03), hip abductors (r=-0.25; p=0.004) and adductors (r=0.17; p=0.05) at supine (knee) position, and between-limb imbalance adduction at 45^{o} (r=-0.23; p=0.023) and abductors (r=-0.26; p=0.04) at supine (ankle) position.

2.8 Discussion

2.8.1 Normative data

Normative data are presented for female athletes across a range of novel field tests used to assess isometric hip adductors and abductors, and isometric and eccentric knee flexor strength. To determine the normative values of the healthy female athletes, the highest peak force of hip adductors, abductors and knee flexors from the athletes' attempts were used from the database. The degree of correlations between strength values and anthropometrical data (body mass, stature, age) were also examined. The results of this chapter were therefore used to answer the four research questions of study 2. The descriptive statistics provide clinicians with a frame of reference that currently is unavailable. These data can be used to guide in the decision making process to assist in the physical preparation of athletes and the development of training goals but also to set rehabilitation goals for muscle strength after injury. Specifically, rehabilitation programmes after lower limb injuries in female athletes require methods that can facilitate comparison of knee flexors, hip adduction and abduction strength against a sports population-specific reference standard before returning back to competition. The descriptive statistics provide clinicians with a frame of reference that currently is unavailable. These data can be used in decision making process to assist in the physical preparation of athletes and development of training goals but also to set rehabilitation goals for muscle strength after injury.

At each testing position, strong positive correlations (range from 0.55 to 0.90) between adductors (ADD) and abductors (ABD) were obtained. These findings support the use of ADD: ABD ratio as a point of reference for female athletes similar to previous studies involving male athletes. The ADD:ABD ratios were found to range 1.18 to 1.23 depending on the testing angle, which are higher than previously reported obtained from different protocols. Thorborg et al. (2014) using a handheld dynamometer found different ratios between injured and control male elite soccer players.

Specifically, it found that players with adductor-related groin pain have isometric hip ADD/ABD ratio of 0.92 (0.23) compared to the control asymptomatic group 0.99 (0.18) when obtained from supine testing position (Thorborg et al., 2014).

Tyler et al. (2001), suggested that an ADD/ABD ratio less than 0.8 increased the risk of adductor-related groin injury about 17 times compared to uninjured players which were found to have ratio of 0.95. The lower ratios compared to the male reference data reported in previous studies, highlight the importance of obtaining population specific measures. There are many differences between the current and previous studies beyond the equipment used. For example: the athletes previously measured were male; the sports from which the athletes came from are different between studies, thus exhibit different specific performance demands, and consequently the risk profile for injuries in sports may also differ. For example, in tennis, repetitive short high-intensity movements are required that impose an elevated concentric and eccentric load on the adductor muscles, while in hockey, multiple different movements at several intensities are performed (Sánchez-Migallón et al., 2020).

To our knowledge, normative values for hip ADD:ABD ratio have not been previously evaluated and established for female athletes obtained from the GroinBar. Although, male athletes have been observed as stronger and gender differences for muscle strength has been reported previously, studies are mainly focused on male hip strength and ratios (Brophy et al., 2009). Therefore, there was a need to evaluate hip ADD/ABD strength ratio in female athletes.

The knee flexor strength was tested in two different positions and under eccentric and isometric muscle actions. No relationship between measures obtained using eccentric and isometric muscle action of knee flexor muscles was found indicating that it is unlikely they are assessing similar constructs and that one cannot predict the other. The lack of relationship between the test scores can be explained by the underpinning mechanisms used for each type of muscle action. The differences are well known and discussed in detail elsewhere, but under eccentric muscle actions the capacity to produce force is more than when a muscle is acting isometrically (Huxley, 1957; Herzog, 2018). Strength is sport-specific which depends on the long-term sport-specific training adaptations (Izquierdo et al., 2002). Thus, maximum strength differences among athletes in different testing positions may probably exist (Izquierdo et al., 2002; Singh et al., 2002). For example, Pectineus muscle has its greatest activation at 90^o hip flexion with Adductor brevis, Gracilis at 45^o, and adductor Magnus at 0^o (knee) (Lovell, Blanch and Barnes, 2012). Therefore, this variability of maximum muscle strength in each testing position due to the requirement of each sport's discipline may affect the fact of few correlations. In addition, eccentric knee flexor contraction and isometric knee flexor contraction are biomechanically different contractions in nature, as well as muscle activation patterns. Eccentric knee flexor strength testing provides the largest stimulus to changes in the biceps femoris fascicle length, compared to isometrically which requires less force and more energy; this can explain the intervention effect on reducing injury risk since decreased fascicle length has been reported as a risk factor for hamstring injury (Timmins et al., 2016; Bourne et al., 2017; Herzog, 2018).Moreover, eccentric hamstring strengthening training has been shown to decrease the rate of overall, new, and recurrent acute hamstring injury. However, a prior study has found decrements in isometric knee flexion force, after a hamstring injury, which increased the reinjury risk (De Vos et al., 2014). Hamstring strain injury occurs during the late stance and late swing phase of the running gait cycle when a muscle is eccentrically overstretched (Chumanov et al., 2007; Yu et al., 2008). Nevertheless, researchers proposed isometric function of the hamstring fascicles at late swing and that the large force at this phase may become too high for fascicles to remain isometric, and thus cause an eccentric contraction and concomitant vulnerability to injury (Van Hooren and Bosch, 2018). Therefore, training of both contractions may be beneficial for the injury risk management. When it comes to the assessment of players' knee flexor strength, Nordbord, based on the commonly employed Nordic hamstring exercise, is capable of testing isometrically and eccentrically, overcoming the limitations of other testing methods (cost, space, qualified skilled operators).

2.8.2 Correlation with the participants physical characteristics (body mass, stature, and age)

Anthropometric data (body mass, stature, and age) correlated with hip and knee muscle strength at different positions providing predictive equations for hip and knee muscle strength. Specifically, isometric hip adductors and abductors strength at 60^{o} was found to be associated with body mass and stature, while eccentric knee flexor strength was associated only to body mass. Age was shown to correlate positively with isometric hip abductors in supine (knee) position, and correlate negatively with between-limb imbalance of abductors in supine (ankle) position. No association was found between eccentric and isometric knee flexor strength, or between adduction variables in different positions. Despite the fact that both eccentric and isometric tests measure maximal knee flexor strength, it seems that each measures strength mechanical properties differently. Therefore, the values of one test cannot inform the others. Similarly for the hip adductor strength measures, where the same contraction type was tested, it seems that different mechanical positions affected the values, suggesting that each test is independent. This means that asymmetries between limbs may also be identified in a different way between tests. This information suggests that the isometric and eccentric tests for assessing knee flexor strength cannot be used interchangeably. Different contractile activity of the hamstrings may cause these different results between the isometric and eccentric tests (Onishi et al., 2002). Therefore, it may not be adequate to rely on a single strength test during the rehabilitation, but rather a combination of tests would be advisable for better evaluation.

Body mass was correlated to eccentric knee flexor, and hip adductor and abductor strength at 60^{o}, suggesting the influence of muscle mass in the force-generating capacity of muscles. It may possible that heavier athletes require greater muscle mass for movement than their lean counterparts (Janssen et al., 2000). Similarly, Buchheit et al. (2016) study demonstrated positive correlation between body mass and knee flexor strength in soccer players and in the Australian Football League. Buchheit et al. (2016) suggested that this may be associated with the fact that during the Nordic testing, when bending forward, athletes' body mass may affect the force applied to the dynamometers.

Hip adductor and abductor muscle strength at 60^0 was also found to be associated with an athletes' stature suggesting that body size influences muscle strength. Naturally, the body is made symmetrical in relation to the proportions of body parts. According to this, it may reasonable that taller athletes have longer bones and muscles and would be expected to have a greater muscle mass (Janssen et al., 2000). This is confirmed by prior work where stature was found to correlate to hand grip strength in women (Forbes, 1972; Luna-Heredia, Martín-Peña and Ruiz-Galiana, 2005). However, no correlations were found between stature and hip adduction and abduction at supine (knee) position. The absence of these associations may be due to the small sample size at this position which does not allow an adequate representation of this population.

Despite being statistically significant, the low correlation coefficients ($r<0.30$) suggest little relationship between supine abductors (knee) strength, imbalance supine abductors (ankle) and age. The results showed that younger athletes produced lower muscle strength at supine position (knee) and greater between limb imbalance at supine (ankle) position than older female athletes. It has been established that age affects muscle size and strength (Kallman, Plato and Tobin, 1990; Bäckman et al., 1995). However, it has been shown that strength starts to decline during the fifth decade and accelerating thereafter which agrees with our population age range (Larsson, Grimby and Karlsson, 1979; Kallman, Plato and Tobin, 1990). These results enhance the need to establish specific references values for muscular strength at each age category.

The varied impact of body size (i.e., anthropometric data) on strength measures found, may be specific to the position adopted. Body size is a well recognised factor that influences muscle strength when comparisons are taken within a large population (Hurd, Morrey and Kaufman, 2011). Therefore, muscle strength may be scaled to anthropometric data to allow for between-subjects comparisons (Hurd, Morrey and Kaufman, 2011). To normalize the strength measurements for body size differences, allometric scaling can be used. Allometric scaling is based on the concept of geometric similarity assuming that all humans have the same shape and differ only in size (Folland, Mc Cauley and Williams, 2008; Hurd, Morrey and Kaufman, 2011). Normalization of muscle strength will help to facilitate the identification of differences in strength between female athletes with diverse physical characteristics (Pasco et al., 2020). However, in the current study, anthropometrical data was not available for all the female athletes which limits the application of allometric scaling for body size. Therefore, future research should aim to established particular normative data for different demographic profiles of female athletes.

The reference values presented in the current study were constructed using participants from various sporting disciplines instead of including a small sample of one sport. Doing research in a specific sport is often limited to the sample size such as the size of the available cohort, and the results should be interpreted with caution due to potential variation between values. Therefore, this study included athletes from a variety of sports but also tactical athletes to establish reference values. Tactical athlete is a term that has been used to describe individuals who participate in a competition or contest that requires a certain level of physical fitness and skills associated with their work (eg, the military, fire fighters) (Cameron et al., 2016). During the last decade an awareness has been fostered whereby tactical athletes can benefit from using strength and conditioning training that has been used by athletes to improve athletic performance and reducing musculoskeletal injury (Scofield and Kardouni, 2015; Frost et al., 2015). Considering the demands in relation to muscle strength for athletes and tactical athletes, the establishment of reference values is importance.

Strength and limitations

The main strengths of the current study are the high number of female participants, the wide range of ages, the variation of played sports, and the use of commonly used testing positions, ensuring good generalisability of findings. The conditions of how the tests were performed are unknown. Additionally, the anthropometrical data that were evaluated in terms of relationship with muscle strength were limited only to body stature, body mass and age; however, we did not have access to other variables such as length of the lower extremity, muscle mass, and fat mass. Future studies should evaluate more variables in relation to strength which may affect the sport performance.

Conclusion

This study establishes reference ranges for strength of the hip adductor and abductor muscles and knee flexor strength in female athletes. This is the first study to document hip adduction and abduction strength profiles in female athletes using bilateral strength test.

Anthropometrical data was found to influence muscle strength. Body size variables have been suggested as factors that affect muscle strength, suggesting that muscle mass positively affects the ability to generate force or torque, and the taller or heavier an individual is, the stronger they are (Jaric, 2002; Jaric, Mirkov and Markovic, 2005). Therefore, valid comparisons of muscle strength between individuals requires data normalization, allometric scaling or accounted for statistically (Folland, Mc Cauley and Williams, 2008).

These normative values can be applied in the clinical setting to estimate the degree of an athlete's weakness, to guide pre-season athletes' strength training at presentation relative to the predicted normal. Following the recovery progression of injured athletes, normative values will help in decision making and return to play.

Future work is required to investigate whether this data will prove to be useful in predicting injury risk, and subsequently in the development of injury risk management strategies. In addition, it will be useful if normative values can be established for specific female sporting populations.

Chapter 3: Identification of risk factors for lower limb injuries in female team-sport athletes (Study 3)

3.1. Abstract

Background: It is accepted that participation in team sport is associated with injury risk; and it is well established that female athletes face greater risk of lower extremity injuries compared to their male counterparts. Yet, despite the awareness of elevated risk for female athletes, factors associated with injury are not fully understood and many avenues of study have yet to be explored. The inclusion of novel testing, psychological questionnaire, and injury history data obtained at pre-season may establish associations with injury risk. Findings leading to the identification of intrinsic differences could help with the development of prevention strategies and reduce injury risk.

Aims: The purposes of this prospective cohort study were: 1) to assess the association between lower extremity muscle strength and the risk for lower limb injuries; 2) to investigate the potential relationship between life events and lower limb injuries; and 3) to evaluate contributing risk factors, including family history, menstrual cycle and oral contraception with lower limb injuries in female athletes.

Method: One hundred and thirty-five female athletes aged 14-31 years with no significant lower limb injury at the time of testing volunteered to participate in this study. All participants were engaged in team sports, including rugby union (n=47), football (n=72), and netball (n=16) at Academy, University, or National level. Baseline screening tests were conducted prior to the competitive season and assessed isometric hip and groin, eccentric hamstring strength, and single leg jumping. Demographic data, life-event stress, and injury history were collected. Participants were followed prospectively for 12 months.

Results: In total, 109 players provided one-year follow-up injury data. Of them, 44 athletes suffered at least one injury, and 60% of them were noncontact. Negative life events were positively associated with lower limb injuries (p=0.027). Weak hip adductor strength (OR: 0.88; 95%CI: 0.78-0.98; p=0.017), and between-limb adductor (OR: 5.65; 95%CI: 1.61-19.7; p=0.007) and abductor (OR: 1.95; 95%CI: 1.03-3.71; p=0.039) strength imbalances, were associated with risk of future non-contact lower limb injury. Previous ankle injury (RR: 1.80; 95%CI: 1.16-2.81; p=0.033) and oral contraception use were associated with the subsequent lower limb injury (RR: 0.51; 95%CI: 0.27-0.98; p=0.032).

Conclusion: Negative life events, and hip adductor strength and imbalance play an important role in female players who sustain a lower limb injury. These findings may inform how female athletes are cared for and managed through athlete screening, monitoring and physical preparation targeted at reducing non-contact injuries.

3.2 Introduction

Women's participation in sport has not followed a linear path; and gender equality has been a ranging battle for some considerable time. Male athletes have dominated scholarship awards, sponsorship deals and salaries. However, since the introduction of parity legislation (Title IX of the Educational Assistance Act) in 1972, more women began to compete in collegiate athletics (Hepler, 2013). Consequently, in high school, the number of female athletes has increased from just 295,000 in 1972 to more than 3 million in 2019 (National Federation of State High School Associations, 2018-19). In addition to the presence of women taking part in sports, the number of women who play sport at a highly competitive (national teams, Olympic games) level has increased as well. For example, in the Montreal Olympic games (1976), the percentage of women amongst the total athletes was 21%, whereas in Rio 2016, it was 45% (Nunes, 2019).

However, the increased participation of women in competitive sports has brought about the prevalence of sport-related injuries and pathologies that are different to male athletes. Although sports injury rates for both male and female athletes are similar, female athletes have a higher propensity for certain injuries than males.

3.2.1 Injury definition

Defining and classifying injuries is of high importance for the accurate description of injury patterns in a sport. The variation of definitions for reporting injury has been an issue for both researchers and practitioners as it can cause substantial discrepancies in the results and conclusions from sports injuries surveillance. The appropriate injury definition facilitates a balance between reporting reliability and correct representation of injury risk. Therefore, a consensus statement on the definition of injury and data collection procedures in different sports such as football, rugby, tennis, athletics has been developed (Fuller et al., 2006; Fuller et al., 2007; Pluim et al., 2009; Timpka et al., 2014).

For example, in football an injury is defined as: ''Any physical complaint sustained by a player that results from a football match or football training, irrespective of the need for medical attention or time loss from football activities. An injury that results in a player receiving medical attention is referred to as a ''medical attention injury", and an injury that results in a player being unable to take a full part in future football training or match play as a ''time loss'' injury'' (Fuller et al., 2006).

Injuries can also be classified according to its onset such as acute or overuse or to the mechanism by which it occurs. An acute injury is referred to as an injury resulting from a specific, identifiable event, whereas as an overuse injury is defined as an injury caused by repetitive microtrauma, without a single identifiable event (Fuller et al., 2006). Injuries are also classified as contact and noncontact. Contact is defined as an injury which occurs with another player or other object whereas as noncontact is defined as one occurring with no bodily contact with another player (Fuller et al., 2006; Waldén et al., 2015). Injuries are also classified by location, type, body side, and whether the injury was a recurrence (Fuller et al., 2006).

3.2.2 Sex differences in sports-related injuries

Sports-related injuries are commonly observed in athlete populations, with the most common occurring in the lower extremities (Powell and Barber-Foss, 1999). Injuries to the lower extremities occur due to a dynamic interaction of multiple risk factors. Specifically, it has been reported that the prevalence for injury in the lower extremity area was found to be 59.9%, whereas for the upper extremity it was 20.8% (Powell and Barber-Foss, 1999); however, this is differentiated by sport.

Evidence suggests that the prevalence of certain injuries can be linked to the sex of the athletes. Specifically, females have more acute ligament injuries (44% vs 33%), while male athletes more muscle injuries (44% vs 31%) (Ristolainen et al., 2009). Specifically, male athletes had a greater injury rate in the posterior thigh compared to female (RR 5.8, 95% CI 1.3-26.4, $p<0.05$) (Ristolainen et al., 2009; Larruskain et al., 2018). In particular, hamstring strains were found to be the major cause of absence in men (Larruskain et al., 2018), and exhibited a higher frequency of recurrent hamstring strains compared with women (20% vs 10%) (Cross et al., 2013). Similarly, groin pain is more common in men than in women (12.8% vs 6.9%) (Waldén et al., 2015). Male athletes have showed higher velocities in sprinting and change of direction which is associated with greater stress and loading, and this could explain the higher rates of hamstring strains and groin pain in male athletes compared to female (Korhonen, Mero and Suominen, 2003; Sheerin, Besier and Reid, 2018; Freitas et al., 2019).

In relation to lower extremity joints, both male and female athletes have reported a high incidence of knee and ankle injuries, however, female athletes have more major knee injuries, more severe, and which require surgical intervention such as in ACL ruptures (Stergioulas et al., 2007; Iwamoto et al., 2008; Ingram et al., 2008; Ristolainen et al., 2009; Ito et al., 2015; Larruskain et al., 2018). Specifically, in a study by Ristolainen and colleagues (2009), six ACL injuries were identified where five of them were occurred in female athletes. The ACL injury prevalence rates do vary across sports; however, female athletes compared to male athletes, often have more ACL injuries in basketball (24.4% vs 10.5%), volleyball (20.5% vs 4.5%), or skiing (41.4% vs 26.5%). In general, female athletes are two times more likely to require surgery for knee injuries than males and were more likely to sustain knee injuries that prohibited participation for more than 3 weeks (Ingram et al., 2008).

Regarding injury mechanisms, female athletes are twice as likely to have knee injuries via noncontact mechanisms compared to males, especially in soccer players (Ingram et al., 2008). Similar sex biases in injury mechanisms have been observed for the ankle, where women were injured 1.2 times more often than men through acute noncontact mechanisms, and almost two times more likely than men to have a recurrent injury (Tummala et al., 2018). Female athletes are more prone to certain injuries of the lower extremities such as ACL injuries which reflect underlying sex differences and contrasting playing styles. The identification of intrinsic differences could help with the development of prevention strategies.

3.2.3 Sports prevention models

The epidemiological approach to prevention is based on the assumption that pathologies/injuries do not occur at random and have causal and preventive factors that can be identified through systematic investigation (Gabriel, 2001). Although so much of the literature is focused on the athletes' injuries rehabilitation, it is also important to prevent injuries from occurring. Injury surveillance reports provide important information in understanding injury profiles, serving a theoretical base for the effective athlete prevention strategies which addresses the improvement of sports safety. Therefore, to accurately target and develop prevention strategies, it is important to understand the interaction of risk factors and the mechanism by which injuries occur.

To understand the interaction between different factors, sport injury risk management models have been proposed. Injury risk management research, referred to as the sports ''injury prevention model'' by Van Mechelen, Hlobil and Kemper (1992) presents a ''sequence prevention model'', with four step process: 1) Identification of injury problem and establishing the extent of the injury. 2) Establishing the factors and mechanisms of the injury. 3) Introduction of preventive measures. 4) Assessing the effectiveness of preventive measures by repeating step one (Van Mechelen, Hlobil and Kemper, 1992). This model has been expanded later by Finch (2006), by adding two further stages to the original van Mechelen (1992) model, to take into account the significance of the implementation process in sport settings and context and then evaluating its effectiveness.

The value of risk factor identification, especially when they are modifiable allows the medical team/staff to adjust practice in order to address the issues with the aim to reduce the injury risk (Kolt, 2013). However, injury prediction is one of the most challenging issues in sports; and therefore, a multi-factorial injury model has been suggested to understand the complex relationships between risk factors/predictors and injuries (Meeuwisse et al., 2007).

In their early work, Meeuwisse (1994) suggested a linear model of multifactorial aetiology in athletic injury that attempts to account for the interaction of both internal and external risk factors, thus permitting the assessment of multiple risk factors. Specifically, the model proposed that a predisposed athlete that is characterised by intrinsic factors (e.g., age, previous history) can become prone to injury when interacting with extrinsic risk factors (e.g., game conditions, playing equipment) (Meeuwisse, 1994).

However, Meeuwisse et al. (2007) later recognised that a linear approach does not reflect the true onset of sports injuries and that injuries tend to have a more likely non-linear behaviour pattern. This revised model suggested that there are recurrent changes in the susceptibility to sports injuries and when exposed to the primary risk factors exposed can produce adaptations within the context of sport that alter risk and affect aetiology (Meeuwisse et al., 2007; Bittencourt et al., 2016). Later, Bittencourt et al. (2016) proposed a model suggesting that units (e.g., fatigue, attention level, anxiety) of varying magnitudes of influence interact and collectively to create a web of determinants, which in turn, influence an athlete's response leading to an injury or positive adaptation (Roe et al., 2017). Therefore, identifying the risk factors is important in order to move research from isolated risk factors to injury pattern recognition, where a context-specific and dynamic injury risk management strategy can be developed.

Many studies that have attempted to determine the risk factors for sports injuries have not used the multifactorial paradigm approach. Sports injuries have multifactorial aetiology; thus, the risk factors should be examined by controlling other factors to yield a true picture of how this contributes to the injury (Meeuwisse, 1994). The univariate approach allows the identification of some risk factors; however, it limits the determination of the truly casual factors and the combination of them (Meeuwisse, 1994). Observing an association does not mean that a risk factor is the cause of injury (Meeuwisse, 1994). Although an association may exist between the two variables (risk factor and injury), this does not mean that the converse is necessarily true. The suggested model by the Meeuwisse (1994) can help in the accomplishment of the multifactorial causation assessment by distinguishing the relative contribution of each risk factor, and then the proper analysis of the interrelationship between multiple risk factors can be assessed.

3.2.4 ACL injury

Anterior cruciate ligament (ACL) rupture accounts for 21% of all knee injuries affecting athletes both in the short and long term. Females athletes have a 2-3 times higher incidence of sustaining an ACL injury than do male athletes (Arendt and Dick, 1995; Myklebust et al., 1998; Prodromos et al., 2007; Waldén et al., 2011a, b). However, women have not only a higher likelihood of ACL injury, but also a greater risk of ACL reinjury and suffer secondary injury if they return to play. In addition, while it has been demonstrated that female athletes are four times more likely to suffer an ACL reinjury they are six times more likely to suffer a contralateral injury than male counterparts (Paterno et al., 2012).

It is estimated that around 70% to 84% of ACL injuries are as a result of noncontact events, such as landing from a jump, forceful deceleration, cutting, or pivoting over a planted foot (Boden et al., 2000; Krosshaug et al., 2007; Steffen et al., 2017). From a video analysis study, which captured 10 female and 7 male ACL-injured players and 6 female controls performing similar landing and cutting tasks, it was observed that female athletes had greater lateral trunk and knee abduction angles compared to males during ACL injury (Hewett et al., 2009). Similarly, Krosshaug and colleagues (2007) performed analyses of 39 videos of ACL injury situations and found that valgus knee collapse was a common ACL injury mechanism in female basketball players compared with that of male basketball players. These observed gender differences could explain the higher incidence rate in female athletes. Therefore, the identification of factors associated with the mechanisms that increase risk of ACL injury in female athletes will help to establish those who are at increased risk, so that an intervention can be targeted at them.

3.3 Risk Factors for lower extremity injury

Injuries to the lower extremities are common in female athletes, with high incidence rates well established in the literature. In many cases, injuries lead to a prolonged time-loss for the athlete from sport, and sometimes to career termination. Career determination after an injury is more common in female than male athletes (Ristolainen et al., 2012). Therefore, an understanding of the multifactorial risk factors of injury is important and will help to develop effective prevention strategies for female athletes.

Risk factors can be divided into two categories, modifiable and non-modifiable. Modifiable risk factors are those that can be altered and are the focus of prevention strategies that aim to reduce injury rates. These included; muscle strength, flexibility, playing time, playing surface, warm-up, balance, equipment, and fitness level (Caine, Maffulli and Caine, 2008). Non-modifiable risk factors cannot be altered (Caine, Maffulli and Caine, 2008) and include race, age, previous injuries, muscle composition; while modifiable include lack of muscle flexibility, fatigue, strength imbalance, and insufficient warm–up (Liu et al., 2012).

Previous injury

Several studies have reported previous injury as a major risk factor for future injury secondary to changes along the kinematic chain, i.e., proprioceptive deficits, excessive flexibility. There is strong evidence indicating that athletes with previously sustained ACL injuries were more likely to reinjure in female athletes compared to those with no history of ACL injury (Faude et al., 2006; Paterno et al., 2014; Steffen et al., 2016; Krosshaug et al., 2016; Steffen et al., 2017). The two studies by Steffen and associates reported a 3.14 and 2.86-fold increased risk of sustaining a new injury compared to those who had no history of ACL injury (Steffen et al., 2016; Steffen et al., 2017). Paterno et al. (2014)

reported the risk for ACL reinjury as being over four times for those with a history of ACL; Faude et al. (2006), more than five times; while Krosshaug et al. (2016) found that the relative risk of sustaining a new ACL injury with previous ACL history was 3.8. Similar findings for risk were demonstrated by a recent cohort study, where female soccer players with a history of knee injury within the previous year had an increased risk of injury to the lower leg or foot by more than 3-fold (Nilstad et al., 2014).

Reinjury was proposed to be associated with deficits in neuromuscular factors that may affect movement mechanics (Dargel et al., 2007). Following injury, alterations occur in strength, proprioception, and kinematics, which may lead to compensatory movement patterns, long-term maladaptations and re-injury (Lepley and Kuenze, 2018).

Strength deficits between injured and uninjured lower limbs as well as imbalances between muscle groups have been well documented in previous hamstring strain, ACL rupture, and Achilles tendon rupture in male athletes (O'Sullivan et al., 2008; Gajhede-Knudsen et al., 2013; Norouzi et al., 2019; Messer et al., 2020), however, data for female athletes in this regard is limited and further exploration is required as to whether lower limb injuries are associated with subsequent injuries.

Muscle strength

A theoretical framework of the association between muscle dysfunction and lower limb injury has been suggested with limited scientific evidence in female athletes. Specifically, in female athletes, lower limb muscle strength has been associated with certain injuries such as ACL, and patellofemoral pain syndrome. Investigations assessing a range of strength measures have been conducted but with contradictory findings. Shimozaki et al. (2018) evaluated hip abduction muscle strength using a handheld dynamometer, and the hamstring to quadriceps (H/Q) ratio using an isokinetic dynamometer and found that female basketball players who sustained an ACL injury had greater hip abductor strength than the control group. Authors suggested that it may be possible that the athletes with greater hip abductor strength may try to counterbalance it and be predisposed to hip adduction, contributing to a knee valgus motion and ACL injury. In contrast, Khayambashi and colleagues (2014) tested hip strength (external rotation and abduction) in male and female athletes using a handheld dynamometer and demonstrated that hip abductor and external rotation strengths are independent risk factors for ACL injuries. Weak hip abductors can predispose the individual to a greater hip adduction and internal rotation, causing increased knee valgus motion and ACL injuries. In contrast, Steffen et al. (2016) measured the peak concentric isokinetic quadriceps and hamstring torques (60°·s^{-1}), hamstring-to-quadriceps ratio, and isometric hip abduction strength using handheld dynamometer in female handball and football players and found no association between lower extremity strength and ACL injury.

Nevertheless, the prospective studies by Khayambashi and colleagues (2014) and Steffen et al. (2016) collected injury data based on participants' interviews at the end of the season, which may cause recall bias and potential misclassification of the mechanism of injury. Additionally, studies (Khayamashi et al., 2014; Steffen et al., 2016; Shimozaki et al., 2018) used a hand-held dynamometer to measure the strength of hip abductors. Hand-held dynamometry (HHD) is a reliable way of strength measurement; however, the reliability is questioned when testers are of different sex, and strength, especially when performed on strong individuals, such as athletes (Kelln et al., 2008; Thorborg et al., 2014). Finally, Shimozaki and colleagues (2018) measured the strength of the teenager athletes only at the time of high school admission, and assessments of changes in lower limb muscle strength were not performed during the 3-year period after admission.

ACL injuries and strength of the muscles that cross both knee and hip have also been investigated. Myer and colleagues (2009) measured the isokinetic (concentric) knee extension/flexion strength (300 degrees/s) and found no association between lower extremity strength and ACL injury in female soccer and basketball players. However, trunk strength has been suggested as a risk factor for ACL injuries by some (Raschner et al., 2012). Specifically, in a 10-year retrospective study, it was found that uninjured ski racers had greater trunk flexion strength compared to those who had previously sustained an ACL injury (Raschner et al., 2012). During sporting activities, adequate trunk musculature along with neuromuscular control is required to maintain lower limb dynamic joint stability (Zazulak, Cholewicki and Reeves, 2008). In case of a control deficit, the lower limb is predisposed to uncontrolled displacements, and excessive loading which can cause mechanical failure (Zazulak, Cholewicki and Reeves, 2008; Wilkerson, Giles and Seibel, 2012). However, in the Raschner et al. (2012) study, even though the athletes underwent testing more than once throughout the 10-year period, only one set of strength data was included in the study and they failed to report any change in strength, which may affect the risk of sustaining injury.

Vacek et al. (2016) reported that increased trunk flexion strength was linked to ACL injury in female athletes. However, the findings are limited since they obtained the risk factor measures (e.g., strength) after the injury had occurred and considered the uninjured leg representative of the injured limb before injury (Vacek et al., 2016).

Hip muscle strength has been also associated with patellofemoral pain syndrome in female athletes (Herbst et al., 2015). Specifically, adolescent female basketball players were tested for isokinetic strength of the knee (flexion and extension) and hip (abduction), and found that greater hip abduction strength was associated with increased risk of PFP (Herbst et al., 2015). Hip muscles control pelvic stability and leg alignment, and therefore, in the absence of sufficient hip strength (hip abductors and external rotators), there may be excessive femoral internal rotation, hip adduction movements, increasing knee valgus motion during sports activities, which may alter patellofemoral tracking and increase lateral patellar-contact pressure (Cichanowski et al., 2007).

In contrast, no association was found with lower limb injuries in a study that measured isokinetic muscle strength for quadriceps and hamstring muscles of female soccer players (Östenberg and Roos, 2000). However, absence of an association does not mean that lower limb muscle strength isn't associated with lower limb injuries, but rather that certain strength deficits tend to be correlated with specific injuries such as patellofemoral pain syndrome.

Physical function, such as dynamic balance and agility, that involve quick changes of body weight from one leg to the other in order to progress the body in any direction, require control, which is provided by the hip abductors and adductor muscles (Francis et al., 2018; Inacio et al., 2018; Lanza et al., 2021). Hip abductor muscles perform an important role in stabilizing the trunk and pelvis, as they maintain lower limb alignment through sports activities (Ireland et al., 2003; Francis, Gray and Perrem, 2018). The hip abductors have the ability concentrically to abduct the hip, isometrically to stabilise the pelvis and eccentrically to control hip adduction and internal rotation (Dostal, Soderberg and Andrews, 1986). Hip abductors reduce accelerations of the centre of mass in both the sagittal and frontal plane in response to postural perturbation (Francis, Gray and Perrem, 2018). Therefore, hip abductor weakness is responsible for poor lower extremity control which can lead to knee valgus which occurs as a consequence of coupled hip adduction and internal rotation (Powers, 2010). This greater knee valgus during dynamic tasks has been reported in those female athletes with ACL injuries and patellofemoral pain (Ireland et al., 2003; Power, 2010).

Activation of the hip adductors occurs not only in hip adduction, but has secondary joint actions on hip rotation, flexion or extension depending on initial joint position (Levangie and Norkin, 2011; Leighton, 2006; Hrysomallis, 2009; Chaudhari et al., 2014). So, when the hip is flexed, the adductor muscles are mechanically prepared to augment the other extensor muscles, and when the hip is closer to full extension, they are mechanically prepared to augment the other hip flexors (Neumann, 2010).

In addition to providing movement, the hip adductors may generate significant tension while stabilizing the hip and controlling the alignment of the lower limb (Chaudhari et al., 2014). A decrease in adductors strength may obstruct the ability to eccentrically control sudden, powerful over-stretching of the adductors during lateral stride manoeuvres involving abduction and external rotation. This may lead to adductor muscle strains in sports that include movements such as side-to-side cutting, striding, sudden change of direction and quick acceleration and deceleration (Tyler et al., 2001; Engebretsen et al., 2010).

The hamstrings are important for these sporting activities that involve sprints, jumps, tackles, cutting manoeuvres and kicking and are prone to injuries during high-velocity running due to eccentric over-loading at the end of the swing phase (Jönhagen et al., 1994; Ekstrand et al., 2012). It has been shown that in male rugby players the between-limb imbalance in eccentric knee flexor strength of ≥15% and ≥20% increased the risk of hamstring injury by 2.4-fold (95% CI, 1.1-5.5; p=0.033) and 3.4-fold (95% CI, 1.5-7.6; p=0.003), respectively (Bourne et al., 2015).

Strength imbalances (approximately 10-15%) between limbs feature commonly in players of different sports where they are exposed to high volumes of practising and competition, and where there is a preferred limb dominance (e.g. soccer, tennis) (Vagenas and Hoshizaki, 1991; Fousekis, Tsepis and Vagenas, 2010). Research studies have established that between limb asymmetry beyond that of typical values is a potential risk factor for injury, as it has been hypothesized that the strength asymmetry is a characteristic of poor control of body movements, adding load on soft tissue structures; however, studies in female athletes are limited (Knapik et al., 1991; Rahnama, Lees and Bambaecichi, 2007; Grygorowicz et al., 2010).Conclusive evidence for muscular strength as risk factor for ACL injury was not found, whereas evidence for patellofemoral pain syndrome is limited. Therefore, more studies are required to investigate the association between lower limb strength and injuries in female athletes and whether an asymmetry between-limb imbalance affects the development of lower limb injuries using reliable testing methods. Additionally, it seems that injuries in female athletes likely has a multifactorial aetiology, such as ligament laxity, hormonal, and potentially psychological parameters; and therefore, it is plausible that contributing and confounding variables should be also controlled.

Menstrual cycle, hormones, and laxity

The menstrual cycle is controlled by the pituitary-hypothalamic-ovarian axis and involves the complex interaction of hormones (estrogen, progesterone, relaxin and testosterone). The typical menstrual cycle is 28 days long, beginning with the follicular phase where estrogen levels starts rise, followed by the ovulatory phase where estrogen continues to prevail and reaches its peak, and ends with the luteal phase where secretion of progesterone extending that of estrogen levels (Zazulak et al., 2006; Belanger et al., 2013). Relaxin is reaching its peak during the luteal phase, whereas testosterone fluctuates throughout the cycle (Wreje et al., 1995; Nóbrega et al., 2009).

Menstrual cycle phases have been referenced to affect knee laxity, increasing the risk for ACL injury. Specifically, it has been demonstrated that knee laxity and anterior knee displacement are increased during the ovulation (estrogen levels high) and luteal (progesterone levels high) menstrual phases (Heitz et al., 1999; Hicks-Little et al., 2007). Hicks-Little et al. (2007) measured the anterior tibial displacement (mm) measurements by using a KT1000 knee arthrometer on three different menstrual phases in female student athletes found significant increases in anterior displacement are shown during the ovulation and luteal phases of the menstrual cycle suggesting that during these phases the risk for an ACL injury is increased (Hicks-Little et al., 2007). Similarly, Heitz et al. (1999) study found greater ACL laxity during luteal phase compared to the menstruation phase.

Dragoo et al. (2011) found that females who had sustained an ACL injury had higher serum relaxin concentration compared to those without an ACL injury during the mid-luteal phase. Long term exposure to high levels of serum relaxin may compromise the structural integrity of the female ACL. More specific, serum relaxin concentration raises the activation of the relaxin receptors on the ACL over time, which reduces the ACL integrity and increases the risk for a potential rupture (Dragoo et al., 2003). Besides the relaxin receptors, it has been demonstrated that human ACL cells have both estrogen and progesterone receptor sites (Liu et al., 1996; Dragoo et al., 2003). It is likely that sex hormones have an effect on ACL structure and composition, and this could explain why females are more prone to ACL injuries (Liu et al., 1996). This has generated further speculation that compounds such as oral contraceptives, which change relaxin, estrogen, and progesterone levels, may also influence ACL injuries. A recent systematic review suggests that the use of oral contraception decreases the risk for ACL injury; however, the quality of evidence was very low, and conclusions were not completed (Konopka, Hsue and Dragoo, 2019).

Finally, an association between menstrual cycle irregularity and injury has been reported. Specifically, it was found that high school athletes with irregular menstrual cycles sustained a higher percentage of severe injuries (missing ≥22 days of practice or competition) than those who reported normal menses (Thein-Nissenbaum et al., 2012). It should be noted that menstrual cycles tend to be more irregular in young teenage women during the first few years after menarche (De Sanctis et al., 2014). A higher prevalence of irregular menstrual cycle, as well as lower hormone levels in female athletes compared to the non-athletic population are concerning because of their negative consequences, including the association with the female athlete triad (Nichols et al., 2008; Genç et al., 2019). The female athlete triad is defined as the interrelatedness of energy availability, menstrual function, and bone mineral density (BMD) (Otis, Drinkwater and Johnson, 1997). Sex hormones have been shown to impact ACL injury risk. However, given the lack of research in female athletes and of consensus on the phase at which laxity is affected and musculoskeletal injury occurs, more studies are required particularly concerning adult athletes where the menstruation cycle is regularized.

Family ACL injury history

Familial disposition to ACL injuries has been suggested as a risk factor in female soccer players. Specifically, it has demonstrated that female youth soccer players who had a parent and/or sibling with previous ACL injury had an almost 4-fold increased ACL injury rate, and almost 2-fold higher rate of acute knee injury overall (Hägglund et al., 2016). This supports prior work in the non-athletic population where there was a high probability of familial predisposition to many of the identified risk factors for ACL injury (Harner et al., 1994; Flynn et al., 2005). Flynn and colleagues (2005) showed that participants with an ACL injury had almost greater than twice the likelihood to have a first-degree relative with an ACL injury compared to participants without injury; whereas Harner and colleagues (1994) demonstrated that the incidence rate of ACL injury in a family member of the ACL-injured group was 35% compare to the control group which was 4%.

The significantly higher incidence of ACL injuries in the family of the injured group further indicates a possible congenital predisposition to ACL injury. It may be possible that anatomical or genetic factors may contribute to this increased ACL injury risk (Hägglund et al., 2016). However, although female athletes are more prone to ACL injuries, evidence is limited in this population, and therefore, more work should be done.

Genetics

The concept of familial predisposition towards ACL injury has led researchers to investigate genetic factors. Specific genes related to collagen with different polymorphism have been associated with ACL tears (Posthumus et al., 2009; Posthumus et al., 2010; John et al., 2016). Specifically, it found polymorphisms in COL5A1 and COL12A1 genes in females with ACL rupture compared to the control groups. The COL5A1 gene encodes for the α1 chain in type V collagen, which makes up around 10% of the collagen content in ligaments while COL12A1 gene encodes the α1 chains of type XII collagen and is predominantly expressed in ligaments in response to mechanical loading (Posthumus et al., 2009; Posthumus et al., 2010). However, the same polymorphisms were not identified in males, which further reinforce the possibility that these polymorphisms may predispose only females to ACL ruptures.

Gender differences in the expression of three genes (ACAN, FMOD, and WISP2) related with structure and integrity of ligaments have been found suggesting that the ACL matrix composition and integrity may differ according to sex and female ACL tissues structurally are weaker than males (Johnson et al., 2015). Although some data have been generated regarding different polymorphisms and gene expressions, more genetic studies are needed in these specified areas to clearly understand the mechanisms of these polymorphisms with ACL rupture.

Notch Width

Bone morphology of the knee joint and ACL injury risk has received significant attention in the literature. The intercondylar notch, or intercondylar fossa, is the area of the posteroinferior aspect of the distal femur between lateral and medial condyles (Hirtler, Röhrich and Kainberger, 2016). Within it are located the knee ligaments, anterior cruciate ligament (ACL), posterior cruciate ligament (PCL), and the meniscofemoral ligaments (Hirtler, Röhrich and Kainberger, 2016). A relation between stenosis of the intercondylar notch and ACL injuries has been found in athletes. Miljko et al. (2012) found injured handball players had higher inner angle of the lateral femoral condyle in the axial plane and narrower intercondylar notch width. Similarly, Souryal and Freeman, (1993) found that the female athletes with ACL injuries had narrower intercondylar notch than non-injured. Whitney et al. (2014) reported that the risk for ACL injury is increased in females with a decreased femoral notch size.

The mechanism to explain why a small femoral notch predisposes the ligament to greater injury risk remains unclear. It may result in less robust structural properties, alternatively, it may produce a bony impingement against the small ACL, which predisposes the ligament to a higher risk of rupture (Simon et al., 2010). A small femoral notch may also be linked to familial predisposition to ACL. When the siblings of ACL injured participants were evaluated and compared with the control group, the siblings of ACL injured participants all exhibited significantly narrower notches than their counterparts and this could partly explain the familial predisposition of ACL injuries (Keays, Keays and Newcombe, 2016).

Q angle

Q angle (quadriceps angle) or patellofemoral angle was described first by Brattström (1964). Q angle is formed by the intersection of two lines that cross at the center of the patella, one lines going from the anterior superior iliac spine (ASIS) to the center of the patella, and the other line is from the anterior tuberosity of the tibia to the center of the patella (Brattström 1964). A large Q angle has been suggested to pose greater risk of knee injury due to excessive lateral forces, which could affect the knee's mechanical alignment (Heiderscheit, Hamill and van Emmerik, 1999; Duffey et al., 2000). Normally, the Q angle is 13° for males and 18° for females (Magee, 2013). Any angle less than 13° may be associated with chondromalacia patella, patella alta; while an angle greater than 18° predispose to patellar subluxation (Magee, 2013; Cleland, Koppenhaver and Su, 2015).

The reported Q angle associated with knee injuries varies a lot between athletes. In a prospective cohort study that included high school cross-country runners, they found that female runners with Q angle ≥20°, and for boys Q-angle 15° to 20^0 had a higher risk of knee injury (Rauh et al., 2007). Based on that gender difference, it has been suggested that the higher Q angle alters the mechanics of the lower limb during high risk manoeuvres such as cutting and landing, placing the knee at a high risk for valgus stress and for an ACL injury (Horton and Hall, 1989; Guerra, Arnold and Gajdosik, 1994; Arendt and Dick, 1995). However, stature differences between men and women were unaccounted for, and when Q angle was adjusted for stature gender differences became trivial (Grelsamer, Dubey and Weinstein, 2005; Merchant et al., 2008). Accounting for stature may explain why four studies found no association between Q angle and ACL injuries in the female athletes (Loudon, Jenkins and Loudon, 1996; Kramer et al., 2007; Liederbach, Dilge and Rose, 2008; Miljko et al., 2012).

Shoe design and properties

Shoes offer external support, but factors other than support, including shoe-surface interaction may be linked with injuries (Murphy, Connolly and Beynnon, 2003). The shoe–surface interaction is referred to the friction force between the athlete's shoe and the surface on which athlete trains; and is defined as the force that resists the relative motion of two surfaces sliding against one another (Noyes and Barber-Westin, 2018). In a cohort study of Lambson, Barnhill and Higgins (1996) in American football players found that the cleats with an edge design produced significantly higher torsional resistance than other shoe designs and was associated with a significantly higher ACL rupture rate (Lambson, Barnhill and Higgins, 1996). Shoes can alter the fixation of an athlete's foot to the training surface, and movement alterations contributes to biomechanical changes which can lead to ACL injury (Noyes and Barber-Westin, 2018). Heidt et al. (1996) conducted a study where the shoe-surface interaction of 15 football shoes (cleat, court molded cleat shoes, turf shoes) were evaluated in both anterior translation and rotation using a specially designed pneumatic testing system and found that 73% of these athletic shoes had an "unsafe" or "probably unsafe" rating.

In basketball players, it demonstrated that players wearing shoes with air cells in the heel were 4.3 times more likely to injure an ankle than those wearing shoes without air cells suggesting that air cells may decreased rearfoot stability (McKay et al., 2001). The ideal footwear minimises rotational friction but optimises transitional friction to allow peak performance in sports movements, such as cutting and decelerating (Ekstrand and Nigg, 1989; Silvers and Mandelbaum, 2007). However, most studies have been performed in males and therefore, conclusions cannot be drawn for female athletes.

Surfaces

Playing surface has been proposed as a prominent environmental risk factor for lower limb injuries, as it can alter the grip of the athlete's feet during movement (Noyes and Barber-Westin, 2018). However, the reports are mixed. A case-control study by O'Kane and colleagues (2017) in female soccer players, found that acute lower limb injuries were approximately three times more likely to occur on grass than artificial turf (O'Kane et al., 2017).

Nevertheless, a study by Olsen et al. (2003) in male and female handball players during seven seasons between wooden and artificial floors, found that ACL injuries were more common on the artificial playing surface compared to wooden floors. In contrast, three studies reported no relationship with grass or artificial floor and ACL injuries in female athletes (Fuller et al., 2007; Meyers, 2013; Hägglund and Waldén, 2016).

Weather (climate) and temperature

Weather conditions has been suggested as a risk factor for the ACL injuries as it affects the shoe–surface interaction by two ways. The one way is the water content of the surface which depends on the amount of rainfall and evaporation and the temperature of the shoe–surface interaction which varies within seasons. Orchard and Powell (2003) found that in cold weather American footballers had lower knee and ankle injury risk for both natural grass and AstroTurf compared with hot and dry weather in open stadiums, and this is probably due to reduced shoe-surface traction. Similar findings provided by Scranton et al. (1997) where they observed that ACL injuries in Americans footballers were more frequent in dry surface conditions than the wet. Orchard et al. (2001) conducted a study in American footballers for the period 1992 to 1999 to identify risk factors that affect the development of ACL injuries. They found that dry field conditions -high water evaporation in the month before the match, and low rainfall in the year before the match increased the rate of ACL injury (Orchard et al., 2001). Authors concluded that low water evaporation and high rainfall significantly decrease the risk of ACL injuries as the ground is softening leading to lower shoe-surface traction (Orchard, Seward and McGivern, 1999) and likely to impair speed of movements. In a lab study, where five different football shoes (a flat–soled basketball style turf shoe, a natural grass soccer-style shoe, and three multistudded turf shoes) were evaluated on dry AstroTurf at five temperatures, 52°, 60°, 78°, 92°, 110°F, found that as the temperature increased, the shoe–surface friction places potentially the athlete's knee and ankle at risk of injury (Torg, Stilwell and Rogers, 1996).

Recently a study involving female ski jumpers observed that the majority of severe injuries and 69% of all acute ski jumping injuries occurred in windy and/or snowy conditions (Stenseth et al., 2020). The out-run is important for ski jumpers' landing and poor weather conditions may impair the athletes' ability to maintain stability on their skis, leading to injury. Therefore, poor weather conditions place additional task demands on athletes to stabilise when performing activities.

Psychological factors

Although models of injury risk have included psychological factors, the scientific knowledge regarding the relationship between psychological factors and injuries remains limited. In an effort to conceptualize the effect of psychological variables on injury predisposition, models that specify the psychological risk factors have been established. Among the most influential and well known is Williams and Andersen’s (1998) “stress-injury model” (Figure 2.3a), which divides psychological risk factors into three main categories: personality factors, history of stressors, and coping resources (Williams and Andersen, 1998). According to the stress-injury model, when athletes are put in a stressful situation such as a demanding practice or crucial competition, the athlete's history of stressors, personality characteristics, and coping resources contribute interactively or in isolation to the stress response determining whether injury will occur (Williams, 1996). The model also addresses potential mechanisms behind the stress-injury relationship and suggests specific interventions to diminish the likelihood of injury (Andersen and Williams, 1988).

As can been see in figure 3.3a, the stress response is at the core of the stress-injury model and is characterized by two components: cognitive appraisal and physiological/attentional changes. Their relationship is bi-directional (Andersen and Williams, 1993). For example, an athlete may experience different cognitive responses during a sporting situation, either positive (e.g., excitement) which can help them to remain focused on the task, or negative (e.g., anxiety). If the athlete perceives inadequate resources for coping with the demands of the sporting situation (and it is important to succeed), the physiological and attentional aspects of the stress response will be affected (Williams and Roepke, 1993). Similarly, such changes affect cognitive appraisal bidirectionally.

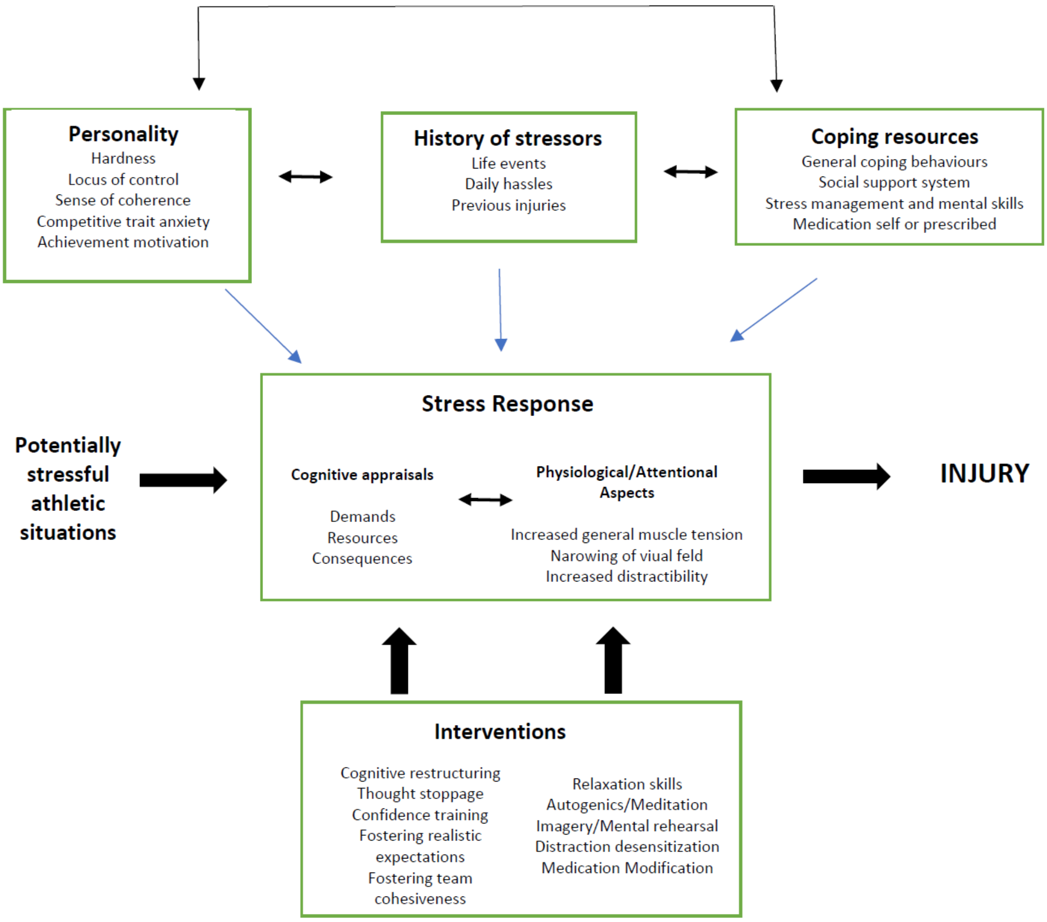


Figure. 3.3a. The stress-injury model.

According to the model, these physiological and attentional changes could increase vulnerability to injury. Specifically, it has been hypothesized that rises in generalized muscle tension, narrowing of the visual field, and increased distractibility are the primary culprits in the stress-injury relationship (Williams, 1996). These proposed mechanisms are supported by findings on athletes who experienced a high number of major stressors and showed a greater narrowing in peripheral vision when placed in a more stressful situation compared to those who had experienced low stressful events (Williams, Tonymon and Andersen, 1990; Williams, Tonymon and Andersen, 1991).

Generalized muscle tension can lead to fatigue and reduced flexibility, motor coordination difficulties and muscle inefficiency, increasing the possibility for injuries (e.g., strain, sprain etc.) (Andersen and Williams, 1988). However, attention change is the most frequently cited component in the stress-injury relationship (Bramwell et al., 1975; Cryan and Alles, 1983; Williams, Tonymon and Wadsworth, 1986). Attentional disruptions could result from concerns with stressful events that may lead to a narrowing of peripheral vision, and as a result an injury could occur by not picking it up or responding in time to important cues in the environment (Williams, 1996).

Above the stress response core of the model are three major areas, personality factors, history of stressors, and coping resources. Based on Andersen and Williams' (1988), it is hypothesized that one's stress history contributes directly to the stress response while personality factors and coping resources may act on the stress response either directly or through the effects of the history of stressors (Andersen and Williams, 1988). As reported by Williams and Andersen (1998) coping resources refer not only to coping skills but also to the quantity of received social support (Devantier, 2011).

The role of an individual's history of stressors (major life events, chronic daily problems, and previous injuries) on the stress response and injury risk have been explored by prior work. Consistently negative life event stress among athletes has been the best predictor for lower limb injury (Coddington and Troxell, 1980; Passer and Seese, 1983; Andersen and Williams, 1999; Gunnoe et al., 2001; Ivarsson et al., 2017). However, most of the studies have been concerned with adolescent athletes. Specifically, a study by Gunnoe et al. (2001) examined 331 high school football players and found that players who experienced negative life events were at greater risk of becoming injured and of sustaining multiple injuries, postulating that a player’s emotional state increases injury risk. Passer and Seese (1983) demonstrated that football players who had experienced greater negative life events incurred a significant time-loss injury than noninjured players. Coddington and Troxell (1980) found that high school football players who experienced life events such as family instability, parental divorces and deaths, were five times more likely to sustain an injury than those who didn’t experience these life events. In all of these studies only young boys were examined, and therefore, the data cannot be generalized to older female athletes in different sports. Additionally, Coddington and Troxell (1980) used the Life Event Scale for Adolescents (LES-A) to examine life events, which includes items about life events in the domains of family, school, and peer events and not regarding the participation in sports and issues that may have occurred.

Johnson and Ivarsson study (2011) demonstrated that life event stress, but also somatic trait anxiety increased the vulnerability for injury in both male and female adolescent soccer players. Similar findings were demonstrated by Andersen and Williams (1999), where they recruited adult male and female athletes from different sports and used the Life Events Survey for Collegiate Athletes (LESCA) to examine the life events. They demonstrated that the only significant predictor of injury was negative life event stress. Johnson and Ivarsson (2011) included young soccer players and, therefore, the findings cannot be generalized across older athletes or to athletes of different sports. Furthermore, both studies (Andersen and Williams, 1999; Johnson and Ivarsson, 2011) examined male and female athletes together, and did not analyse males and females separately for potential sex differences regarding the association with the injury occurrence; and thus, generalizations cannot be made, since during adolescence, gender differences become more apparent with different biological and psychological vulnerabilities, and may significantly affect the way that life events are perceived (Harkness et al., 2010).

One cohort study, among female football players (14–16 years) reported the injury risk for during a season was 70% higher with a high level of perceived life stress compared with those with a presumed low level of life stress (Steffen, Pensgaard and Bahr, 2009). A study with a wider age range (16-36) was conducted by Ivarsson, Johnson and Podlog (2013), including 56 athletes (females and males). From comparisons made between the sexes in that study, women were reported to experience more negative life events and more injuries than male athletes; however, the overall results indicated that negative-life-event stress had an indirect effect on injury occurrence through daily hassle in male and female soccer players. Nevertheless, the small sample size may be considered a limitation of this study, but the findings warrant further exploration. Overall, it is likely that negative life events are associated with injury, but also with injury severity. Specifically, in a study by Hanson, McCullagh and Tonymon (1992) where 181 athletes (123 males, 58 females) from a variety of sports were examined for life events using the athletic Life Experience Survey (ALES), they concluded that as negative life stress increased, so did the severity of injury. Greater stress leading to more severe injuries should be a concern, since more time away from sport is known to increase likelihood of future reinjury.

Beyond the stress of life events, other psychological factors have been suggested as predictors of ACL injuries among elite female athletes (Galambos, 2005). Vacek et al. (2016) investigated if personality characteristics were associated with ACL injury and found statistical significance only for the reward dependence subscale of the participants' temperament in female athletes. Individuals with reward dependence personality try hard to accomplish tasks in order to gain approval of others (Han et al., 2006). This suggests that athletes with reward dependence behaviour will tend towards overemphasis in winning, that may lead to an aggressive performance, and as a consequence to injury occurrence.

Kosaka et al. (2016) used the Diagnostic Inventory of Psychological Competitive Ability (DIPCA.3) to examine female, high school handball and basketball players and found that injured athletes had significantly higher scores in six of the psychological competitive ability scales (patience, aggressiveness, volition for self-realization, volition for winning, judgement, and cooperation) compared with the uninjured players. The high levels of competitive ability and associated ACL injures found by Kosaka et al. (2016) were suggested to be related to the athletes' perfectionistic tendencies, leading to excessive forces and injuries. The link to injury may be explained since perfectionist athletes would train harder and for longer periods than the non-perfectionist athletes, thereby increasing the risk for injury through exposure to prolong periods of repetition. Nevertheless, since evidence is limited, further studies are needed to draw firm conclusions.

Despite a growing recognition over recent years that the sport injury process is multifaceted, research that has explored a combination of psychological, historical and physical fitness risk factors in female footballers has been notably sparse. This is particularly surprising given the wide-ranging health, social and economic benefits afforded to participation in football (e.g., improved life satisfaction, overall reduction in mortality and morbidity), the threat injury poses to these, and the increased incidence of sport-related injuries reported globally (Leppänen et al., 2014). More studies in adult female athletes that evaluate the influence of psychological factors on the risk of sports injuries are needed for improving prevention programs and reducing the occurrence rate of injuries.

3.4 Rationale

Female competition in sports is rapidly growing at all levels worldwide; especially, after the enactment of the Title IX Education Amendment in 1972. However, sports, is accompanied by an increased risk of lower limb injuries, including subsequent short- and long-term consequences. Sex differences in injuries rates may propose potential sex differences in risk factors that contribute to this increased risk of certain injuries in female athletes. To successfully developing effective injury risk management strategies, it is essential the identification of the contributing multifactorial risk factors.

The role of lower extremity strength, as a modifiable risk factor to effectively stabilize joints and protect from injuries and pathologies has been suggested. However, while the relationship between lower limb force production and injuries has been studied in male athletes, the influence of strength in lower limb injuries in female athletes remains unknown.

Given the importance of the function of hip adductors and abductors and knee flexors during sporting activity, it is feasible that the reduced unilateral strength drive increased strength asymmetry that results in further altered movement patterns, leading to a predisposition of lower limb injuries such as ACL, hamstring injuries, patellofemoral pain, groin injury. However, studies explored the association between isometric hip adductor and abductor strength and prospectively occurring lower limb injury in female athletes are very limited.

Imbalances may exist in athletes due to previous injury, pain and incomplete recovery (Rahnama, Lees and Bambaecichi, 2005; Schiltz et al., 2009; Castanharo et al., 2011; Fulton et al., 2014; Fort-Vanmeerhaeghe et al., 2016). Prior work has been shown that professional male football players with prior history of hamstring injury present between-limb strength asymmetry >10% (Ribeiro-Alvarez et al., 2020; Vicens-Bordas et al., 2020). Similarly, in female soccer players, where lower limb strength was significantly different in those with and without ACLR. Specifically, players with a history of ACLR displayed between-leg asymmetry in eccentric knee flexor strength, isometric hip abductor strength while KOOS pain score was lower compared to those with no history of injury (Collings et al., 2021).The majority of strength and conditioning training programmes may help athletes, but it seems that this is not enough to reduce injury rates. Although, it is well established that stressors are related to athletes' performance, however, the focus has been targeted to physiological and biomechanical parameters when investigating risk factors for sports injuries; whereas most studies describing risk factors in female athletes have almost exclusively focused on ACL injury.

Thus, the purposes of this prospective cohort study were: 1) to assess the association between functional lower extremity muscle strength and the risk for lower limb injuries; 2) to investigate the potential relationship between life events and lower limb injuries; and 3) to evaluate contributing risk factors, including family history, menstrual cycle and oral contraception with lower limb injuries in female athletes. Accordingly, the following research questions were addressed in female team-sport athletes:

1. Is there an association between functional lower extremity muscle strength and risk for lower limb injury?
2. Do negative life events increase the risk of lower limb injury?
3. Is family ACL history, menstrual cycle regularity and oral contraception associated with lower limb injury?

3.5 Method

3.5.1 Participants

One hundred and thirty-five female athletes aged 14-31 years with no significant lower limb injury (i.e., no injury that resulted in greater than six weeks of convalesces until return to given sport) in the previous six months at the time of data collection volunteered to participate in this study. All participants were engaged in team sports, including rugby union (n=47), football (n=72), and netball (n=16) at Academy, University, or National level. Participants were excluded if they were: injured (upper or lower limb); and experienced any pain at the time of inclusion precluding them from performing the test protocol. In addition, those participants who did not complete all three strength tests (i.e., missing data points) were excluded from the final analyses.

3.5.2 Procedure

The study was approved by the University of South Wales research ethics committee (approval number: 201708MW01). Prior to commencing data collection, permission from an appropriate member of management who had the authority was obtained to contact the team to invite them to consider volunteering for the study. Once permission to approach potential participants had been obtained in writing, teams' physiotherapists or graduate sport therapists were contacted and invited to participate to the current study providing the information sheet. Consent, assent and parental consent forms (Appendix 2) were supplied via email in advance of the visits to the teams were arranged. Players under the age of 18 years were invited to take part in the study and written parental informed consent and child assent were obtained. Data collection was conducted at the training venue of the team/squad at the start of the pre-season between July and August 2018 (Figure 3.5.2a outlines the study design, and 3.5.2b shows the study groups). On the day of testing, consent, assent and parental consent forms were collected, and two questionnaires were provided to the participants: 1) the injury and menstrual history questionnaire, and 2) life events survey for collegiate athletes (LESCA) questionnaire (Petrie, 1992). Both questionnaires can be found in Appendix 2. On completion of the questionnaires, body mass, using a digital scale (Seca 813) and stature using portable stadiometer (Seca 213) were measured; athletes were then assessed using a suite of field-based tests for isometric hip adductor and abductor strength, eccentric Nordic hamstring exercise (NHE) strength and a single leg jump task.

Participants were followed prospectively for 12 months. The team's physiotherapist or graduate sport therapist were responsible for the collection and recording of injury data. All injury data were entered in the institution athletes' injury management database by the team physiotherapist at the time of injury. Clinical notes made by the physiotherapists at the time of injury were also available from the two institutions to better confirm injury details. Two out of the three institutions provided the following injury history data for each athlete: injury location, diagnosis, injury mechanism and what rehabilitation was carried out. The third institution only provided data for type of injury for each athlete: ACL, hamstring or other lower limb injury, with the injury mechanism.

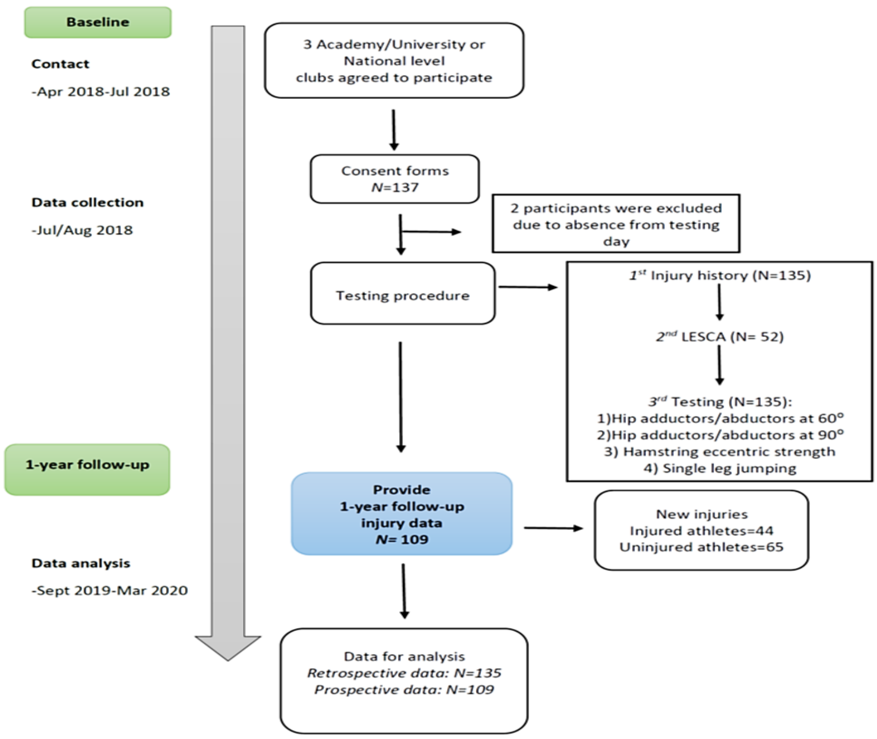


Figure 3.5.2a. Flowchart of the study procedure.

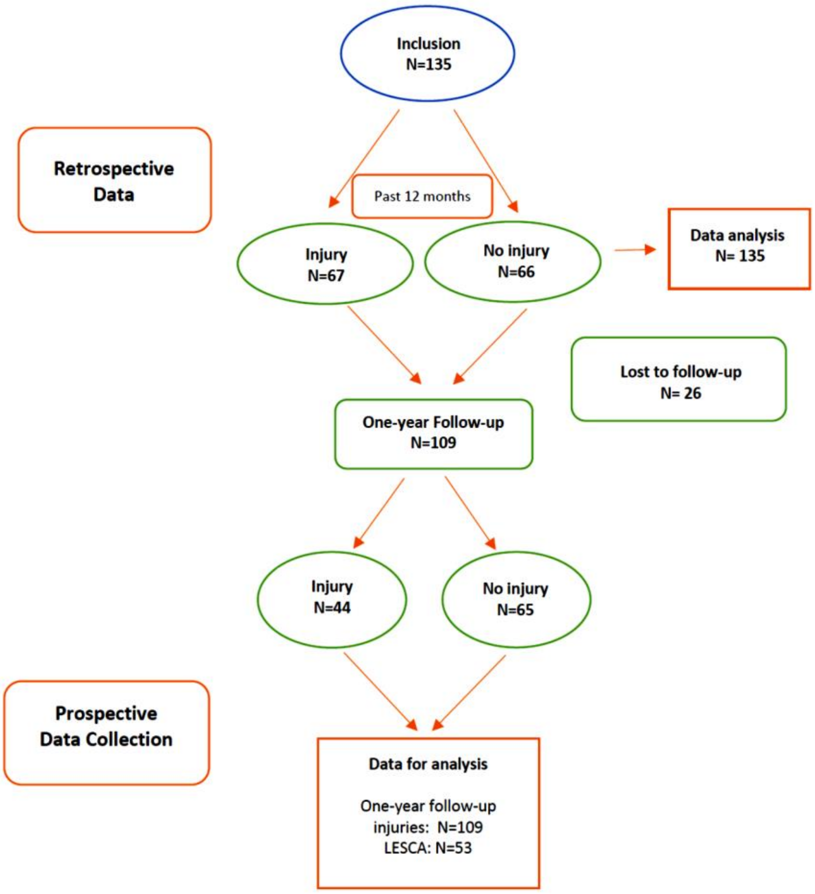


Figure 3.5.2b: Study flowchart showing the groups of participants in retrospective and one-year follow-up.

3.5.3 Questionnaires

Injury and menstrual history questionnaire

The injury and menstrual history questionnaire consisted of four parts that were asking the following:

1) Participant and sport characteristics (e.g., age, preferred leg, years of playing experience)

2) Family ACL history (whether a family member had an ACL injury)

3) Participant’s injury history (previous injury in the last 12 months, location, diagnosis, treatment, contact/no contact injury, surface that occurred, and time loss)
4) Menstrual and oral contraception history (age of menarche, menstrual cycle regularity, and duration and oral contraception use).

Life events survey for collegiate athletes

The Life Events Survey for Collegiate Athletes (LESCA) questionnaire was used to measure the athlete’s general and specific life event stress (Petrie, 1992). The questionnaire has been validated and shown to be reliable. Construct and criterion related validity has been previously demonstrated by correlations between the negative ($r=0.55$; $p<0.001$) and positive life-stress scores ($r=0.22$; $p<0.05$) and the SARRS (Petrie, 1993). In addition, a 1-week test-retest correlation of the LESCA has been reported to range from 0.76 to 0.84 (Petrie, 1992).

The LESCA questionnaire was provided only to participants who were over 18 years old. It includes items not suitable for children, such as: death of a close family member or friend; breaking up with partner; marriage; failing an important exam or course; not attaining personal goals in sport; receiving scholarship; and being dropped from the team. A suitable validated alternate was unavailable and censoring the inappropriate questions would render the questionnaire invalid. The questionnaire comprises a list of 69 items that reflect possible life events that participants may have experienced. Participants were asked to indicate those events they had experienced in the previous 12 months. For each event, the participant rated the experience of the stressors, on an 8-point Likert scale, with the range -4 (“extremely negative”) to +4 (extremely positive). The LESCA was calculated via two outcomes, positive and the negative life events. The positive score was derived from the sum of all positive responses, and the negative score was derived from the sum of all negative responses as suggested by Petrie (1992).

3.5.4 Strength Measures

Isometric hip adductor and abductor strength

Hip and groin adduction and abduction strength was assessed by using a prototype GroinBar Hip Strength Testing System (Vald Performance, Queensland, Australia). The GroinBar has been designed to enable measurement of adductor and abductor muscles strength of both limbs simultaneously, to enhance measure standardization, and to reduce the variability related to examiner strength and testing technique (Desmyttere, Gaudet and Begon, 2019). It comprises an adjustable rig fitted with four independent and adjustable custom-made uniaxial load cells and can estimate the force ratios between agonist and antagonist muscle groups around the hip joint, as well as asymmetries between both limbs (Engebretsen et al., 2010; Desmyttere, Gaudet and Begon, 2019; O'Brien et al., 2019).

In a recent study by Ryan et al. (2019) the reliability of a GroinBar to measure adductor strength in professional Australian footballers was investigated. It was reported that GroinBar has greater reliability (ICC=0.94) compared to a HHD or a sphygmomanometer (ICC=0.70 and 0.90 respectively) concluding that the GroinBar possessed greater precision when assessing adductor strength, allowing practitioners to interpret real changes in strength confidently, compared to the other methods (Malliaras et al., 2009; Buchheit et al., 2017; Ryan et al., 2019). Furthermore, greater precision and reliability due to standardisation of the test, knees in a 60° position, allows for comparisons of subjects regardless of within-subject limb length differences (Ryan et al., 2019). The advantage of the fixed frame rather than the HHD is reduced reliance on the skill and strength of the tester when using HHD (Kemp et al., 2013).

Hip adduction (ADD) and abduction (ABD) isometric strength were evaluated at two test positions: 60^o and 90^o. As shown in Figure 3.5.4a, the 60^o position involved both the hip and knee positioned at approximately 60^{o} and feet placed flat on the floor. The 90^{o} position, involved both the hip and knee at approximately 90^{o} so that the shin was parallel to the ground and feet held in the air (Figure 3.5.4a).

The two positions were chosen due to the different activation of hip adductor muscles. At the 90° position the focus of testing is: pectineus and adductor brevis, whereas at the 60° position is associated with greatest activation of adductor longus.

Musculoskeletal geometry affects the activation of the muscles' activation and could explain the functional differentiation. For instance, when hip joint is deep flexed the majority of the hip adductors function as extensors (Neumann, 2010). In particular, when the hip is flexed, the posterior head of adductor's magnus plays a fundamental role as primary extensor (Neumann, 2010), supporting BFlh in tolerating the demands of both swing and stance phases (Wiemann and Tidow, 1995); and therefore, may play an important role in reducing hamstring injuries caused by muscle elongation during running (Benn et al., 2018). Similarly, when the hip is flexed greater than 60^{o}, the line of pull of the abductor longus falls posterior to the medial later axis of the hip, allowing it to perform as a hip extensor, similar to the adductor magnus, and when the hip is in an extended position, the line of pull of the adductor longus falls anterior to the medial lateral -axis of the hip, therefore, it flexes the thigh at the hip joint (Neuman, 2010; Muscolino, 2016; Kato et al., 2019). Therefore, adductors function as a useful source of hip flexion and extension torque during sporting movements such as sprinting, change of direction, rising from the squat and this, the switching from flexor to extensor may explain the relative high susceptibility of the adductors to muscle strain injuries while running at high velocities (Mansfield and Neumann, 2013). Therefore, the testing positions had to be considered carefully in order to test adductors accurate. Previous studies have shown that pectineus and adductor brevis have its higher activation levels at the 90^{o} position while adductor longus at the 60^{o} (Neumann, 2010; Lovell et al., 2012).

For the testing of isometric hip ADD and ABD strength at 60^{0}, participants were required to lie beneath the GroinBar (Vald Performance Albion, Australia) in a standardise supine position, with their knee joint at an angle of 60^{0} as described by Ryan et al. (2019). For the isometric hip ADD strength test, the femoral and tibial condyles were positioned central to the force pads and the isometric hip ABD test lateral femoral condyle and head of the fibula were central to the outer force pads (O'Brian et al., 2019). After the participants undertook a familiarisation with the equipment and test, two warm-up contractions were performed prior to the testing.

Firstly, the participants completed one set of three bilateral maximal voluntary isometric hip adductor contractions pushing their femoral medial condyles against the pads for 3-5 s each; and then, following a short rest, the participants repositioned so that lateral femoral condyle and head of the fibula were central to the outer force pads (see Figure 3.5.4a), then one set of three bilateral maximal voluntary isometric hip abductor contractions for 3-5 s against the lateral pads was performed. The investigator ensured that all participants maintained contact with the floor, not raising legs, tilting pelvis or lifting their heads in order to standardise position.

On completion of the 60^{o} position, the participants prepared to be assessed in the 90^{o} position. This involved the athletes' lifting their feet in the air so that their hips and knees were at 90^{o} flexion. Once the standardised position was adopted and the participant was comfortable and indicated they were ready, they performed one set of three bilateral maximal voluntary isometric hip adductor contractions for 3-5 s each pushing their femoral medial condyles against the pads providing a measure of force (N) for left and right limbs. Following a short rest, on the same position one set of three bilateral maximal voluntary isometric hip abductor contractions for 3-5 s against the lateral pads was performed. During the testing, a strong verbal encouragement was provided to encourage maximal effort. If the athlete displayed excessive hip or knee extension/flexion or elevated pelvis, then the repetition was rejected. A repetition was successful if the force trace plateaued after reaching a distinct peak, indicating the development of maximal force.

Force data for both the right and left ADD, and ABD exercises were measured from force transducers sampling at 50Hz. Isometric hip strength was determined for each leg from the peak force during the best of three repetitions of 5 s of ADD and ABD (Ryan et al., 2019).

The highest peak forces from three attempts for abductors and for adductors for 60^{o} and 90^{o} were used in the analysis. The peak force for both limbs, and for both positions was determined automatically through the Scoreboard software and expressed as absolute (N), and percentage imbalance between limbs was also provided based on the following equation: IF(Left Limb<Right Limb,1-MIN(Left Limb: Right Limb)/MAX(Left Limb: Right Limb),-1+MIN(Left Limb: Right Limb)/MAX(Left Limb: Right Limb) x 100). Negative percentage imbalances indicate that the left limb’s score was greater than the right limb. The force data were uploaded to a personalized account and exported into a customized Microsoft Excel spreadsheet (Microsoft, Redmond, USA) for analysis. The mean strength from both limbs was used for analysis.

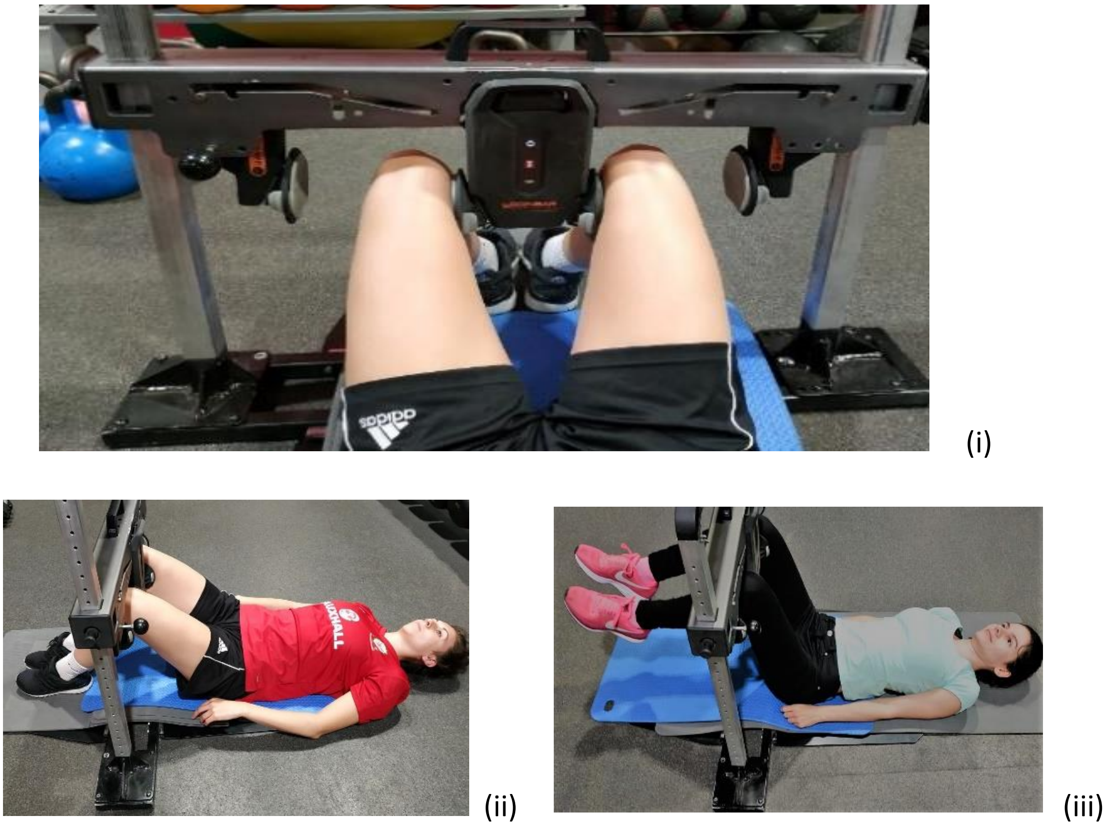

(i) (ii) (iii)

Figure 3.5.4a: Isometric Hip and Groin strength testing positions: (i and ii) at 60°; (iii) at 90°.

Nordic hamstring exercise strength

The assessment of eccentric hamstring strength was conducted using the NordBord device (VALD Performance, Brisbane, Australia) to measure eccentric knee flexor strength. The reliability of the prototype device has been described (ICC 0.83-0.90) previously (Opar et al., 2013). All participants were familiar performing the NHE since it is a common exercise used in team sport conditioning and included in injury risk management protocols (Van Dyk, Behan and Whiteley, 2019). Prior to testing a demonstration of NHE test was performed on the device to each athlete, and two warm-up NHE contractions were performed prior to the testing. The participants kneeled on the device, with the ankles secured immediately superior to the lateral malleolus by individual ankle hooks. Participants were instructed to hold their hands across the chest, and gradually to lean forward at the slowest possible speed so that the chest approached the ground while maximally resisting this movement with both limbs and keeping the trunk and hips in a neutral position throughout (Figure 3.5.4b). The guidelines for performing the test were consistent with those previously described by Opar et al. (2013). The participants were given a countdown of “3, 2, 1 GO,” before each repetition. During the testing, verbal encouragement was given to participants throughout each repetition to provide maximal effort (Opar et al., 2013).

Three maximal repetitions of the Nordic hamstring exercise were performed. A repetition was considered as acceptable when the force output reached a peak which indicates maximal eccentric strength, followed by a rapid decline which occurred when the player was no longer able to resist the force of gravity acting on the segment above the knee joint. If the player displayed excessive hip movement (e.g., breaking hip or trunk) or did not control the descent from the beginning of the movement, then the repetition was rejected. Force data were captured from each limb and transferred to a personal computer at 100 Hz through a USB cable and forces determined by Scorebord data collection app. The maximum scores of left and right limbs of the three repetitions were used for further data analysis. Eccentric hamstring strength was recorded in absolute force in Newtons (N) for each limb and the data was presented as a mean from both limbs. The limbs asymmetry was calculated as the difference between limbs using the following equation: IF(Left Limb<Right Limb,1-MIN(Left Limb: Right Limb)/MAX(Left Limb: Right Limb),-1+MIN(Left Limb: Right Limb)/MAX(Left Limb: Right Limb)), and was expressed as percentage. Where negative percentage imbalances indicate that the left limb’s score was greater than the right limb.

Figure 3.5.4b: The start and end points for the Nordic Hamstring exercise.

Single leg jump

Single leg jumping is a common test used to evaluate lower limb performance by applying similar stimulations as those experienced during sporting activities (Laudner et al., 2015; Shin, Lee and Song, 2015). All participants were from team sports where running, jumping and cutting are regularly performed with therefore were familiar to the demands of the test.

The single leg jumping was used to assess the functional performance ability of both lower limbs, and the inter-limb asymmetry between limbs providing an indication of imbalance. For the purpose of identifying inter-limb asymmetry between limbs, the asymmetry index was calculated using the following formula: Highest performing limb–Lowest performing/ Highest performing limb x100 (Impellizzeri et al., 2007; Read et al., 2018; Fort-Vanmeerhaeghe et al., 2020). The highest performing was defined as the side with the highest value of jumping height. It is suggested that an asymmetry index ≥ 90% should be considered in the normal range; and that an asymmetry ≥ 10% is associated with sport-related injuries (Schiltz et al., 2009; Brumitt et al., 2013). Therefore, if there is ≥ 10% difference between the two lower limbs is abnormal, and asymmetry exists. The test-retest reliability (ICC = 0.88–0.97) of the single leg jumping has been reported previously (Petschnig, Baron and Albrecht, 1998; Brosky et al., 1999).

The single leg jumping was performed on a portable force platform (AccuPower, AMTI, Graz, Austria) sampling data at 1000Hz. The participants were instructed to stand on one leg in the centre of a force plate surface in an upright position, with eyes open, with their hands placed on their hips and the opposite hip flexed and knee flexed and to jump as high as possible (Figure 3.5.4c). The guidelines for performing the test were consistent with those previously described by Read et al. (2016). One practice attempt on each leg was undertaken for familiarization of the procedure while avoiding fatigue. A verbal command of “3, 2, 1 JUMP” countdown was given before each jump. Participants then performed a jump upwards attempting to maximize the vertical height, landing using the same leg close to the centre of the forceplate. On landing, the participants returned to the quiet standing position holding it stable for at least 2 s.

Three jumps on each leg were completed alternating between efforts and with limited rest in between. Successful trials required a stable landing. This jump protocol has been described in previous literature (Read et al., 2018).

The test was repeated if the participant placed the contralateral foot onto the force plate and/or landed outside the force plate dimensions. The single leg jump height was obtained for each trial by determining the vertical displacement of the participant from the standing position to the highest point reached. Jump height was automatically obtained from the custom designed software (AccuPower, AMTI, Graz, Austria) of the force plate for all jumps. The jump height was calculated for each jump sequence based on the resultant take off velocity of each jump and was recorded in centimetres. The highest attempt for each leg was provided for the calculation of asymmetry index.

Figure 3.5.4c: Single leg jumping: (i) Starting position; (ii) Fight position; (ii) Landing position (D) Stable holding position.

3.5.5 Statistical analysis

All statistical analyses were performed using JMP 14.1 (SAS Institute, Inc) and IBM statistics SPSS version 26 (IBM Corporation, Chicago, IL). To describe the dataset, mean and standard deviations (SD) of age, stature, body mass, years of playing experience, first menstrual period, eccentric knee-flexor strength for the left and right limb and between-limb imbalance (%), isometric hip abductor strength at 60° (N), and at 90^{o} for the left and right limb and between-limb imbalance (%), isometric hip adductor strength at 60^{o} and 90^{o} for the left and right limb and between-limb imbalance (%) and jump height for the left and right limb and between imbalance (%) were reported.

Retrospective analysis

Group membership was defined as: lower limb injured participants who had any physical complaint in lower limbs sustained during a match or training session that prevented the player from taking a full part in all training activities or match play for more than 1 day following the day of injury (Fuller et al., 2007), and uninjured participants who were deemed as medically fit and cleared for participation in the sport (Houston, Hoch and Hoch, 2016).

Comparisons between those who previously sustained a lower limb injury, and those avoided injury were conducted using independent t-tests for demographic, anthropometric data, and for the following variables: single leg jump height, eccentric knee-flexor strength for the left and right limb, isometric hip adductor force at 60° and 90°, isometric abductor force at 60° and 90°, and between limb imbalances for all variables of the injured and uninjured groups.

As part of the data screening, injured participants were found to be heavier than the uninjured for all lower limb injuries (past 12 months) and therefore, analysis of covariance (ANCOVA) was used with body mass as a covariate to remove (control for) the effect of body mass difference from the comparison of strength variables between injured and uninjured participants. *S*tandard deviation for the adjusted means of ANCOVA was obtained from the standard error of the adjusted mean by multiplying by the square root of the sample size (Field, Miles and Field, 2012).

Significance was set at a $p<0.05$ and where appropriate Cohen's *d* (Cohen, 1988) (mean difference/pooled SD) was reported for the effect size of the comparisons, with the levels of effect being judged to be small (d=0.20), medium (d=0.50) or large (d=0.80) as recommended by Cohen (1988).

Prospective analysis

For this part of the analysis the association between measures and injuries sustained between pre-season testing and the end of the season was explored. Fisher's exact probability test was used to determine if there was an association between menstrual cycle regularity, family history for ACL injuries, use of oral contraception, and previous injury as dichotomous categorical variables. This was adopted based on the recommendations of Kim (2017) since small frequencies were observed. Relative Risk (RR) was used to express the strength of association for the prospective data; this was interpreted as the ratio of the probability of the outcome occurring in one group (i.e., exposed) to the probability of the outcome occurring in another group (i.e., non-exposed) adapted from the guidelines of Barton and Peat (2014).

Haldane-Anscombe correction was used for calculation of relative risk in small frequency samples when an event did not occur in one of the groups. When RR was inappropriate, Odds Ratio (OR) was determined (Schechtman, 2002).

In this study, a PCA was undertaken to identify logical combinations of the eight strength measures: hip adductors, abductors and between-limb imbalances at 60^o and 90^o and to summarize the patterns of correlations of the elements, to reduce their number to a minimal number of factors. The Kaiser-Meyer-Olkin (KMO) measure was used to verify the sampling adequacy of the data, with a value of 0.5 used as a threshold for acceptability (Kaiser, 1974), and Bartlett's test of sphericity was also used to determine the suitability of the data for PCA, with significance accepted at an α level of $p \leq 0.05$.

PCA can further defined as a linear combination of optimally weighted elements that explains a maximal amount of variance in the data set (Andrew, Pedersen and McEvoy, 2019). Eigenvalues are yielded by PCA, that reflect the amount of variance that is being accounted for by each component. Every variable contributes 1 unit of variance to the total variance of the data set and therefore, component with an eigenvalue of greater than 1 means that the component is explaining a greater amount of variability than had been contributed by 1 other element. Therefore, components with an eigenvalue of 1 and greater were retained (Guttman, 1954; Kaiser, 1960; Kaiser, 1970).

Additionally, to determine the association between strength and imbalance variables and principal components, univariate and multivariate logistic regression analyses were conducted with the prospective occurrence of a lower limb injuries (yes/no), noncontact lower limb injury, hamstring injuries (Yes/No), noncontact ACL injuries (Yes/No) as the dichotomous dependent variable and strength and imbalance variables as continuous independent variables in separate analyses. Multivariate logistic regression was carried out to identify independent risk factors for lower limb injuries. All variables were initially included in the multivariate model, and elimination of non-significant factors was performed using a stepwise backward elimination approach. Level of significance, adjusted odds ratios (ORs), and 95% CIs were calculated for each variable. For all analyses, alpha was set at $p<0.05$.

Following initial screening of the LESCA data for outliers and assumption testing, there were significant issues with the distributions. All data were skewed and not normally distributed (Negative life events: Kolmogorov–Smirnov statistic, $p<0.001$; Skewness=2.0; Kurtosis=3.8; Positive life events: Kolmogorov–Smirnov statistic, $p<0.001$; Skewness=1.1; Kurtosis=0.8), and all transformations failed. Therefore, Ward's two-way hierarchical clustering procedure, was used to classify groups based on the LESCA data (Ward, 1963). Ward's method generates a series of clusters that represent homogeneous subgroups through sequential aggregation of similar characteristics among data obtained from measures (i.e., LESCA positive and negative events). The cluster analysis yielded three groups characterised by high negative and low positive events (group 1); low negative and moderate positive events (group 2); and low negative and very low positive events (group 3).

The classification of groups was done visually via plots of LESCA scores by group and confirmed by group comparisons of negative and positive life events using one-way analysis of variance (ANOVA), with Bonferroni post-hoc test to identify statistically significant differences between specific cluster groups. Fisher's exact test was used for the analysis of the contingency table between the life events groups and one-year follow-up injuries, oral contraception and menstrual cycle regularity.

3.6 Results

3.6.1 Anthropometrical characteristics and injury details

One hundred and thirty-five female athletes (N=135) aged between 14 and 31 years (Mean=18.8 (3.6) years) volunteered to participate in the study. Sixty of the athletes (N=60) were over 18 years of age at the time of the testing. Descriptive statistics for the study participants are shown in Table 3.6.1a.

Table 3.6.1a. Demographic and anthropometric characteristics of the study participants (N=135); N=newtons, cm=centimetres, kg=kilograms of body mass.

Participants' characteristics	**Mean (SD)**
Age (years)	18.8 (3.6)
Stature (cm)	165.8 (6.5)
Body Mass (kg)	67.4 (12.3)
Years of playing experience	8.7 (4.5)
Age of first menstrual period (years)	12.9 (1.5)
Jump height (cm)-Two limb average	9.8 (2.6)
Absolute jump imbalance (%)-Between-limb	11.4 (8.8)
Eccentric knee Flexor Force (N)	261 (64)
Eccentric knee flexor-Absolute Nordic Imbalance (%)	10.6 (8.3)
Isometric hip abductor Force-Pull 60° (N)	243 (53)
Isometric hip abductor-Absolute Imbalance (%) pull 60°	6.5 (4.5)
Isometric hip adductor force-Squeeze 60° (N)	293 (53)
Isometric hip adductor-Absolute imbalance squeeze 60° (%)	4.5 (3.6)
Isometric abductor force-Pull 90° (N)	217 (59)
Absolute imbalance % pull 90°-Between-limb	8.8 (7.4)
Isometric adductor force-Mean Squeeze 90° (N)	292 (49)
Isometric Absolute imbalance % squeeze 90°-Between-limb	4.8 (4)

3.6.2 Retrospective data collection

Based on the injury history questionnaire that was collected during the testing day, sixty-seven of the female athletes sustained at least one lower limb injury in the past 12 months, sixty-six did not report any injury, and two athletes did not report. Injury location data and mechanism are presented in Table 3.6.2a.

Table 3.6.2a. Distribution of the N=86 injuries by injury location and mechanism, during the past 12 months**;** NR: Not Reported.

	Total	**Contact**				**Noncontact**					**NR/None**
Injury location	**N (%)**	**Total N (%)**	**Training N (%)**	**Competition N (%)**	**NR/None N (%)**	**Total N (%)**	**Training N (%)**	**Competition N (%)**	**Both N (%)**	**NR/None N (%)**	**N (%)**
Hip	6 (7)	1 (16.7)	0	1 (16.7)	0	3 (50)	0	0	1 (1.2)	2 (33.3)	2 (33.3)
Knee	26 (30.2)	12 (46.2)	0	12 (46.2)	0	14 (53.8)	8 (30.8)	3 (11.5)	0	3 (11.5)	0
Ankle	22 (25.6)	8 (36.4)	1 (4.5)	6 (27.3)	1 (4.5)	13 (59.1)	8 (36.4)	4 (18.1)	0	1 (4.5)	1 (4.5)
Foot	5 (5.8)	2 (40)	0	2 (40)	0	1 (20)	0	1 (20)	0	0	2 (40)
Groin	6 (7)	1 (16.7)	1 (16.7)	0	0	5 (83.3)	4 (66.7)	1 (16.7)	0	0	0
Quadriceps	3 (3.5)	0	0	0	0	3 (100)	1 (33.3)	1 (33.3)	1 (1.2)	0	0
Hamstring	3 (3.5)	0	0	0	0	3 (100)	2 (66.7)	0	0	1 (33.3)	0
Calf	7 (8.1)	2 (28.6)	1 (14.3)	1 (14.3)	0	5 (71.4)	0	1 (14.3)	0	2 (28.6)	0
Shinbone	2 (2.3)	1 (50)	0	1 (50)	0	1 (50)	1 (50)	0	0	0	0
Peroneal	1 (1.2)	0	0	0	0	1 (100)	1 (100)	0	0	0	0
ACL	5 (5.8)	2 (40)	0	2 (40)	0	3 (60)	0	3 (60)	0	0	0
Overall	**86**	**29**	**3**	**25**	**1**	**52**	**25**	**16**	**2**	**9**	**5**

Table 3.6.2b. Frequency of N=81 injuries by injury mechanism, by sport and by nature for the past 12 months**.** NR: Not Reported.

Sport	**Total (%)**	**Contact (%)**	**Noncontact (%)**	**NR/None (%)**	**Training (%)**	**Competition (%)**	**NR/None (%)**	**Both (%)**
Football	55.6	9.9	40.7	4.9	19.8	19.8	13.6	2.5
Netball	9.9	3.7	6.2	0	6.2	3.7	0	0
Rugby	34.6	19.8	13.6	1.2	7.4	22.2	4.9	0

As presented in Table 3.6.2a, the knee was the most common site of injury, while noncontact injuries were more common than contact. In addition, most prominently for ankle and knee injuries was the noncontact mechanism. For the football players, noncontact injuries were most common while for rugby players were contact injuries (Table 3.6.2b).

Seventeen athletes (N=17) from the cohort reported previous ACL injury with five of them sustaining an ACL injury in the past 12 months. From these athletes, two also had a previous ACL injury, while all five ACL injuries within the past 12 months occurred during competition.

All injuries

Descriptive statistics and comparison results for the two groups (injured and uninjured) for all lower limb injuries (past 12 months) are shown in Table 3.6.2c. No significant between group differences were observed for age, stature and years of playing experience. However, injured female athletes seemed to be heavier compared to the uninjured for all lower limb injuries (past 12 months), yet the difference between the two groups was of borderline significance and effect was small (p=0.066, d=0.33).

Table 3.6.2c. Comparison between uninjured and all previous lower limb injured (past 12 months) athletes regarding age, body mass, stature, and years of playing experience. *p<0.05; cm=centimetres, kg=kilograms of body mass.

Variables	**Uninjured Mean (SD) N=66**	**Injured Mean (SD) N=67**	**Mean Difference**	**95%CI**	***p***	***Cohen's d***
Age (years)	18.5 (3.2)	19.2 (4)	0.7	-0.5 to 2.0	0.24	0.19
Stature (cm)	165.0 (6.9)	166.8 (6.1)	1.80	-0.5 to 4.1	0.11	0.28
Body mass (kg)	65.5 (11.5)	69.5 (12.9)	4.00	-0.2 to 8.2	0.06	0.33
Years of playing experience	8.5 (4.4)	8.8 (4.7)	0.27	-1.3 to 1.8	0.73	0.07

Descriptive statistics for all strength variables and between-limb imbalances for the injured and uninjured groups can be found in Table 3.6.2d. The injured group was found to have a 3.2% (95%CI=0.2 to 6.2%; p=0.039) greater imbalance for eccentric knee flexor strength, but a 1.4% (95%CI=0.2% to 2.6) lower imbalance for isometric hip adductor strength at 60° (p=0.028) compared to the uninjured athletes.

Table 3.6.2d: Comparison between uninjured and all lower limb injured athletes for muscle strength variables and between-limb imbalance. *p<0.05; N=Newtons, cm=centimetres.

	Adjusted Means for Mass					
	N Uninjured Injured	**Uninjured Mean (SD)**	**Injured Mean (SD)**	**Mean Difference (95% CI)**	***p***	**Cohen's d**
Eccentric knee Flexor Force (N)	62 64	261 (57)	263 (57)	2 (-19 to 22)	0.881	0.04
Eccentric knee flexor Absolute Nordic Imbalance (%) Between-limb	62 64	9.0 (8)	12.2 (8.4)	3.2 (0.2 to 6.2)	0.039*	0.39
Isometric hip abductor Force-Pull 60° (N)	61 65	239 (44)	250 (44)	11 (-5 to 26)	0.191	0.25
Isometric hip abductor Absolute Imbalance (%) pull 60° Between-limb	61 65	6.3 (4.5)	6.7 (4.6)	0.4 (-1.3 to 2)	0.662	0.09
Isometric hip adductor force - Squeeze 60° (N)	61 65	287 (49)	300 (49)	13 (-4 to 31)	0.131	0.27
Isometric hip adductor Absolute imbalance Squeeze 60° (%) Between-limb	61 65	5.2 (3.5)	3.8 (3.5)	-1.4 (-2.6 to -0.2)	0.028*	0.40
Isometric abductor force- Pull 90° (N)	60 62	213 (47)	222 (47)	9 (-8 to 26)	0.277	0.19
Isometric hip abductor Absolute imbalance Pull 90° (%) Between-limb	60 62	9.1 (7.5)	8.7 (7.6)	-0.4 (-3.1 to 2.3)	0.767	0.05
Isometric hip adductor force-Squeeze 90° (N)	60 64	286 (48)	298 (48)	12 (-5 to 29)	0.159	0.25
Isometric hip adductor Absolute imbalance Squeeze 90° (%) Between-limb	60 64	5.2 (4.1)	4.4 (4.1)	-0.8 (-2.3 to 0.6)	0.263	0.20
Jump height (cm) Two limb average	61 57	9.6 (2.5)	9.8 (2.6)	0.2 (-0.8 to 1.1)	0.704	0.08
Absolute jump imbalance (%) Between-limb	61 57	10.3 (8.7)	13 (8.8)	2.7 (-0.4 to 6)	0.089	0.31

Risk factors for injury

Thirty (22%) out of the 135 athletes who completed the baseline questionnaire reported an irregular menstrual cycle, ninety-five regular, two athletes did not have their menstrual period after getting a hormonal contraceptive implant, and eight failed to report. Ninety-five (70%) of the athletes in this study reported they were not been taking any form of oral contraception, while thirty-seven reported they had used oral contraception and three athletes did not respond. Twenty-one athletes reported a family ACL injury history. Athletes with a family predisposition to anterior cruciate ligament injury were four times more likely to have suffered an ACL injury (Table 3.6.2e). Similarly, those three athletes that suffered an ACL injury in the preceding 12 months to testing also reported having irregular menstrual cycles and those who reported regular menstrual cycles were less likely to have had noncontact ACL injury compared to players with an irregular menstrual cycle (Table 3.6.2e). No association was found for those who suffered lower limb injuries and menstrual cycle irregularities.

Table 3.6.2e. Association for lower limb injury, ACL injury, familial predisposition for ACL and menstrual related factors**.** NC: noncontact. [1]Haldane-Anscombe correction was used for calculation of odds ratio. *$p<0.05$; OR=Odds Ratio.

Variables		**All lower limb injuries (past 12 months)**			**p**	**OR**	**95%CI**
		Yes	**No**	**Total**			
Menstrual cycle	Regular	49	44	93	0.675	1.27	0.56 to 2.90
N=123	Irregular	14	16	30			
		NC ACL injuries (past 12 months)					
		Yes	**No**	**Total**			
Menstrual cycle	Regular	0	93	93	0.013*	0.042[1]	0.002 to 0.84[1]
N=123	Irregular	3	27	30			
		ACL injuries at any point in time					
		Yes	**No**	**Total**			
Family history	Yes	7	14	21	0.014*	4.3	1.4 to 13.2
N=117	No	10	86	96			

3.6.3 Prospective data collection

One-year follow-up

One-year after testing, one hundred and nine athletes were followed-up. Injuries were reported by the teams' physiotherapists during the follow-up period. Twenty-six athletes left the teams and therefore team physiotherapists had no record of their follow-up injuries. Those lost to follow-up were 6kg (95%CI: 2 to 10 kg; p=0.004) lighter for body mass, 20.5% lower rate of oral contraception use, 1.98 % (95%CI: 0.23 to 3.72%: p=0.028) less hip abductor at 60^0 imbalance, 1.98 cm (95%CI: 3.40 to 0.50 cm; p=0.012) higher single leg jumping height and greater mean difference 5.13% (95%CI: 9.86 to 0.39 %; p=0.034) single leg jumping imbalance compared to those followed-up for lower limb injuries.

In total, of the remaining 109 athletes who continued in the study forty-four (40%) athletes suffered at least one injury by the end of the one-year follow-up. Five athletes during the 12-month period sustained an ACL injury. Two of the athletes with noncontact ACL injury also had prior history of ACL injury(but not in the past 12 months). Injury frequency data by location, mechanism and sport are presented in Table 3.6.3a. Nearly 60% (N=28) of injuries were noncontact and 40% (N=19) were contact. For the football players, noncontact injuries were most common while for netball players were contact injuries.

Table 3.6.3a: One-year follow-up injury location data and mechanism by sport.

Injuries	N	Contact	Noncontact
ACL	5	2	3
Hamstrings	5	0	5
Other lower limb injury	37	17	20
Total	47	19	28
Sports	**N**	**Contact**	**Noncontact**
Football	16	1	15
Netball	7	6	1
Rugby	24	12	12
Total	47	19	28

Risk factors for injury

As presented in Tables 3.6.3b-e an association between lower limb injuries and those taking oral contraception was found, where athletes who were taking oral contraception had by 49% lower risk to develop lower limb injury compared to those who didn't take (Table 3.6.3b). An association was found with previous ankle injuries and sustaining a future lower limb injury (RR=1.80; 95%CI=1.16 to 2.81; p=0.033). No significant association was observed between any of the other individual previous injuries and future injuries at one-year follow up.

Table 3.6.3b: Association between all one-year follow-up lower limb injuries and previous injury, oral contraception and menstrual cycle regularity. *p<0.05; RR=Relative Risk.

		All lower limb injuries (one-year follow-up)			p	RR	95%CI
Previous Lower limb injury		**Yes**	**No**	**Total**			
n=107	Yes	22	29	51	0.560	1.15	0.72 to 1.83
	No	21	35	56			
Previous ankle injury	Yes	11	6	17	0.033*	1.80	1.16 to 2.81
N=109	No	33	59	92			
Oral contraception	Yes	8	24	32	0.032*	0.51	0.27 to 0.98
n=106	No	36	38	74			
Menstrual cycle	Regular	30	44	74	>0.999	0.96	0.57 to 1.62
n=100	Irregular	11	15	26			

Table 3.6.3c: Association between one-year follow-up noncontact lower limb injuries and previous noncontact injury, oral contraception and menstrual cycle regularity; NC: noncontact; RR=Relative Risk.

		All NC lower limb injuries (one-year follow-up)			P	RR	95%CI
Previous lower limb injury		**Yes**	**No**	**Total**			
n=107	Yes	22	29	51	0.560	1.15	0.72 to 1.83
	No	21	35	56			
Oral contraception	Yes	7	24	31	0.460	0.70	0.33 to 1.49
n=87	No	18	38	56			
Menstrual cycle	Regular	18	44	62	>0.999	1.02	0.47 to 2.22
n=83	Irregular	6	15	21			

Table 3.6.3d: Association between one-year follow-up noncontact ACL injury and previous ACL injury, hamstring injury, family history of ACL injury, oral contraception, and menstrual cycle regularity. NC: noncontact. [1] Haldane-Anscombe correction was used for calculation of relative risk; RR=Relative Risk.

		NC ACL injury (one-year follow-up)			p	RR	95%CI
		Yes	**No**	**Total**			
Previous ACL injury (past 12 months)	Yes	1	2	3	0.130	8.67	1.34 to 56
n=107	No	4	100	104			
Previous hamstring injury	Yes	0	2	2	>0.999	5.05[1]	0.33 to 77.6[1]
n=107	No	3	102	105			
Family history of ACL injury	Yes	1	17	18	0.430	2.47	0.24 to 25.8
n=107	No	2	87	89			
Oral contraception	Yes	2	30	32	0.220	4.5	0.42 to 47.9
n=104	No	1	71	72			
Menstrual cycle	Regular	1	72	73	0.160	0.17	0.016 to 1.81
n-98	Irregular	2	23	25			

Table 3.6.3e: Association between one-year follow-up hamstring injury and previous hamstring injury, oral contraception, and menstrual cycle regularity. [1] Haldane-Anscombe correction was used for calculation of relative risk; RR=Relative Risk.

		Hamstring injuries (one-year follow-up)					
		Yes	**No**	**Total**	**p**	**RR**	**95%CI**
Previous Hamstring injury	Yes	0	2	2	>0.99	3.27[1]	0.23 to 46.7[1]
n=109	No	5	102	107			
Oral contraception	Yes	0	32	32	0.32	0.21[1]	0.01 to 3.63[1]
n=106	No	5	69	74			
Menstrual cycle	Regular	5	69	74	0.32	3.96[1]	0.23 to 69.3[1]
n=100	Irregular	0	26	26			

3.6.4 Muscle strength

For the one-year follow-up, injured and uninjured athletes were compared. From the anthropometric, muscle strength variables and between-limb imbalance measures, injured athletes had greater isometric hip abductor at 60° imbalance (p=0.011) and hip adductor at 90° imbalance (%) (p=0.047) at pre-season compared to the uninjured group (Table 3.6.4a).

When non-contact injuries were considered, those who sustained noncontact injures, had weaker hip adductor strength at 60^{0} (p=0.007) and had greater hip adductor imbalance at 90^{0} (p=0.018) than the uninjured group (Table 3.6.4b).

Table 3.6.4a: Comparison between uninjured and 1-year follow-up lower limb injured athletes for anthropometric and muscle strength and imbalance variables. *p<0.05; N=newtons, cm=centimetres, kg=kilograms of body mass.

	N Uninjured Injured	Uninjured Mean (SD)	All lower limb Injured (1-year Follow - up) Mean (SD)	Mean difference (95% CI)	*P*	Cohen's d
Age (years)	65 44	19.1 (4.1)	18.6 (2.6)	-0.5 (-1.8 to 0.7)	0.395	0.15
Stature (cm)	64 44	165.8 (6.4)	165.5 (6.3)	-0.3 (-2.7 to 2.2)	0.825	0.05
Body mass (kg)	65 44	68.8 (11.9)	68.7 (14.3)	-0.1 (-5.3 to 5.1)	0.973	0.008
Years of playing experience	64 44	9 (4.7)	7.9 (4.2)	-1.1 (-2.8 to 0.6)	0.184	0.246
Eccentric knee Flexor Force (N)	60 42	262 (62)	269 (71)	7 (-20 to 34)	0.624	0.11
Eccentric knee flexor Absolute Imbalance (%) Between-limb	60 42	9.5 (8.3)	10.6 (7.7)	1.1 (-2 to 4)	0.487	0.14
Isometric hip abductor Force Pull 60° (N)	63 40	247 (56)	240 (49)	-7 (-28 to 14)	0.511	0.13
Isometric hip abductor-Absolute Imbalance (%) Pull 60° Between-limb	63 40	5.9 (4)	8.5 (5.2)	2.6 (0.6 to 4.5)	0.011*	0.56
Isometric hip adductor force - Squeeze 60° (N)	63 40	296 (53)	283 (50)	-13 (-34 to 8)	0.224	0.25
Isometric hip adductor- Absolute imbalance squeeze 60° (%) Between-limb	63 40	4.3 (3.6)	4.9 (3.2)	0.6 (-0.7 to 1.95)	0.373	0.18
Isometric hip abductor force Pull 90° (N)	62 38	224 (61)	213 (64)	-11 (-37 to 14)	0.373	0.18
Isometric hip abductor Absolute imbalance (%) Pull 90° Between-limb	62 38	7.7 (6.9)	9.8 (8.3)	2.1 (-1.1 to 5.3)	0.190	0.28
Isometric hip adductor force Squeeze 90° (N)	63 38	292 (49)	289 (48)	-3 (-23 to 17)	0.762	0.06
Isometric hip adductor Absolute imbalance (%) Squeeze 90° Between-limb	63 38	4.3 (3.5)	6.1 (4.8)	1.8 (0.03 to 3.6)	0.046*	0.43
Jump height (cm) Two limb average	58 38	9.1 (2.1)	9.9 (2.4)	0.8 (-0.1 to 1.8)	0.080	0.35
Absolute jump imbalance (%) Between-limb	58 38	10.6 (8.9)	10.4 (7)	-0.2 (-3.4 to 3.1)	0.941	0.02

Table 3.6.4b: Comparison between uninjured and 1-year follow-up of non-contact lower limb injured athletes for anthropometric and muscle strength and imbalance variables; NC: non-contact. *p<0.05; N=newtons, cm=centimetres, kg=kilograms of body mass.

	N Uninjured Injured	Uninjured Mean (SD)	NC lower limb Injured (1-year follow-up) Mean (SD)	Mean difference (95% CI)	*P*	Cohen's d
Age (years)	65 23	19.1 (4.1)	18.5 (2.6)	-0.6 (-2.1 to 0.8)	0.391	0.17
Stature (cm)	64 25	165.8 (6.4)	164.2 (4.5)	-1.6 (-4 to 0.8)	0.195	0.29
Body mass (kg)	65 25	68.8 (11.9)	67.2 (14.4)	-1.6 (-8.1 to 5)	0.631	0.12
Years of playing experience	64 25	9 (4.7)	9.1 (4.3)	0.1 (-2 to 2.2)	0.901	0.02
Eccentric knee Flexor Force (N)	60 23	262 (62)	242 (64)	-20 (-52 to 11)	0.195	0.32
Eccentric knee flexor Absolute Imbalance (%) Between-limb	60 23	9.5 (8.3)	12.3 (8.6)	2.8 (-1.4 to 7.1)	0.181	0.33
Isometric hip abductor Force Pull 60° (N)	63 21	247 (56)	233 (45)	-14 (-39 to 10)	0.245	0.28
Isometric hip abductor Absolute Imbalance (%) Pull 60° Between-limb	63 21	5.9 (4)	7.9 (4.8)	2 (-0.4 to 4.4)	0.102	0.45
Isometric hip adductor force Squeeze 60° (N)	63 21	296 (53)	263 (42)	-33 (-56 to -10)	0.007*	0.69
Isometric hip adductor Absolute imbalance (%) Squeeze 60° Between-limb	63 21	4.3 (3.6)	4.8 (3.6)	0.5 (-1.3 to 2.4)	0.541	0.14
Isometric hip abductor force Pull 90° (N)	62 20	224 (61)	202 (65)	-22 (-56 to 11)	0.187	0.35
Isometric hip abductor Absolute imbalance (%) Pull 90° Between-limb	62 20	7.7 (6.9)	11.9 (9.2)	4.2 (-0.4 to 8.8)	0.070	0.52
Isometric hip adductor force Squeeze 90° (N)	63 20	292 (49)	270 (40)	-22 (-44 to 0.2)	0.052	0.49
Isometric hip adductor force Absolute imbalance (%) Squeeze 90° Between-limb	63 20	4.3 (3.5)	7.6 (5.5)	3.3 (0.6 to 6)	0.018*	0.72
Jump height (cm) Two limb average	58 22	9.1 (2.1)	9.5 (2.2)	0.4 (-0.7 to 1.5)	0.450	0.19
Absolute jump imbalance (%) Between-limb	58 22	10.6 (8.9)	11.3 (7.4)	0.7 (-3.2 to 4.7)	0.705	0.09

3.6.5 Principal components

Principal components analysis was used to reduce the number of variables based on a matrix of correlations between the measured variables (Munro, 1997). Hip adductors and abductors strength at 60^{o} and 90^{o} and between-limb imbalance variables (total of 8 variables) were included in the PCA (Table 3.6.5a). The Kaiser-Meyer-Olkin value found 0.64, and Bartlett's test of sphericity attained statistical significance ($p=0.0001$). Three principal components were identified with Eigenvalues >1 and were retained for subsequent analysis (Table 3.6.5a). Principal component 1 (PC1) included all strength variables (mean hip isometric adduction and abduction at both 60^{o} and 90^{o}); the main feature of principal component 2 (PC2) was 90^{o} adductor between-limb imbalance; and the main feature of principal component 3 (PC3) was 90^{o} abductor between-limb imbalance). In total, the 65.48% of the variance was explained by the PC1, PC2 and PC3. Descriptive statistics for all three PC are presented in Table 3.6.5b.

Table 3.6.5a: Eigenvalues for hip adductor and abductor strength and imbalance. Principal component 1: captured the mean adduction and abduction strength; Principal component 2: captured the adductor 90^{o} between-limb imbalance (%) and abductor 60^{o} (%) between-limb imbalance; Principal component 3: captured the abductor 90^{o} (%) between-limb imbalance and adductor 60^{o} (%) between-limb adduction imbalance.

Principal Component	Eigenvalue	Percent	Cum Percent
1	**2.7646**	**34.558**	**34.558**
2	**1.3515**	**16.893**	**51.451**
3	**1.1227**	**14.033**	**65.484**
4	0.9266	11.583	77.067
5	0.7532	9.414	86.482
6	0.6036	7.545	94.027
7	0.2805	3.507	97.533
8	0.1973	2.467	100.000

Table 3.6.5b. Descriptive statistics for hip adductor and abductor strength and imbalance. Principal component 1: captured the mean adduction and abduction strength; Principal component 2: captured the adductor 90^o between-limb imbalance (%) and abductor 60^o (%) between-limb imbalance; Principal component 3: captured the abductor 90^o (%) between-limb imbalance and adductor 60^o (%) between-limb adduction imbalance.

	Uninjured **N=62** **Mean (SD)**	**All lower limb Injured** **(one-year follow-up)** **N= 38** **Mean (SD)**	**Total** **N=100** **Mean (SD)**
PC1	0.15 (1.67)	-0.28 (1.76)	-0.01 (1.71)
PC2	-0.18 (0.91)	0.49 (1.28)	0.07 (1.11)
PC3	0.11 (1.13)	-0.06 (1.04	0.05 (1.1)
	Uninjured **N=62** **Mean (SD)**	**NC lower limb injured (one-year follow-up)** **N=20** **Mean (SD)**	**Total** **N=82** **Mean (SD)**
PC1	0.15 (1.67)	-0.88 (1.64)	-0.10 (1.71)
PC2	-0.18 (0.91)	0.55 (1.41)	-0.01 (1.09)
PC3	0.11 (1.13)	-0.11 (1.21)	0.06 (1.15)

Based on the multivariate logistic regression, the PC2 had a positive significant relationship with the incidence of non-contact lower limb injuries at one-year follow-up (Table 3.6.5c). As such, for every 1 unit increase in PC2 (hip adductor 90^o between-limb imbalance), the risk of lower limb injury was increased by 1.8 times.

Table 3.6.5c: Multivariate logistic regression analysis for the relationship of non-contact lower limb injuries follow-up and PCs. Principal component 1: captured the mean adduction and abduction strength; Principal component; 2: captured the 90^o adductor between -limb imbalance (%); Principal component 3: captured the abductor 90^o (%) between-limb imbalance PC, principal component. *p<0.05; OR=Odds Ratio

	Non-contact Lower limb injuries (one-year follow-up)		
	N	**p**	**OR (95%CI)**
PC1	82	0.052	0.71 (0.51 to 1.00)
PC2	82	0.036*	1.80 (1.04 to 3.13)
PC3	82	0.578	0.88 (0.57 to 1.37

Univariate analysis

Using univariate logistic regression, abductors and adductors imbalance (between-limb) had a significant positive relationship with the incidence of lower limb injuries (Table 3.6.5d). A 1 standard deviation (SD) increase in abductors imbalance at 60^{o} and adductors imbalance at 90^{o}, the risk of lower limb injury was increased by almost twice. Similarly, association was identified for the noncontact lower limb injuries. As such, for every 1 SD increase in adductors and abductors imbalance at 90^{o}, the risk for noncontact lower limb injury was increased by 2.4 and 1.4 times, respectively. Additionally, adductors strength at 60^{o} had a significant inverse relationship with the incidence of noncontact lower limb injury. As such, for every 10N increase in adductors strength at 60^{o}, the risk of noncontact lower limb injury was reduced by 12%. Finally, for every 1 SD increase of abductors imbalance at 90^{o}, the risk for hamstring injury was increased by almost twice times (Table 2.6.5e).

Table 3.6.5d: Univariate logistic regression analysis for the relationship between muscle strength and between limb imbalance and lower limb injuries at one-year follow-up. NC: noncontact; Relationship is significant at the $p<0.05$ level. *$p<0.05$; N=Newtons, cm=centimetres, OR=Odds Ratio.

Muscle strength risk factors	**All Lower limb injuries (one-year follow-up)**				**NC lower limb injuries (one-year follow-up)**			
	N	**OR**	**95%CI**	***p***	**N**	**OR**	**95%CI**	***p***
Mean isometric hip abductor strength at 60° (pull) [by 10 N increment]	103	0.98	0.9 to 1.05	0.52	84	0.95	0.86 to 1.04	0.29
Isometric hip abductor at 60^{o} imbalance (%) [by 10% increment]	103	3.46	1.34 to 8.88	0.010*	84	2.81	0.89 to 8.88	0.079
Mean isometric hip adductor strength at 60° (squeeze) [by 10 N increment]	103	0.95	0.88 to 1.03	0.228	84	0.88	0.78 to 0.98	0.017*
Isometric hip adductor at 60^{o} imbalance (%) [by 10% increment]	103	1.67	0.53 to 5.28	0.383	84	1.52	0.4 to 5.79	0.53
Mean isometric hip abductor strength at 90° (pull) [by 10 N increment]	100	0.97	0.9 to 1.04	0.364	82	0.94	0.87 to 1.03	0.169
Isometric hip abductor at 90^{o} imbalance (%) [by 10% increment]	100	1.466	0.85 to 2.52	0.172	82	1.95	1.03 to 3.71	0.039*
Mean hip adductor at 90° (squeeze) [by 10 N increment]	102	0.99	0.9 to 1.07	0.76	83	0.90	0.8 to 1.01	0.078

Isometric hip adductor at 90^o imbalance (%) [by 10% increment]	102	2.94	1.06 to 8.12	0.038*	83	5.65	1.61 to 19.7	0.007*
Mean Nordforce [by 10 N increment]	102	1.02	0.96 to 1.08	0.612	83	0.95	0.88 to 1.03	0.184
Nordforce imbalance (%) [by 10% increment]	102	1.18	0.73 to 1.93	0.49	83	1.45	0.84 to 2.52	0.178
Mean single leg jump [by 1 cm increment]	96	1.19	0.98 to 1.44	0.074	80	1.10	0.87 to 1.39	0.43
Single leg jump imbalance (%) [by 10% increment]	96	0.98	0.59 to 1.63	0.943	80	1.10	0.62 to 1.97	0.72

Table 3.6.5e. Univariate logistic regression analysis for the relationship between muscle strength and between limb imbalance and noncontact ACL injuries and hamstring injuries. NC: noncontact; Relationship is significant at the p<0.05 level; N=Newtons; cm=centimetres, OR=Odds Ratio.

Muscle strength risk factors	**NC ACL injuries (one-year follow-up)**				**Hamstring injuries (one-year follow-up)**			
	N	**OR**	**95%CI**	***p***	**N**	**OR**	**95%CI**	***p***
Mean isometric hip abductor strength at 60° (pull) [by 10 N increment]	101	0.90	0.68 to 1.21	0.514	103	0.886	0.714 to 1.09	0.258
Isometric hip abductor strength at 60° (pull) Imbalance (%) [by 10% increment]	101	1.1	0.06 to 21.2	0.949	103	4.725	0.87 to 25.4	0.072
Mean isometric hip adductors strength at 60° (squeeze) [by 10 N increment]	101	0.745	0.53 to 1.05	0.091	103	0.83	0.67 to 1.03	0.097
Isometric hip adductors strength at 60° (squeeze) Imbalance (%) [by 10% increment]	101	6.51	0.34 to 126.8	0.215	103	4.15	0.42 to 41.4	0.224
Mean isometric hip abductor strength at 90° (pull) [by 10 N increment]	98	0.86	0.64 to 1.14	0.284	102	0.92	0.78 to 1.10	0.395
Isometric hip abductor strength at 90° (pull) Imbalance (%) [by 10% increment]	98	1.77	0.4 to 7.86	0.45	100	3.305	1.17 to 9.39	0.024*
Mean isometric hip adductor at 90° (squeeze) [by 10 N increment]	100	1.04	0.78 to 1.41	0.784	102	0.96	0.776 to 1.20	0.725
Isometric hip adductor at 90° (squeeze) Imbalance (%) [by 10% increment]	100	0.47	0.008 to 28.1	0.72	102	3.91	0.62 to 24.16	0.145
Mean Nordforce	100	0.94	0.78 to 1.14	0.538	102	0.97	0.83 to 1.14	0.727

[by 10 N increment]								
Nordforce Imbalance (%) [by 10% increment]	100	2.14	0.79 to 5.79	0.132	102	1.21	0.39 to 3.71	0.737
Mean single leg jump (cm) [by 1 cm increment]	95	1.27	0.76 to 2.12	0.357	96	1.29	0.82 to 2.02	0.270
single leg jump Imbalance (%) [by 10% increment]	95	0.98	0.23 to 4.05	0.974	96	1.28	0.42 to 3.87	0.665

3.6.6 Life events

Overall, fifty-three LESCA questionnaires were received (fifty-six athletes were under the age of 18).

Descriptive statistics of all the variables are shown in Table 3.6.6a.

Table 3.6.6a: Descriptive statistics of the study participants that completed LESCA questionnaire. *Median (min, max) shown for variables with non-normal distributions. N=newtons, cm=centimetres, kg=kilograms of body mass.

Variables	Mean (SD)
Age (years)	22.1 (3.6)
Stature (cm)	166.9 (7.1)
Body mass (kg)	71.4 (13.8)
Years of playing experience	11.2 (5.3)
First menstrual period (age)	13.1 (1.6)
Single leg jumping (cm)	9.7 (2.4)
Single leg jumping (%)	12.2 (10)
NordForce (N)	271 (70)
Nordforce (%)	12.9 (8.8)
Mean isometric hip abductor strength 60° (Pull)	247 (50)
Hip isometric hip abductor Absolute imbalance (%) (pull) 60°	5.5 (4.6)
Mean isometric hip adductor strength 60° (Squeeze)	299 (48)
Isometric hip adductor Absolute imbalance (%) (squeeze) 60°	3.6 (2.7)
Mean isometric hip abductor strength 90° (Pull)	232 (55)
Isometric hip abductor Absolute imbalance (%) (pull) 90°	8.2 (6.7)
Mean isometric hip adductor strength 90° (Squeeze)	292 (50)
Isometric hip adductor	3.9 (3.3)

Absolute imbalance (%) (squeeze) 90°	
Negative life events	14 (0, 128) *
Positive life events	11 (0, 51) *

A Ward’s two-way cluster analysis of the LESCA data generated the dendrogram shown in Figure 3.6.6a. The three groups were determined as the following: Cluster 1, was characterised by high (86±27) negative and low (21±11) positive scores, Cluster 2 characterised by low (16±11) negative scores and moderate (29±11) positives scores, while Cluster 3 was characterised by low (13±11) negative and very low (6±5) positive scores. This was confirmed by significant differences across clusters for the positive ($p<0.0001$) and negative life events ($p<0.0001$).

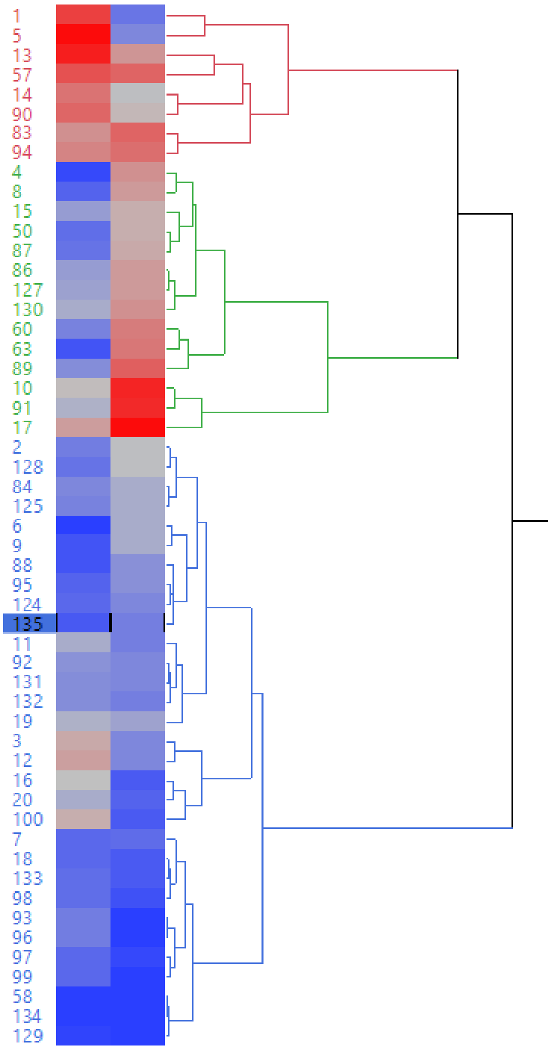


Figure 3.6.6a: Dendrogram from cluster analysis of LESCA negative and positive scores.

After a Bonferroni correction, the results of one-way analysis of variance (ANOVA) indicated that groups were different across positive life events. However, no significant difference between groups 2 and 3 was found regarding negative life events (Table 3.6.6b).

Table 3.6.6b: Comparison between clusters using ANOVA for negative and positive life events**.** 1: High negative, low positive life events; 2: Low negative, moderate positive life events; 3: Low negative, very low positive life events; *p<0.05.

Life events	Clusters		Mean Difference	95%CI	Sig.
Negative	1	2	69	57 to 82	<0.0001*
		3	73	61 to 84	<0.0001*
	2	1	-69	-82 to -57	<0.0001*
		3	3	-6 to 13	0.464
	3	1	-73	-84 to -61	<0.0001*
		2	-3	-13 to 6	0.464
Positive	1	2	-8.2	-15 to 1	0.022*
		3	14	8 to 21	<0.0001*
	2	1	8.2	1 to 15	0.022*
		3	23	18 to 28	<0.0001*
	3	1	-14	-21 to -8	<0.0001*
		2	-23	-28 to -18	<0.0001*

Comparison results between the three cluster groups for all the variables are presented in Table 3.6.6c. No statistical significance between the groups for all the variables was found apart for the age of first menstrual cycle (p=0.005). Post-hoc analysis revealed that the cluster 1 were the youngest group to have their first menstrual period, followed by cluster 2 and then cluster 3.

Table 3.6.6c: Comparison between clusters for anthropometric and strength variables. Significant at the p<0.05 level; N=newtons, cm=centimetres, kg=kilograms of body mass.

Variables	Clusters	Number	Mean (SD)	F	*p*
Age (years)	1	8	22.5 (2.9)	1.16	0.323
N=53	2	14	20.9 (2.9)		
	3	31	22.6 (3.9)		
Stature (cm)	1	8	163.9 (6.7)	0.83	0.444
N=52	2	14	167.6 (5.2)		
	3	30	167.4 (7.9)		
Body mass (kg)	1	8	72.7 (19.3)	1.16	0.321
N=53	2	14	75.7 (11.5)		
	3	31	69.1 (13)		
First menstrual Period (age)	1	8	11.4 (2.2)	5.89	0.005*
N=52	2	14	12.7 (1.4)		
	3	30	13.5 (1.4)		

Years of playing experience N=53	1	8	12.4 (5.7)	3.07	0.056
	2	14	8.4 (4.3)		
	3	31	12.3 (5.3)		
Eccentric knee Flexor Force (N) N=47	1	8	298 (81)	1.65	0.205
	2	13	287 (65)		
	3	26	255 (67)		
Eccentric knee flexor Absolute Nordic Imbalance (%) N=47	1	8	11.6 (5.8)	0.10	0.900
	2	13	13 (6.5)		
	3	26	13.3 (10.7)		
Isometric hip abductor Force-Pull 60° (N) N=47	1	8	248 (57)	0.19	0.830
	2	13	253 (53)		
	3	26	243 (48)		
Isometric hip abductor-Absolute Imbalance % pull 60° N=47	1	8	5.5 (5.4)	0.55	0.581
	2	13	6.6 (6)		
	3	26	5 (3.4)		
Isometric hip adductor force-Squeeze 60° (N) N=47	1	8	294 (47)	0.06	0.946
	2	13	300 (25)		
	3	26	300 (58)		
Isometric hip adductor-Absolute imbalance squeeze 60° (%) N=47	1	8	5.2 (1.9)	1.87	0.166
	2	13	3 (2.6)		
	3	26	3.4 (2.9)		
Isometric abductor force-Pull 90° (N) N=46	1	8	244 (64)	0.59	0.558
	2	13	245 (50)		
	3	25	226 (56)		
Absolute imbalance % pull 90°-Between-limb N=45	1	7	6 (4.3)	0.63	0.538
	2	13	7.7 (5.8)		
	3	25	9.1 (7.7)		
Isometric adductor force-Mean Squeeze 90° (N) N=47	1	8	295 (41)	0.85	0.436
	2	13	306 (37)		
	3	26	284 (58)		
Isometric Absolute imbalance % squeeze 90°Between-limb N=47	1	8	2.9 (3.2)	1.60	0.214
	2	13	5.2 (2.6)		
	3	26	3.6 (3.5)		
Jump height (cm)-Two limb average N=41	1	6	10.9 (3.9)	1.41	0.256
	2	12	8.8 (1.8)		
	3	23	9.7 (2.3)		
Absolute jump imbalance %-Between-limb N=40	1	5	13.2 (15.8)	0.83	0.443
	2	12	8.8 (8.3)		
	3	23	13.3 (9.7)		

Life events clusters were not associated with menstrual cycle regularity, however, athletes in the low negative and very low positive life events cluster (Cluster 3) had mainly regular menstrual cycle compared to the other two groups (Cluster 1 and 2) and irregular menstrual cycle was most common in the high negative and low positive life events score cluster (Cluster 1) (Table 3.6.6d). Athletes in cluster 3, were found to have 6.7 times higher likelihood of having a regular menstrual cycle, when compared to the athletes belonging to the cluster 1 (OR=6.7; 95%CI= 1.23-36.1) (Table 3.6.6e).

Furthermore, cluster membership was associated with one-year follow-up injuries (p=0.027). Where the cluster 3 had the highest proportion of uninjured athletes compared to the other clusters. Most notably, all athletes from cluster 1 sustained an injury (Table 3.6.6d). There was no cluster membership with taking oral contraception.

Table 3.6.6d: Association between clusters and lower limb one-year follow-up injuries, oral contraception and menstrual cycle. *p<0.05.

		Groups				
		High negative Low Positive (Cluster 1)	**Low negative Moderate positive (Cluster 2)**	**Low negative and very low positive (Cluster 3)**	**Total**	**Fisher's Exact test**
Lower limb injury (one-year follow-up) N=41	**Yes**	6	6	7	19	0.027*
	No	0	6	16	22	
Oral contraception N=52	**Yes**	1	3	13	17	0.190
	No	7	11	17	35	
Menstrual cycle N=50	**Regular**	3	8	24	35	0.067
	Irregular	5	4	6	15	

Table 3.6.6e. Univariate logistic regression analysis for the relationship between clusters and oral contraception, and menstrual cycle regularity. Relationship is significant at the p<0.05 level; OR=Odds Ratio.

Variables	**OR**	**95%CI**	**p**
Oral contraception (Ref: High negative, Low positive)			
Low negative moderate positive	1.9	0.16 to 22.2	0.605
Low negative and very low positive	5.4	0.58 to 49	0.138
Menstrual Cycle Regularity (Ref: High negative, Low positive)			
Low negative moderate positive	3.3	0.52 to 21.6	0.206
Low negative and very low positive	6.7	1.23 to 36.1	0.028*

3.7 Discussion

Study 3 presents the results of a prospective cohort study that examined the association between functional lower extremity muscle strength, negative life events, contributing risk factors (family ACL history, menstrual cycle history and oral contraception) and lower limb injuries in female team-sport athletes in order to answer the three research questions of this chapter. Principal components analysis was used to reduce the data of the eight hip strength measures: ADD and ABD, and between-limb imbalances, at 60^{o} and 90^{o}, and logistic regression determined the association between hip strength measures and the prospective occurrence of non-contact lower limb injuries. Ward's two-way cluster analysis was used to identify groupings within life events data, and one-way analysis of variance examined significant differences between cluster groups. Relative risk and odds ratios were calculated to assess the association between family ACL history, menstrual cycle history, use of oral contraception and lower limb injury risk in female team-sport athletes. The most notable finding that emerged from this study was that history of negative life events was a significant risk factor for lower limb injuries in female athletes. Additional observations of note included: 1) weak hip adductor strength, and between-limb adductor and abductor strength imbalances, were associated with risk of future non-contact lower limb injury; 2) other strength measurers including eccentric knee flexor strength, single leg jumping and between limb-imbalances were unaffected and did not infer an increased risk for lower limb injury; 3) a history of ankle injury and the use of oral contraception were associated with the subsequent lower limb injury; 4) yet, no association was found for the history of injuries, and menstrual cycle regularity and subsequent injury.

3.7.1 Association between negative life events and subsequent injury

As outlined in the dynamic, recursive model of aetiology in sports injury (Meeuwisse et al., 2007), the training environment and athletes' physical qualities cannot account for all sports injuries, therefore, attempts to identify psychosocial and personality factors related to injury risk require further investigation. The association found between negative life events and subsequent injury are in general agreement with several previous studies from a range of populations (Coddington and Troxell, 1980; Passer and Seese, 1983; Williams and Andersen, 1998; Gunnoe et al., 2001; Steffen, Paensgaard and Bahr, 2009). While most of the prior work has been specifically concerned with adolescent athletes in a sensitive psychosocial developmental phase, with less developed coping skills, it seems that negative life events affect adult athletes similarly (Ivarsson and Johnson, 2010). The relationship between psychological factors and injury risk is established, however, studies on female athletes are limited. Steffen, Pansgaard and Bahr (2009) examined female soccer players. However, their study included only adolescent athletes of soccer players, and the findings cannot be generalized to older female athletes from different sports.

Most stress-injury studies have focused on both negative and positive life events, however, it has been suggested that only negative life events place athletes at risk for injury, in both female and males. In comparison to prior work (where athletes were classified into high and low negative and positive life events), the athletes in the current study were grouped using a classification tool (Cluster Analysis) based on their positive and negative life events scores. Subsequently, three distinct clusters emerged with the following life events score characteristics: high negative and low positive; low negative and moderate positive; and low negative and very low negative and their independence was clarified statistically. All athletes classified with high negative and low positive life events sustained an injury suggesting that these life event characteristics should be considered a potential injury risk factor. Gunnoe and colleagues (2001) conducted a comparative analysis between athletes with high and low scores for positive and negative life events. In that study, athletes were placed in high and low negative and positive groups according to pre-set thresholds, which is a different approach to the current study, but they found that high negative life events were associated with prospective injuries. The link between injury with perceived negative life events is likely explained since being exposed to negative events requires more adaptive or coping skills on the part of the athlete compared to positive life events (Sarason, Johnson and Siegal, 1978). If an athlete does not perceive adequate resources to meet the situational demands, a stress response is triggered from accumulation of life stress and this seems to predispose the athlete to injury (Williams and Andersen, 1998). Andersen and Williams (1988) has suggested that stress can increase the risk of injuries via cognitive features (attentional perturbations such as peripheral narrowing) thought to predispose an athlete to injury. However, it is acknowledged that this is a complex issue and other factors such as hormones may also contribute to the stress injury relationship beyond peripheral narrowing. Specifically, psychological stress is related with the release of cortisol as a response to the stress. Increased exposure to high levels of cortisol has been linked with a suppressed immune system, depression, sleep disturbance and an increased risk of illness and injury (O'Connor et al., 1989; Kerr and Goss, 1996; Segerstrom and Miller, 2004; O’Donnell et al., 2008; Pawlow and Jones, 2002). Furthermore, the group with the highest proportion of athletes who reported having irregular menstrual cycles, were in the cluster that had high levels of negative life events, while both the other groups who reported fewer negative life events had far lower proportions of athletes with irregular menstrual cycles. Previous studies on the non-athletic population have suggested that women with high ‘life stress’ were more likely to have experienced irregular menstrual cycles (Yamamoto et al., 2009; Chang et al., 2009; Kollipaka, Arounassalame and Lakshminarayanan, 2013; Nagma et al., 2015). Although the exact underlying mechanism is not clarified, one mechanism linking stress with menstrual function occurs via dysregulation of the hypothalamic–pituitary–adrenal (HPA) axis which is a normal function of the psychosocial stress response. In turn, glucocorticoids have reciprocal interactions with ovarian hormones, which influence a woman’s menstrual cycle regulation (Chrousos, Torpy and Gold, 1998; Sanders and Bruce, 1999). Therefore, it may be possible that the athletes in the current study might not possess the necessary coping resources to mitigate the effects of any stressful life events they experience. In their model, Williams and Andersen (1998) proposed several coping resources that can moderate the relationship between life stress and injury occurrence. Coping strategies and social support are two mechanisms that can help athletes to deal with negative life events and unpleasant emotions, reducing the potential for injuries.

Well-developed coping skills are required for athletes to handle stressful situations (Radochoński et al., 2011). The importance of promoting coping skills is suggested to assist the athletes to control their feelings, attention and energy, thereby minimizing the exposition injuries. The role of personality variables in the stress injury model is strongly related to cognitive appraisal. Certain personality traits such as trait-anxiety and low self-confidence make some athletes perceive situations and events as less stressful or are less susceptible to the effects of the stressors (Petrie, 1993). However, the current study measured only the life events and did not explore the effects of coping resources on severity and frequency of injuries. Future studies should consider a more comprehensive treatment of Andersen and Williams's model including personality variables and coping resources. A future study of a larger sample population might help to elucidate the association between life events and menstrual cycle regularity and the potential role of coping resources in predicting injury.

3.7.2 Muscle strength and subsequent injury

Hip adductors and abductors strength

Previous studies have identified weak hip adductor strength as a risk factor for adductor muscle strain injury and as a result the introduction of strengthening exercises for prevention for hip/groin injury in male athletes is becoming a common practice (Tyler et al., 2001; Engebretsen et al., 2010; Delahunt, Fitzpatrick and Blake, 2017; Harøy et al., 2019). In the current study, athletes with greater hip adduction strength had significantly reduced the odds of suffering a future non-contact lower limb injury. In contrast, a previous study by Verrelst et al. (2018) using isokinetic testing for hip strength measurements found no association between lower limb injuries and hip adductors or abductors strength in female physical education students. Although, the authors of that previous study followed a prospective study design, the small number of injuries was limited to 34 and impact the statistical power. Additionally, the participants of Verrelst and colleagues (2018) study were physical education students, and may differ regarding the speed they run and change direction, training volume and exposure hours with the current study's players who were performing at national level. Elite athletes exhibit greater speed in running, change of direction and agility performance compared to other populations (Kaplan, Erkmen and Taskin, 2009; Trajković et al., 2020). High-speed running has been reported to increase the biomechanical load and the possibility of injury (Sado, Yoshioka and Fukashiro, 2019). Similarly, higher match and training volumes have been found as predictors for injury (Hartwig et al., 2019).

Despite being located on the inner thigh, the hip adductors (adductor longus and adductor magnus) adopt the role of hip extensors during functional activities such as in sprinting. When the hip is flexed, adductor magnus has a positional leverage to act as a hip extensor, and vice versa when it is in hip extension (Neumann, 2010; Mansfield and Neumann, 2013). Therefore, the adductors serve as a useful source of extension torque for the hip during common sporting activities for the players in the current study, such as sprinting.

Based on this, clinicians should consider the hip position when seeking to screen for injury risk and improve the strength of the hip extensors. Given, the paucity of female athlete data, based on the present observations from this study's data the role of hip adductor strength as a potential candidate for risk identification and mitigation for females deserves further work and may be a factor in the higher risk of knee pathologies.

In contrast, no association between hip abductor strength and injury risk was observed from the current study. This was an unanticipated finding, given a study by Khayambashi and colleagues (2016), previously identified the association between hip abductors and ACL risk injury. Moreover, when biomechanical analysis of both low- and high-intensity movements are considered, females adduct the hip more than males due to low hip abductor strength (McLean et al., 2003; Hewett et al., 2005; Hewett et al., 2006; Hewett et al., 2011). On reflection of the current non-significant and the strength of evidence from previous work, when screening athletes to assess injury risk during pre-season the inclusion of an isometric hip abduction strength assessment should still be considered worthwhile and not omitted.

Cohort studies in male athletes are mainly focused on the association between weak hip adductor muscles and groin injuries (Tyler et al., 2001; O' Connor, 2004; Engebretsen et al., 2010; Mosler et al., 2018). However, the findings from male athletes cannot be generalized to female athletes as gender differences in lower extremity muscle activation have been shown previously (Zazulak et al., 2005; Hanson et al., 2008; Brophy et al., 2010). Specifically, it has demonstrated decreased hip abductor activation and greater hip adduction in the supporting limb during the soccer kick in female athletes compared with males (Brophy et al., 2010). Additionally, female athletes were found to land with greater external hip adduction angles compared with males at initial contact during a single-leg agility maneuver (Hewett et al., 2005). Hip adduction moment has been associated to knee abduction moments in ACL injured athletes (Hewett et al., 2005). In a biomechanical study, female athletes performed a single-leg squat with greater hip adduction than their male counterparts suggesting that females may have difficulty controlling activation of gluteus medius, during a dynamic movement which will tend to move into adduction (Zeller et al., 2003). Furthermore, the current study included all lower limb injuries rather than only adductor muscle strains.

Bilateral reference values for hip strength in female athletes have not been reported previously, making comparison with normal values difficult. However, the study 2 presents normative data for the hip and knee flexor strength. In comparison with these, the obtained data of the current study seems to be weaker in all variables compared to the normative data. The difference ranged from 30 to 70 N for hip adductor and abductor strength, and when the reference value is compared with the injured group the difference increases, varying from 52 to 85N. It is commonly accepted that the Adductors: Abductors ratio can be used as a reference guide to determine the injury risk suggesting that a ratio <0.80 increases the possibility for groin injuries in male athletes and a ratio close to 1 indicates low risk for injury in male athletes. However, the current study identified ratios of: 1.24 (0.26) for 60°, and 1.44 (0.44) for 90° on the testing day. In comparison with the normative data found in study 2, an ideal ratio for 60° and 90° should be around 1.22 (0.04), and 1.23 (0.05), respectively. However, more studies are needed in female athletes to clarify the ratios associated with injury risk.

Between-limb hip adduction and abduction imbalance

In the current study, players with lower between-limb hip adduction and abduction had significantly reduced odds of suffering a future lower limb injury. Given that, this study is the first to investigate the association between hip adduction and abduction imbalance obtained at two different positions (60° and 90°) and lower limb injuries in female athletes, comparison to previous work is not possible and the mechanism(s) underpinning the observed effect remain unclear.

Imbalance may persist in athletes for a number of reasons and predispose. This may be due to repetitive asymmetrical sport-specific demands (kick, changes of direction), previous injury, pain and incomplete recovery (Rahnama, Lees and Bambaecichi, 2005; Schiltz et al., 2009; Castanharo et al., 2011; Fulton et al., 2014; Fort-Vanmeerhaeghe et al., 2016).

The hip muscles assist in the stabilisation of the pelvis and leg alignment in all three movement planes, frontal, sagittal, and transverse plane (Power, 2010). The hip abductors act as a dynamic stabilizer of the pelvis by eccentrically controlling femoral internal rotation and influencing hip adduction during weight-bearing and functional activities, and impairment can lead to dysfunction in the kinetic chain and injuries of the lower extremity (Souza et al., 2010). For example, previous studies in female athletes with unilateral patellofemoral pain have demonstrated weaker ipsilateral hip abductors whereas uninjured controls had no side-to-side difference. While another study reported significantly weaker abductors on the involved side of runners with unilateral lower extremity overuse injuries (Niemuth et al., 2005; Cichanowski et al., 2007).

It has been suggested that weak hip abductors alter joint kinematics predisposing players to a greater hip adduction and medial rotation causing increased knee dynamic valgus angle which with weight bearing activities will be more excessive leading to a heightened risk of ACL injury (Ireland et al., 2003; Souza et al., 2010). This increased valgus motion at the knee can lead to altered patellofemoral tracking and increases lateral patellar-contact pressure which repeatedly can cause pain and injury to the patellar retinaculum, retropatellar articular cartilage, and subchondral bone (Fulkerson, 1983; Fulkerson, 2002; Ireland et al., 2003).

The injured group had significantly higher between-limb strength asymmetry in isometric adductor strength compared with the uninjured group; however, the observed group difference was not ≥ 10% as has been suggested previously of other muscle groups (Knapik et al., 1991; Rahama, Lees and Bambaecichi, 2007). Hip adductor asymmetry has been studied previously in relation to the risk for groin injuries. In our study, however, all lower limbs injuries were included in the analysis. Therefore, direct comparison with prior work due to these differences is precluded. Additionally, previous studies are focused on male athletes as the groin injuries rate is 2.5 times greater than women due to sex-related differences in groin anatomy as well as pelvic and hip joint morphology (Orchard, 2015;

Schache et al., 2016). More specific, women have a wider true (or lesser) pelvis, with greater mediolateral diameter of the pelvic inlet and the pelvic outlet and the angle between the inferior pubic rami in women is larger than in men (Tague, 2000). Thus, the frontal plane angle between body midline and the line-of-action of the hip adductors is probably greater for females than for males (Schache et al., 2016). Therefore, future studies should prospectively evaluate whether preseason training is effective at reducing the incidence of risk for lower limb injuries.

Eccentric knee flexor strength

Retrospectively, the current study found significant between-limb asymmetry (>10%) in eccentric knee flexor strength in the injured group when compared to those who had reported no previous injuries; and this finding suggests that those previously injured athletes have persistent strength deficits or imbalance despite returning to training and competition, following an injury; with strength deficits or possibly as a function of compensatory mechanisms, the acute impact of neuromuscular inhibition had led to asymmetrical loading leading to chronic strength deficits. Previous studies have found that female athletes with a history of lower limb injury display deficits that persist for years suggesting the possible presence of neuromuscular inhibition. Specifically, it has been found that elite athletes with a history of ACLR had deficits in eccentric knee flexor strength for up to 10 years following surgery (Bourne et al., 2019; Messer et al., 2020). Similar findings were shown in male athletes where eccentric knee flexor strength deficits were observed 1-9 years after ACLR (Timmins et al., 2016). In addition, asymmetry is observed in athletes with a history of previous hamstring injury (Ribeiro-Alvares et al., 2020).

In the current study, a small effect size (d=0.39) was observed for the comparison between eccentric knee flexor between-limb imbalance in previously injured and uninjured which raises the prospect that this study was insufficiently powered to identify this unexpected difference. However, in the one-year follow-up, the eccentric knee flexor strength and between-limb imbalance was not identified as a risk factor for prospective lower limb injuries. This may be due to other factors having greater impact, or the sample size was smaller in the one-year follow-up and this may be underpowered or unable to detect the desired difference.

Single leg Jumping performance

Vertical jumping is widely used as a surrogate measurement of lower limb muscle function. It is also commonly used to evaluate injury risk, and to assist with return to sport decision-making (Hewit, Cronin and Hume, 2012). Substantial lower limb asymmetry with regard to strength has been suggested as an important risk factor for sport injuries and linked to sports performance decrements (Newton et al., 2006; Impellizzeri et al., 2007; McElveen, Riemann and Davies, 2010). The results of the current study indicated that female athletes with between-limb asymmetry greater than 10% were not associated with the risk of lower extremity injury. Prior work by Fort-Vanmeerhaeghe et al. (2016) using a similar protocol to the current study in uninjured female athletes found jump heights to be 11.1 (2.5) cm for the weak limb and 12.7 (2.8) cm for the stronger, and deficits between-limbs to be 14.3 (10.4)% (Fort-Vanmeerhaeghe et al., 2016). However, the participants in the Fort-Vanmeerhaeghe et al. (2016) study were basketball and volleyball players, and thus, higher jump heights than the current study's findings could be explained. However, authors found higher imbalance between-limb than the current study suggesting that a 10-15% threshold of between-limb asymmetry strength could be considered as normal physiological variability (Fort-Vanmeerhaeghe et al., 2016).

The evidence whether the physical demands of sport lead to different jumping scores or if all the athletes performed similarly is not conclusive (Myers et al., 2014). Although there are few studies correlating the between-limb imbalance with ACL reinjury (Paterno et al., 2010), there does remain a lack of consensus about the real relationship between-limbs asymmetry and the potential risk of sports injuries. Future studies should examine single leg test scores that are specific to athlete gender, age, sport, and level of physical activity.

Strengths and limitations

One strength of the current study was the tool that was used for measuring the life events. According to Petrie (1992), LESCA tool is a valid measure of life stress, especially for the negative score, and found a better predictor of athletic injury than other tools (Petrie, 1992). Unfortunately, in the current study, some of the athletes were less than 18 years old and could not use the LESCA questionnaire. LESCA includes items not suitable for children, such as: death of a close family member or friend; breaking up with partner; marriage; failing an important exam or course. Further studies are required to develop a validated life events questionnaire suitable for younger athletes.

The use of life event scales in research studies have come under scrutiny as a result of their retrospective nature whereby participants are asked to report those life events that they have experienced during the previous year. However, problems of memory recall or biased recall may be obstacles with this format. It may be possible that athletes exaggerated their past events in order to justify subsequent injuries, reporting more life events in attempt to explain their difficulties (Rabkin and Struening, 1976). Another potential limitation of the current study is that the sample consisted only of elite female athletes; this may limit the degree to which the results can be generalised to other performance levels, or gender.

Finally, there is a lack of athlete exposure data (training time and competitive participation) and injury severity information from the institutions, and these did not allow the determination of injury incidence relative to their exposure to training and match play (per 1000 athletes' exposure hours [EAs]). Therefore, in our study, the variable of injury was treated as binary and differences in the psychological profile of a player who sustains a minor injury compared to another who sustained one more severe could not be evaluated. Sports injury data are usually reported as incidence rates per 1000 hours played, and less often total number of injuries and number of matches played, taking account of the exposure time at risk (Phillips, 2000). Incidence rates that do not consider exposure may present difficulties when used in injury incidence comparison in further epidemiological analysis, such as a meta-analysis.

To develop a prevention strategy, suitable injury definitions need to be used for all epidemiological studies. An important issue that has been on debate is the identification of the most suitable definition of an injury. Although the definition of injury sustained in association with sports participation by Fuller et al. (2007) is used widely, there is still a debate about the correct way of reporting injuries. Fuller's injury definition provides three different injury definitions: "any physical complaint", "medical attention injury" and "time loss injury". However, the choice of injury definition can influence the injury rate reported in studies, as players don't always seek medical attention, and not all injuries result in time-loss from competition and training. Therefore, the "physical complaint" definition could lead to a higher injury rate compared to the ''medical attention'' definition with the "time loss" definition demonstrating the lowest rate (Bahr, 2009). For example, the ''time-loss'' definition can have inherent limitations in individual sports where competition events are seldom with only few time-loss injuries but an abundance of overuse/chronic performance-limiting injuries (e.g., track and field, gymnastics, swimming) (Bahr et al., 2009). It has been reported that the missed match time definition is the most functional, accurate, and quite likely the only time loss system that can reliably capture 100% of the defined data (Orchard and Hoskins, 2007). However, as not all health problems affect an athlete's participation, broader definitions (self-reported, symptom-based, or performance based) may be useful to capture more health problems (Bahr et al., 2020).

The current study conducted measurements of lower limb function only once at the beginning of the season, and strength modifications following the season could have occurred that could predispose the athlete to injury. However, it has been observed by previous work that muscle strength measures can remain stable, and that the little changes that may occur in dominant legs compared with non-dominant sides are within the range of the standard error of measurement (van Klij et al., 2021). In addition, the more frequent measures of eccentric knee flexor strength across a season does not improve the ability to predict future hamstring strain injuries (Opar et al., 2021).

The present study included adult but also a proportion of young female athletes (51%) during their puberty stage which could affect the muscle strength through the season. Strong association between muscle strength and chronological age and anthropometric characteristics (such as height and weight) have been reported, previously (Seger and Thorstensson, 2000). Specifically, it has been found that females had an increase 52-53% for concentric, and 56-59% for eccentric knee extensors strength between the age of 11 and 16 years old (Seger and Thorstensson, 2000). However, this may be due rather, to the training age, where great responses to strength training during adolescence have been noticed (Dahab and McCambridge, 2009). Therefore, future cohort studies should consider the factor of growth and maturation when young athletes are included in lower limb function testing.

3.7.3 Oral contraception, previous ankle injury, familial history as risk factors

Other potential risk factors that emerged from the data analysis included oral contraception use, previous ankle injury, and familial history of ACL. The ankle is the one of most frequently injured joints in sports (Roos et al., 2017; Andreoli et al., 2018). The current study found that players who self-reported a history of ankle injury were at increased risk of lower limb injury. After an ankle injury, postural stability and muscle recruitment patterns at the hip and ankle can be altered which may have an effect on future episodes of injury. Evidence to support previous ankle injury as a risk factor for future injury has been found which showed a decreased latency of hip muscle activation observed after ankle inversion in the hypermobile population while participants with unilateral chronic ankle sprains had weaker hip abduction strength and less plantar-flexion range of motion on the involved sides (Beckman and Buchanan, 1995; Friel et al., 2006). The current study found increased hip abductor imbalance in injured athletes compared to uninjured. Hip abductors control the lateral pelvic tilt and foot placement during the swing phase of gait depends on hip adductor and abductor moments (MacKinnon and Winter, 1993; Friel et al., 2006). If strength of the hip abductor muscles have been altered because of a previous injury, the position of the foot at initial contact may be more adducted than normal, and the risk for reinjury is increased (MacKinnon and Winter, 1993; Friel et al., 2006).

While training age, sporting experience, anatomic and biomechanical factors likely contribute to this sex disparity in sports injuries, there is some evidence that female hormones, such as relaxin, estrogen, and progesterone suggest a connection with musculoskeletal injuries. Receptors for relaxin, estrogen, and progesterone have been found on a variety of musculoskeletal tissues including the lateral collateral and ACL ligaments, and patellar, Achilles, and posterior tibial tendons (Dragoo et al., 2003; Faryniarz et al., 2006; Bryant et al., 2008; Hansen et al., 2009; Bridgeman et al., 2010; Dehghan et al., 2014). Therefore, studies have attempted to investigate the potential effects of hormones on musculoskeletal (MSK) injuries.

In the current study, players who reported use of oral contraception had less injuries. This finding could support in part the hypothesis that hormonal contraceptives change levels of the relaxin, estrogen, and progesterone affecting MSK function. Receptors of estrogen and progesterone have been localized in ligament tissue suggesting that hormones may influence the mechanical ligament structure and physical properties (Liu et al., 1996; Liu et al., 1997; Sciore et al., 1998). Oral contraception is an exogenous source of synthetic hormones, and therefore, may have the potential to modulate ligament structure and laxity (Martineau et al., 2004). From the little evidence available, it suggests that oral contraception improves postural balance preventing ACL injuries (Martineau et al., 2004; Maged et al., 2007). However, limited analysis has been done to determine the impact of specific contraceptive formulations on ligaments, tendons, and muscles in vitro and in vivo (Konopka, Hsue and Dragoo, 2019).

Family history of ACL has been associated with ACL tears in athletes (Myer et al., 2014; Goshima et al., 2014; Hägglund et al., 2016). In the current study, these previous reports were confirmed and participants with familial predisposition to ACL were four times more likely to sustain an ACL injury. Hägglund et al. (2016) found that female footballers who had a parent or a sibling with a history of ACL injury had more than three times the risk of ACL injury, while Vacek et al. (2016) found the risk was almost five times higher compared to those with no family history of ACL injury. The idea of familial predisposition towards ACL injury has led researchers to investigate genetic factors. Specific genes related to collagen with different polymorphism has been associated with ACL tears (Posthumus et al., 2009; Posthumus et al., 2010; John et al., 2016). In addition, gender differences between females and males in the expression of three genes (ACAN, FMOD, and WISP2) related with structure and integrity of ligaments have been found. Further genetic investigation into familial susceptibility to ACL injuries is needed and should address the morphological characteristics and similarities between siblings and female athletes with ACL injuries (Johnson et al., 2015).

In conclusion, negative life events were found to play an important role in female players who sustain a lower limb injury. This should be considered and monitored when working with female athletes. If athletes do present having reported to being exposed to negative life events, a contingency plan and intervention should be deployed to offset.

Greater hip adduction strength and lower between-limb adductor and abductor imbalance can reduce the likelihood of subsequent lower limb injury in female athletes. Although, in the current study, a small effect size (d=0.43) was observed for the comparison of hip adductor between-limb imbalance at 90^o; a medium effect size (d=0.56) was presented for the comparison of hip abductor between-limb imbalance at 60^o in all lower limb injured and uninjured athletes and for hip adductor between-limb imbalance at 90^o in noncontact injured and uninjured athletes in one-year follow-up indicating some clinical value in importance of hip adductors strength and imbalance between-limbs. These findings may have implications for injury screening and may inform the design of interventions or prevention training targeted at reducing injuries in female athletes.

Chapter 4: Effects of menstrual cycle on muscular strength in female soccer players (Study 4)

4.1 Abstract

Background/aim: With more women engaged in sport than ever before, the demand to better understand the physiological and metabolic responses to exercise, and potential influencing factors such as the sex hormones is high. During the menstrual cycle, sex hormone concentrations fluctuate across the different phases, but the impact on the musculoskeletal system remains unclear. Current opinion suggests that subsequent sex hormone concentration fluctuations as a result of the menstrual cycle impact strength and can be linked with athletic performance and injury risk. Therefore, the aim of this study was to explore the effect of the menstrual cycle phases on the muscle strength in lower limb in female footballers.

Methods: Nine elite female soccer players with regular menstrual cycle participated in this study. Menstrual distress, and isometric hip and groin, eccentric hamstring strength, and single leg jumping were tested during the follicular, ovulatory and luteal menstrual phases.

Results: Isometric hip adductor strength at 60° peaked (p=0.006) during the follicular phase compared to ovulatory and luteal phases in female soccer players. A greater overall menstrual distress symptoms score was reported in the follicular phase (29.9 ± 35.1), followed by the luteal phase (27.6 ± 26.7), with the fewest complaints occurring in the ovulatory phase (3.9 ± 4.6). Soccer players reported significant impaired concentration (p=0.05), behavioural change (p=0.003), water retention (p=0.04), and negative effects (p=0.01) in the follicular, compared to the ovulatory menstrual cycle phase. No evidence of strength fluctuations was observed in all other measures across menstrual cycle phases.
No evidence of strength fluctuations was observed in all other measures across menstrual cycle phases.

Conclusion: Female soccer players with regular menstrual cycle had greater hip adductor strength and menstrual distress symptoms during follicular phase. Based on the findings of study 3, hip adductor strength is a risk factor in lower limb injuries in female athletes. The hip adductors play an important role in stabilizing the pelvis and have synergies with hip flexion and extension torque during sporting movements affecting the sprint running performance. Therefore, an abnormal performance of hip adductor strength may alter the distribution of forces across the joint, affecting performance and predisposing the athlete to muscle strain injuries while running at high velocities. Thus, fluctuations in muscle strength across menstrual cycle phases may affect joint stability which during sporting activities, increases the risk for injury. Sports professionals working with female athletes need to consider the menstrual cycle and be aware of the fluctuations across the cycle whereby exercise performance might be enhanced (follicular phase) or reduced (ovulatory and luteal phases). Education for athletes and staff should be provided to improve symptom management, protecting athletes from negative effects on athletic performance and thus of injury occurrence.

4.2 Introduction

Physiological and morphological differences exist between sexes (Lewis, Kamon and Hodgson, 1986). Sex has been identified as an important determinant of sport performance through the impact of anthropometric features (stature, body mass, body fat, muscle mass), aerobic capacity or anaerobic threshold due to genetic and hormonal differences (Thibault et al., 2010). A distinguishing feature that is present in those with primary female characteristics and not in those with male primary characteristics is the menstrual cycle. The menstrual cycle is controlled by the endocrine system, and it has a duration of 28 days (range: 21-35 days) (Popat et al., 2008). The menstrual cycle can be divided into three phases: follicular phase, ovulation, and luteal phase where four hormonal markers (oestrogen, progesterone, follicle stimulating hormone (FSH) and luteinising hormone (LH)) fluctuate continuously and characteristically throughout the cycle (Frankovich and Lebrun, 2000; Silberstein and Merriam, 2000; De Jonge et al., 2001; Popat et al., 2008).

Fluctuations in female steroid hormones affect the autonomic nervous system, which plays a key role in cardiovascular parameters (heart rate, arterial pressure, the myocardial contractility, venous capacitance) and in metabolic functions so, therefore, may also impact on physiological parameters (via fluid retention, changes in body temperature, and energy metabolism) and on athletic performance (Becker et al., 1982; Florini, 1987; Souza and Tezini, 2013). In the last decade, the increasing participation of women in sports has driven scientific interest to better understand the physiological and metabolic responses of women to exercise, and the potential impact of female hormones on sports injuries. Therefore, a variety of studies have investigated whether female hormones affect laxity, muscle strength, balance and neuromuscular control since any detriment would likely increase the risk of the athlete sustaining a non-contact injury (Dedrick et al., 2008; Lee and Yim, 2016; Yim, Petrofsky and Lee, 2018). Specifically, studies have proposed that the increased hormone concentrations that occurred during the menstrual phases affected the integrity and laxity of the ACL, increasing the risk for injury (Yu et al., 1999). Although, there is evidence that injuries are associated with menstrual phases, the findings were, and remain, controversial. Specifically, studies conducted by Adachi et al. (2008) and Wojtys et al. (2002) revealed a significant increase of non-contact ACL injuries in female athletes during the ovulatory phase compared to other phases, while Beynnon et al. (2006) reported greater injury rate during the follicular phase. However, the evidence is limited and additional studies are needed to address the effect of hormones on the musculoskeletal system.

4.3 The skeletal muscle

Skeletal muscle play essential roles in human physiology by enabling locomotion and movement, enhancing blood flow to organs, and protecting vital body's organs (Goodman, Hornberger and Robling, 2015). Skeletal muscles are contractile organs which produce skeletal movement, maintain posture by stabilizing joints, support soft tissues, regulate the entry and exit of material (swallow, urination, defecation) and maintain body temperature (used energy for muscle contraction produce heat) (Martini, Tallitsch and Nath, 2017). They are comprised by multiple individual muscle fibers bound together by connective tissue that are stimulated by motor neurons (Kuo and Ehrlich, 2015). Muscle fibers are grouped together and with motor neuron form the "motor unit" (Kuo and Ehrlich, 2015).

Each skeletal muscle has three concentric layers, epimysium that surrounds the entire skeletal muscle; perimysium, which divides muscle into internal compartments and wraps bundles of muscle fiber; and the endomysium that surrounds each skeletal muscle fiber (Figure 4.3a) (Martini, Tallitsch and Nath, 2017). At the end of the muscle, collagen fibers of these three layers come together and form a tendon that's attaches the muscle to the bone, cartilage, skin, or another muscle (Martini, Tallitsch and Nath, 2017). Within the connective tissues, nerves and blood vessels lie to supply the muscle fibers (Tortora and Nielsen, 2014; Martini, Tallitsch and Nath, 2017).

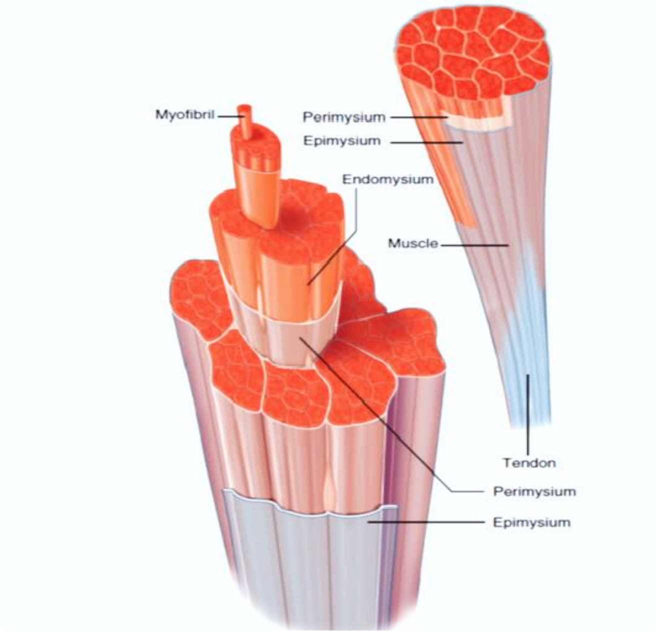


Figure 4.3a: Skeletal muscle structure.
Adopted from: Luomala and Pihlman (2017).

The motor neurons have two parts, the upper and lower motor neurons which connect the motor cortex and muscles (Harvey, 2008). The upper motor neurons originate within motor cortex and travel down the spinal cord with their axons and innervates α (alpha) and γ (gamma) motor neurons in ventral horn and the lower motor neurons are located in ventral horn of spinal cord and with their axons travel to peripherally to innervate muscles (Harvey, 2008). The contraction of skeletal muscle is controlled by the two types of lower motor neurons, α and γ. The alpha motor neurons innervate skeletal muscle (extrafusal muscle), while the gamma motor neurons innervate muscle spindle (intrafusal muscle) (Shapira, 2007). Therefore, α motor neurons cause the contraction of extrafusal muscle fibers upon stimulation and control muscle contraction involved in voluntary movement; whereas γ motor neurons cause the contraction of intrafusal muscle fibers and control muscle contraction in response to external forces acting on the muscle (Parent, 1996). In regard to these external forces, the γ motor neurons induce the involuntary reflexive movement called the stretch reflex (Parent, 1996).

4.4 Menstrual cycle

Menstruation is the cyclic, orderly shedding of the uterine lining, in response to the hormones' interactions produced by the hypothalamus, pituitary, and ovaries (Popat et al., 2008; Maggi et al., 2016). The Hypothalamus, Pituitary, and Ovaries form an endocrine axis (HPO axis) that functions via hormonal regulation governing the regulation of menstruation (Figure 4.4a) (Speroff and Fritz, 2005; Popat et al., 2008; Maggi et al., 2016).

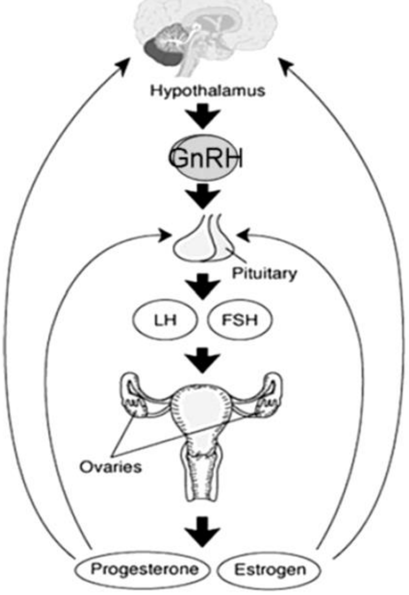


Figure 4.4a: Hypothalamic-pituitary-ovarian axis.
LH and FSH stimulate the ovaries to produce estrogens and progesterone. Depending on the phase of the menstrual cycle, those hormones act back on the hypothalamus and pituitary gland in either a stimulatory or inhibitory manner (Hiller-Sturmhofel and Bartke, 1998). Adopted from: Popat et al., (2008).

Hypothalamus is the ultimate control centre which contains several types of neurons responsible for secreting different hormones that are released into the blood and travel in portal veins to a capillary bed in the anterior lobe of the pituitary where they exert their effects (Brisken and Ataca, 2015). These hypothalamic releasing hormones are the Thyrotropin-Releasing Hormone (TRH), Gonadotropin-Releasing Hormone (GnRH), Growth Hormone-Releasing Hormone (GHRH), Corticotropin-Releasing Hormone (CRH), Somatostatin, and Dopamine (Figure 4.4b).

In anterior pituitary lobe, the tropic hormones that are produced are: Adrenocorticotropic Hormone (ACTH), Growth Hormone (GH), Luteinising Hormone (LH) and Follicle Stimulating Hormone (FSH) (also known as gonadotrophins), and Thyroid Stimulating Hormone (TSH) (Brisken and Ataca, 2015). Hypothalamic central nervous system discharges GnRH which is transported to anterior pituitary, where they stimulate the Gonadotrophs, and in turn the gonadotropins FSH and LH are synthesized, stored, and secreted (La Rosa et al., 2000; Speroff and Fritz, 2005; Popat et al., 2008). Tropic hormones act at another endocrinal glands for the production and secretion of other hormones (Koeppen and Stanton, 2009). Therefore, trophic hormones stimulate the gonads to synthesize and secrete sex steroids that are responsible for the maturation of the reproductive systems and for the development of secondary sex characteristics. Menstrual cycle is the result of the integrated action of the HPO axis and endometrium and any disruption in the HPO axis may result in menstrual cycle disturbances (Speroff and Fritz, 2005; Rosenwaks and Wassarman, 2014). Endometrium, the lining of the body of the uterus changes morphologically its thickness during the menstrual phases as respond to an endocrine environment in preparation for implantation or by shedding its lining in preparation for a new cycle (Keefe and Wright, 2007; Patel, 2008; Clancy, 2009).

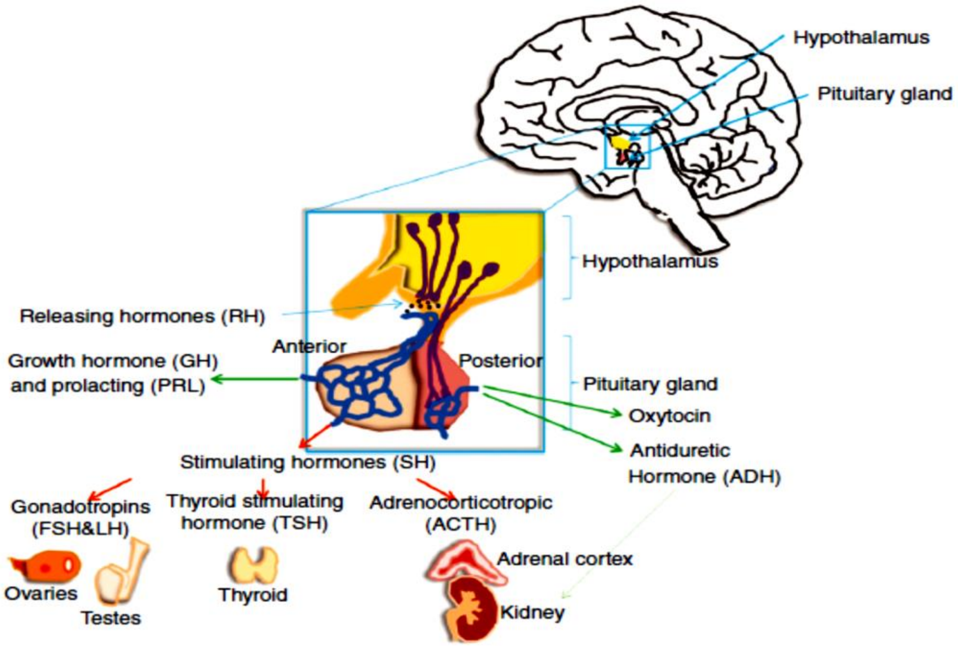


Figure 4.4b: Scheme of hypothalamus-pituitary axis in endocrine system.
Adopted from: Brisken and Ataca (2015).

A female's menstrual cycle has median length of 28 days (Silberstein and Merriam, 2000). Women with menstrual cycles that occur at intervals less than 21 days are termed polymenorrheic, while women with menstrual cycle greater than 35 days, are termed oligomenorrheic (Popat et al., 2008). Absence of menstruation is referred to amenorrhea, which is divided in primary and secondary. Primary amenorrhea is the failure of menses to begin by age 16 years, in the presence of normal growth and secondary sexual characteristics while secondary amenorrhea is referred as the cessation of menses once they have spontaneously begun (Popat et al., 2008).

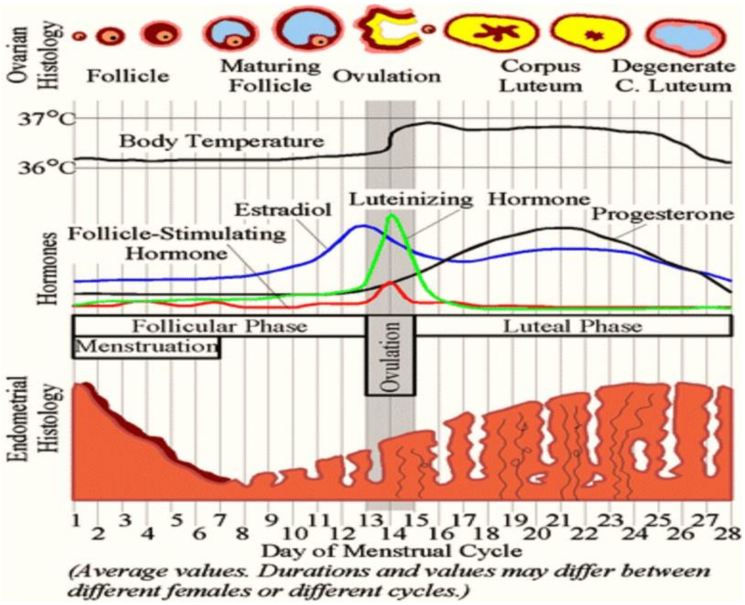
Menstrual cycle is divided into three phases: the follicular phase, the ovulation, and the luteal phase where hormonal changes are occurred continuously throughout the cycle (De Jonge et al., 2001). The follicular phase (or proliferative phase) is the phase which ovarian follicular growth, and results with ovulation; ovulation is the phase in which a mature ovarian follicle ruptures and discharges an ovum (also known as an oocyte, female gamete, or egg), and the luteal phase (or secretory phase) is the latter part of the menstrual cycle and ends before a menstrual period (Frankovich and Lebrum, 2000; Bhagavan and Ha, 2011). The duration of luteal phase is relatively constant 14 days; however, the variability of cycle length is usually derived from varying lengths of the follicular phase (Rosenfield, Cooke and Radovick, 2014). The follicular phase starts on the first day of bleeding (Buffet et al., 1998).

During the menstrual cycle, hormones change between the phases (Figure 4.4c); estrogen starts to rise in the late of the follicular phase reaching its peak before the ovulation phase and then estrogen and progesterone increase in the middle of the luteal phase before returning to baseline (Frankovich and Lebrun, 2000; Draper et al., 2018). The reproductive axis controls the process leading to ovulation and preparation for implantation of the fertilised ovum in the uterus (Cable and Elliott, 2004). More specific, during the follicular early phase, FSH rise which stimulates the development of follicles and the secretion of 17β–Estradiol (Jones and Lopez, 2013). The increase in Estradiol during this phase causes the uterine endometrium to profilate (thickness) and becomes more richly supplied with blood vessels, and water accumulates between cells in the tissues and the smooth muscle of the myometrium begins to contract mildly (Jones and Lopez, 2013). The rise of estradiol levels reaches a maximum (peak) on the 12th day (of a 28–day cycle), while follicles growth in size (Jones and Lopez, 2013). After the peak in estradiol, a surge of LH occurs and cause the ovulation of the follicle. Usually, one large follicle presents by the 13th day in one ovary (Jones and Lopez, 2013).

The levels of progesterone and FSH remain low in the follicular phase until just before ovulation; then progesterone levels rise slightly before ovulation, and a slight FSH surge accompanies the greater LH surge (Jones and Lopez, 2013).

The luteal phase starts after ovulation where a corpus luteum is formed from the wall of the follicle that ovulated (Jones and Lopez, 2013). Estradiol and progesterone are secreted and rise in the middle of the luteal phase; and about 4 days before menstruation begins, they decline, while the corpus luteum starts to degenerate (Jones and Lopez, 2013). If the fertilization does not occur, the corpus luteum degenerates (luteolysis) and stops secreting progesterone (Hinson, Raven and Chew, 2010). The decrease of progesterone secretion causes the breakdown of the endometrium and the signals the start of menses (Hinson, Raven and Chew, 2010).

These hormonal changes affect the female body, with numerous physical and emotional effects occurring (Premenstrual syndrome) (Muizzuddin, Marenus and Schnittger, 2005).



(Average values. Durations and values may differ between different females or different cycles.)

Figure 4.4c: Hormonal fluctuations over the menstrual cycle.
Adopted from: Farage, Neill and MacLean (2009).

4.5 Sex Steroid Hormones

Hormones produced by the human body can be categorized into four classes based on their chemical composition: steroids, peptides, amino acids, and fatty acids (Hu et al., 2010). Steroid hormones are derived from cholesterol and are contained to five major classes: testosterone (androgen), estradiol (estrogen), progesterone (progestin); and corticosteroids hormones which contains cortisol/corticosterone (glucocorticoid), and aldosterone (mineralocorticoids) (Hu et al., 2010).

Testosterone, progesterone, and estradiol are classified as sex-steroids (Hu et al., 2010). Estrogens, progesterone, and androgens in women and androgens in men determine the phenotype and modulate gametogenesis and reproductive function (Fauser et al., 2011).

Steroid hormones are a major determinant of reproductive health in the sexes and display important physiological functions and exert pleiotropic effects on many target organs such as on the gonads, the liver, and the nervous system (Diotel et al., 2018).

They play several important physiological roles, such as the inflammatory response, metabolic regulation, electrolyte balance, reproduction functions, cardiovascular fitness, and can influence behaviour, cognition and mood (Garcia-Gómez and González-Pedrajo, 2012; Del Rio et al., 2018).

Estrogen

Estrogens play key roles in development and maintenance of normal sexual and reproductive function, but they also exert major biological effects in the cardiovascular, musculoskeletal, immune, and central nervous systems (Gustfsson, 2003). A reduction or insufficiency in estrogen can be due to particular conditions such as hypogonadism, hypopituitarism, anorexia nervosa, surgical ovariectomy, chemotherapy, perimenopause, or menopause (Haizlip, Harrison and Leinwand, 2015; Kitajima and Ono, 2016).

Estrogens are produced from cholesterol primarily in the ovaries, corpus luteum, and placenta, although small but significant amounts can be produced by extragonadal organs such as the liver, heart, skin, and brain (Figure 4.5a) (Cui, Shen and Li, 2013). Estrogen is present in three different forms in females: Estrone (E1), Estradiol (E2, or 17β-estradiol), and Estriol (E3) (Cui, Shen and Li, 2013). E2 is the most potent Estrogen during the premenopausal period, E1 is more important after menopause, and E3 is the least potent Estrogen and it plays a larger role during pregnancy when it is produced in large quantities by the placenta (Ciu, Shen and Li, 2013).

Estrogen has been found to affect fiber size, overall muscle weight, muscle regeneration, and contractility, and to induce minimal changes in fiber-type distribution positively (Haizlip, Harrison and Leinwand, 2015). This could be explained by the fact that estrogen receptors are present in all musculoskeletal tissues (muscle, ligaments, tendon, and bone) (Liu et al., 1996; Wiik et al., 2003; Wiik et al., 2009; Bridgeman et al., 2010; Barros and Gustafsson, 2011; Ciu, Shen and Li, 2013; Luo and Kim, 2016).

Estrogens act via two types of receptors: nuclear receptors, the ERa and ERb; and cell-membrane receptors, the GPR30 and the ER-X (Ciu, Shen and Li, 2013). The receptors ERα and ERβ have reported to be expressed at mRNA level in human skeletal muscle affecting protein levels by circulating estrogen levels (Lemoine et al., 2003; Wiik et al., 2009; Baltgalvis et al., 2010). Also, receptors ERα and ERβ are needed for the glucose homeostasis maintenance with ERb predominating in the skeletal muscle and ERa in the adipose tissue (Barros et al., 2009, Barros and Gustafsson 2011; Dey et al., 2013).

Based on this, and given the sex differences in musculoskeletal injury risk and the growing number of active young women, several studies have suggested that estradiol fluctuations during the menstrual cycle affect musculoskeletal system and tissue properties.

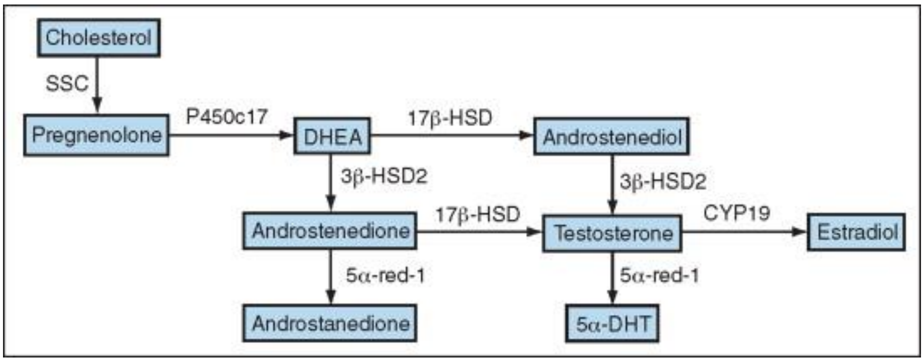


Figure 4.5a: Sex hormones synthesis pathways.
Adopted from: Lip and Hall, 2007.

Effects of estrogen on musculoskeletal

Ligament laxity

The periodic estradiol fluctuations during the menstrual cycle have been associated with increased ligament laxity. Estrogens' receptors have been identified in human ACL cells and are composed of collagen fibers. Therefore, it has been proposed that estrogen concentration may affect the structure and composition of the ACL and increase susceptibility to damage (Liu et al., 1996; Wojtys et al., 1998; Yu et al., 1999). Specifically, Liu et al. (1997) found from an animal study that ACL cultured fibroblasts exposed to supraphysiologic levels of 17B-estradiol had a 40-50% reduction in collagen synthesis. Additionally, using a rabbit model an estrogen treatment group had decreased tensile properties of the ACL and a subsequent decrease in the ACL failure load compared to the controls (Slauterbeck et al., 1999). Although the underlying mechanism of ACL injury in female athletes is yet to be defined, it is suggested that when estrogen concentration is high, ligament integrity may be altered, increasing the risk for injury.

Furthermore a study confirmed the effect of hormones on knee laxity brought by measuring knee laxity across menstrual phases in female athletes. Specifically, during the follicular phase, knee laxity was 4.7(0.8) mm while at the ovulatory phase it was 5.3 (0.7) mm. The findings suggest that knee laxity was affected by higher levels of estrogen during the ovulatory phase that may increase the propensity for injury (Deie et al., 2002). As the main role of knee ligaments is to provide stability and maintenance of large forces during activities, hormone fluctuations could explain the higher incidence of ACL injuries in female athletes compared to their male counterparts due to their higher anterior translation during menstrual cycle phases (Arendt and Dick, 1995; Myklebust et al., 1998; Prodromos et al., 2007; Waldén et al., 2011a, b; Mansfield and Neumann, 2013). A meta-analysis, reported that anterior knee translation is lowest during the follicular phase and greatest in the ovulatory phase; suggesting the risk of ACL tear should be lowest during the follicular phase (Somerson et al., 2019). However, the opposite was found with the highest ACL incidence observed during the follicular phase. During the follicular phase, serum estrogen and progesterone levels are at their lowest. However, the estrogen level is higher than the progesterone level, which could explain the higher presence of ACL injuries during this phase. Although studies have investigated menstrual cycle effects on knee laxity, laxity cannot predict joint behavior during dynamic and functional activities, and the testing procedure within the studies are typically conducted without the compressive joint forces required to properly engage the conforming condylar surfaces, which performs an important role in joint stabilisation (Hewett, 2000; Balachandar et al., 2017).

Neuromuscular effects

Estrogen has been proposed to regulate neuromuscular control across the menstrual phases. Specifically, Khowailed et al. (2015) observed increased quadriceps muscle activity in runners during the early follicular phase compared with the ovulatory phase in the pre-contact and weight acceptance phase of running while hamstring found to be decreased. Alterations, which presented as a significant delayed onset of semitendinosus (ST) muscle activation was observed during the luteal phase of the menstrual cycle than both the early and late follicular phases (Dedrick et al., 2008). Lee and Yim (2016) found greater ankle postural sway in balance tasks during ovulation compared to the early follicular phase proposing that the increased Estradiol concentration during ovulation, increases postural sway, which might subsequently alter the neuromuscular activation of the ankle stabilizing muscles (Lee and Yim, 2016).

However, Abt et al. (2007) and Chaudhari et al. (2007) found no differences across menstrual phases for neuromuscular and biomechanics characteristics that could be related to the menstrual cycle in female athletes. Also, Hertel et al. (2006) find no differences among menstrual phases when female athletes' passive knee joint position sense, and postural control in single leg stance were assessed. Evidence is conflicted and therefore, more investigation is necessary to determine whether the changes in neuromuscular control occur due to alterations in force transmission properties of passive tissues driven by hormonal changes.

Muscle stiffness

Muscular stiffness is defined as muscle resistance to changes in muscle length (McNair et al., 2001; Binder, Hirokawa and Windhorst, 2009). Estrogen has been proposed to be associated with muscular stiffness in women due to the estrogen receptors on the tendon tissue (Wiik et al., 2009; Burgess, Pearson and Onambélé, 2010). Eiling et al. (2007) found that lower limb musculotendinous stiffness of the dominant limb assessed using a unilateral hopping protocol was significantly lower at the ovulatory phase in female athletes compared to the follicular phase (Eiling et al., 2007). In contrast, Sung and Kim (2018) found that in untrained women the muscle stiffness in vastus medialis and semitendinosus were significant higher during ovulation phase (Sung and Kim, 2018). Yet, no differences were observed in handball players across menstrual phases for hamstring muscle (Bell et al., 2009) and patellar tendon (Hansen et al., 2013).

The degree to which the limb resists deformation when subjected to a known force (i.e., limb stiffness) may be dependent upon the menstrual phase (Eiling et al., 2007). Changes observed across menstrual cycle phases, have been shown by Eiling et al. (2007). In their study a hopping test was used which identified differences between ovulatory and follicular menstrual phases. It was suggested that the mechanism driving limb stiffness was hormone fluctuations associated with specific phases, impacting the elasticity of passive and contractile fibres. Similar changes have also been shown via specific muscle training suggesting muscle strength may be a contributing factor to stiffness, and stiffness measures may not be required (Kubo et al., 2010; Oliver et al., 2014; Hug et al., 2015).

Measures of limb stiffness were not included in the study because they are underpinned by strength measures, and neural control has also been shown to regulate limb stiffness. Specifically, limb stiffness has been found to increase with running and hopping at higher stride frequencies (Farley and Gonzalez, 1996). Changes in task demands can be regulated through neural control and to compensate at times when limb stiffness is low, neural control may called upon to re-calibrate and drive greater muscle activity to off-set the hormone induced changes (Leonard et al., 2004). Therefore, within reason limb stiffness can adapt to accommodate for the hormone induced changes in limb stiffness as a result of the menstrual cycle. Studies by Hansen et al. (2013) and Bell et al. (2009) used slow isometric knee extension ramps and isometric hamstring contraction and found no differences between menstrual cycle phases. This contrast in findings could be explained by the fact that limb stiffness is specific to the task and underpinned by muscle force production. In addition, surrogate measures of limb stiffness derived from field testing require significant familiarisation and the error from prediction can be large. This is apparent with the poor reliability (ICC: 0.47 to 0.73) for limb stiffness reported in the literature (Pruyn, Watsford and Murphy, 2016) compared to the testing that is used for the muscle strength like Nordbord (ICC: 0.83 to 0.90) and GroinBar (ICC: 0.94) (Opar et al., 2013; Ryan et al., 2019). Finally, limb stiffness testing adds to the inconvenience of completing the battery of assessments (Pruyn, Watsford and Murphy, 2016). Therefore, testing the effects of the menstrual cycle on lower limb muscle strength was considered to provide a greater understanding of the mechanisms contributing to lower limb injuries in female athletes during specific menstrual cycle phases compared to a surrogate measure of limb stiffness.

Muscle strength

Menstrual cycle is likely to affect the capacity to produce force, based on the specific hormonal fluctuations and this may contribute to injury risk for female athletes at different phases of the menstrual cycle. Therefore, an increased interest on the effects of female hormones on muscle strength and how to combat it has emerged over the years.

Loss of muscle strength after the menopause has been associated with lower levels of estrogen leading to the theory that oestrogen concentrations have a profound effect on muscle strength (Calmels et al., 1995; Pallavi, Souza and Shivaprakash, 2017). Therefore, given the differences in estrogen concentrations in fertile-aged women, few studies have examined muscle strength changes across the menstrual cycle in female athletes, suggesting that during the follicular phase, muscle strength seems to be greater than the other phases. Specifically, Phillips et al. (1996) found a significant increase (10%) in maximal voluntary force in adductor pollicis during the follicular phase of the menstrual cycle in rowers (Phillips et al., 1996). Similar findings were demonstrated by the Rodrigues, de Azevedo Correia and Wharton (2019), where the maximal voluntary contraction on leg press (at 45^{0}) was greater during the follicular phase. In contrast, Shahraki et al. (2020) found higher strength in shoulder abduction, internal and external rotation during the ovulation phase compared to other phases. Romero-Moraleda et al. (2019) found no difference in muscle strength across menstrual phases.

The equivocal evidence is likely due to the use of broad range of muscle strength performance tests used and the different testing time points across menstrual phases. Specifically, Phillips et al. (1996) used a transducer positioned between the proximal phalanx of the thumb and the metacarpal of the index finger with the thumb in the plane of the palm of the hand, that recorded the adductor pollicis force on the one hand isometrically. Additionally, authors measured the muscle cross-sectional area (CSA) using a calliper as the produced maximum muscle force depends on its CSA and therefore, the interpretation of the relationship between MVF measurements and those of the CSA in this small muscle is more reliable (Bruce, Phillips and Woledge, 1997; Skelton and Woledge, 1999). However, due to great muscle CSA variance between participants, the relative force changes during a cycle for each participant were compared to avoid the force large variance due to the different CSA of each participant (Phillips et al., 1996). Isometric testing was also used by Shahraki et al. (2020) that used a hand-held dynamometer to measure shoulder strength only in the dominant hand across three menstrual cycle phases in overhead athletes. However, tester strength is a potential limitation of the hand-held dynamometer, particularly if the testing is performed in strong, explosive, such as athletes, since the upper limb muscle strength of the overhead athlete may exceed the tester's strength, and therefore the validity and reliability may be affected (Ishøi et al., 2019).

Rodrigues, de Azevedo Correia and Wharton (2019) used leg press to evaluate muscle strength. The One Repetition Maximum (1RM) prediction test was adopted with participants completing 2 to 10 maximal repetitions with a fixed load until concentric contraction failure occurred; and then the load was subjected to the following equation for determining MVC: 1RM = weight x [1 + (0.025 x number of repetitions)]. Additionally, in contrast to other studies, Rodrigues, de Azevedo Correia and Wharton (2019) evaluated only the follicular and luteal phases and so potential differences with the ovulatory phase may have been missed. Finally, Romero-Moraleda et al. (2019) used the Smith machine half-squat exercise at increasing intensity (20, 40, 60 and 80 of 1RM) in each phase of the menstrual cycle in triathletes. Although the 1RM strength test is widely used as the gold standard method for assessing muscle strength, obtaining the 1RM is highly stressful for muscles and can lead to early fatigue due to the attempts at achieving one, and only one repetition (Dohoney et al., 2002; Shimano et al., 2006). Additionally, the athletes were doing resistance training, and so changes in strength may have happened for other reason than fluctuations in hormones, therefore impacting the internal validity of the initial 1 RM. These problems, however, could be solved by using a different testing method.

Muscle strength testing and menstrual cycle

Studies investigating the effect of menstrual cycle on muscle strength in athletic populations are limited. As muscle strength has been associated with sports injuries and pathologies, and given the demands of athletes to exert large forces during the activities; to better understand injury risk for female athletes it seems important that the effects of hormones on muscle strength are explored.

In female football players the muscles that cross hip and knee joints are predisposed to injury (O'Kane et al., 2017; Ralston et al., 2020). Considering that eccentric knee flexor strength is fundamental for football performance as it allows greater control of the descending limb during sprinting and jumping that leads to a faster change from eccentric deceleration to concentric acceleration (Lodge et al., 2020) and low eccentric hamstring strength potentially increases the risk of sustaining a hamstring injury (Opar et al., 2015). Similary, hip abductors isometric strength is important for postural pelvic stability and can be linked to lower-extremity injury, including patellofemoral pain (Cichanowski et al., 2007). Assessments to assess these strength qualities may provide insight into the link between strength changes and injury risk across the menstrual cycle. So far, there are no studies investigating the hormonal effects on hip adductor and abductor and knee flexor muscles in female football players have been published. Comparing strength over a small period of time such as the menstrual cycle, it is especially important to use or select a testing method able to detect the small changes, ensuring maximal strength contraction for both limbs. Of the methods available for the assessment of hip strength, hand-held dynamometry (HHD) has been identified as reliable and has been used previously; however, HHD is susceptible to tester error which accounts for considerable discrepancy in data collection with the strength and experience of the assessor influencing testing scores. The GroinBar

(Vald Performance; Brisbane, Australia) is a system that has been developed for adductor strength assessment via hip adduction for the left and right limb to reduce measurement error, enhancing the objectivity of results (Ryan et al., 2019). The device has an appropriate level of reliability (CV of 6.3%) and sensitivity and is able to detect changes over a small period of time (Ryan et al., 2019). When it comes to the assessment of hamstring strength, isokinetic dynamometry is generally considered as the gold standard measure, nevertheless, the device's cost is high and its lack of portability in the field are important limitations to its widespread use (Buchheit et al., 2016). However, Nordbord is a novel field-testing device, fast to record, and reliable for the assessment of hamstring eccentric strength bilaterally based on the commonly employed Nordic hamstring exercise and can be used for the eccentric testing of knee flexors in female athletes (Opar et al., 2013; Buchheit et al., 2016).

Progesterone

Progesterone is produced in the corpus luteum. The major target organ of progesterone is the reproductive tract, but it influences other organs such as the mammary glands, the nervous system and the brain, the heart, the bone, the endocrine and the immune systems (Carp, 2015). It participates in ovulation process, preparation and stabilization of the endometrium before implantation, and also it helps for pregnancy maintenance (Jabbour, 2006; Carp, 2015; Taraborrelli, 2015). During the follicular phase where progesterone is low, estrogen predominates and has a major role in the proliferation of the endometrium (Carp, 2015). During the mid-luteal phase progesterone is responsible for the transformation of stromal cells into decidual cells, an essential act for the establishment of pregnancy (Carp, 2015). In case of pregnancy absence, the demise of the corpus luteum exerts a physiological progesterone withdrawal resulting in menstruation (Carp, 2015).

Effects of progesterone on muscle strength

Very little is known about the effect of progesterone on muscle strength. What has been observed during menopause, where both estrogen and progesterone levels are decreased, strength is lost (Maltais, Desroches and Dionne, 2009). At the menopause, the remaining follicles in the ovary become increasingly resistant to gonadotropin stimulation, the oestrogen concentrations decrease, the hypothalamus becomes overactive (producing high levels of LH and FSH), and finally there is ovarian failure with an associated decrease in progesterone concentration and anovulation (failure to ovulate) ensues (Cable and Elliott, 2004). It has been suggested that progesterone and not estrogen treatment increased the muscle protein fractional synthesis rate by approximately 50% in postmenopausal women who had low levels before hormonal treatment (Smith et al., 2014). Although there is little data for the progesterone effects on muscle strength in postmenopausal women, no available data on fertile-aged women and female athletes is reported, and therefore, more studies are required to investigate the effect of progesterone on muscle strength in female athletes.

Testosterone

Testosterone is considered to enhance athletic performance in both men and women (Wood and Stanton, 2012). It has been used to increase muscle mass and muscle strength, and to enhance physical performance (Bhasin et al., 1996; Wood and Stanton, 2012). However, the use of exogenous testosterone has been officially banned from Olympic competition since 1976 and was classified in the United States as a controlled substance by the Anabolic Steroid Control Act of 1990 (Wood and Stanton, 2012; Huang and Basaria, 2018).

Testosterone is normally circulating in both men and women (Sowers et al., 2001). Androgens Receptors (AR) have previously been found in the myonuclei of human male skeletal muscles (Kadi et al., 2000). Although, the effect of testosterone has been documented in male athletes, in females, AR has only been demonstrated in muscles of postmenopausal women and therefore, less is known about the occurrence and effects of androgens on muscle performance in fertile-aged women. Some epidemiological studies support that testosterone has an anabolic role for muscle and bone, however, clinical trials that have been conducted have been small and of short duration, so the effects of testosterone on musculoskeletal remain uncertain (Davis and Wahlin-Jacobsen, 2015).

Androgens in women, includes the dehydroepiandrosterone sulphate (DHEAS), dehydroepiandrosterone (DHEA), androstenedione (A), testosterone (T), and dihydrotestosterone (DHT). However, the (DHEAS), dehydroepiandrosterone (DHEA), and androstenedione (A) are pro-androgens, which require conversion to T to express their androgenic effects (Burger, 2002). The most potent androgen, T and is secreted by the adrenal zona fasciculata and the ovarian stroma and acts directly as an androgen in addition to being an obligatory precursor for biosynthesis of oestradiol (Longcope, 1986; Simpson and Davis, 2001; Burger, 2002; Davis and Wahlin-Jacobsen, 2015).

Testosterone decreases with age, which commences prior to the natural menopause, affecting muscles and bones (Davison et al., 2005; Haring et al., 2012; Wåhlin-Jacobsen et al., 2014; Islam et al., 2019). Specifically, it has been observed that the decreasing levels of testosterone in older women, over the years, is associated with decreased anabolic effects on the muscles (Häkkinen and Pakarinen, 1993). In fertile-aged women, during the early follicular phase, testosterone is at its lowest concentration and increases to a mid-cycle peak during the luteal phase (Abraham, 1974). This would suggest that muscle strength is greater during the mid-cycle phase, and lower during the follicular phase. However, more studies in young women are needed to get to conclusions.

4.5.1 Premenstrual Syndrome

A link between menstrual cycle and negative mood has been suggested from early 1930s where for first time mooted in scientific literature by the gynaecologist Robert Frank and psychoanalyst Karen

Horney (Stolberg, 2000). The British physician Katharina Dalton described a broad mood somatic premenstrual syndrome (PMS) during the post-World War II years implicating that deficiency of progesterone is the cause (Dalton, 1964).

As Premenstrual Syndrome (PMS) is referred to the group of moderate psychological and physical symptoms (Table 4.5.1a) that occur during the late luteal phase of menstrual cycles in a cyclic pattern which resolves during menstruation (Biggs and Demuth, 2011). However, it is not unusual for symptoms to continue into the next menstrual cycle (Yonkers, O'Brien and Eriksson, 2008). The length of symptoms can vary between a few days and 2 weeks (Yonkers, O'Brien and Eriksson, 2008). When the psychological and physical symptoms are severe then is defined as Premenstrual Dysphoric Disorder (PMDD) (Bharti et al., 2014).

The prevalence of PMS is varied across countries. In Spain, 73.7% of women aged 15-49 had some of the symptoms of PMS during at least one of their last 12 menstrual cycles, 1.1% reported PMDD while 20.3% were asymptomatic (Dueñas et al., 2011). The physical symptoms were the most frequent (breast tenderness, headache, weight gain, and/or bloating), occurring in 81.6% of women, followed by irritability (53%), tearfulness (48.7%), and anxiety (40.5%) (Dueñas et al., 2011). In China, PMS found in 21.1%. and PMDD in 2.1% in women aged 18–45 years , with the most common symptoms were irritability (91.2%), breast tenderness (77.6%), depression (68.3%), abdominal bloating (63.7%) and angry outbursts (59.6%) (Qiao et al., 2012). In the U.K. it was found 24% of the women aged 20-34 to have premenstrual symptoms (Sadler et al., 2010).

Although the cause of PMS is not fully understood, theories have been proposed, suggesting that ovarian steroid hormones play a key role (Lete and Lapuente, 2016). Specifically, it is referred that changes in certain progesterone metabolites (pregnenolone and allopregnanolone) act as positive modulators of the GABAergic system in the brain which can cause PMS (Andréen et al., 2009; Lete and

Lapuente, 2016). Also, neurotransmitters, especially gamma-aminobutyric acid (GABA) an important regulator of stress, anxiety; and serotonin, appear to be involved in the manifestations of PMS/PMDD (Imai et al., 2015). The deficiency of the metabolites seems to be related to PMS (Lete and Lapuente, 2016). It has been found that during the luteal phase serotonergic function seems to be altered and the GABA receptor to be less receptive and of lower levels of this substance (Freeman et al., 2004). Low serotonin levels are associated with mood state such as anxiety and depressive symptoms (Albert, Vahid-Ansari and Luckhart, 2014).

PMS affects work productivity and daily quality of life, but it has also been shown to decrease sports performance in athletes due to symptoms such as headache, depressed mood, irritability, and poor concentration (Choi et al., 2010; Dennerstein, Lehert and Heinemann, 2011; Takeda et al., 2015; Czajkowska et al., 2015; Takeda et al., 2016). Specifically, it found that PMS impaired the productivity in home responsibilities in 48.3%, social life activities in 19.0%, and athletic performance (game and/or practice) in 44.3% in female athletes in Japan (Takeda et al., 2015).

Additionally, PMS affects the postural sway and increases the threshold for detection of passive motion in the knee joints, more than in women without PMS. Suggesting a link between injury risk and PMS. However, evidence from athletic populations is limited and further studies in athletic population should be done to get conclusions of the full effects (Fridén et al., 2003b). The physiological and psychological changes across the menstrual cycle has been poorly investigated in female athletes and therefore, more studies are required to investigate the distress symptoms and changes during a menstrual cycle.

Table 4.5.1a Symptoms of PMS.
Adopted by Freeman (2003).

Physical	**Behavioural**	**Mood**
Swelling	Sleep disturbances	Irritability
Breast tenderness	Appetite changes	Mood swings
Aches	Poor concentration	Anxiety tension
Headache	Decreased interest	Depression
Bloating weight	Social withdrawal	Feeling out of control

4.5.2 Injury and Menstrual cycle

Injury has been associated with menstrual cycle phases. Specifically, characteristic changes in estrogen, progesterone, and relaxin concentration during each phase of menstrual cycle occur and athletes may experience increases in anterior knee laxity, which may lead to ACL injury (Park et al., 2009; Shultz et al., 2015). Case control studies have been conducted to investigate the ACL injury occurrence during and across menstrual cycle phases, however, so far, the findings remain controversial. Specifically, Arendt, Bershadsky and Agel (2002), Beynnon et al. (2006) and Ruedl et al. (2011) found that female athletes had more noncontact ACL injuries during the follicular phase. However, Adachi et al. (2008) observed that during the ovulation phase ACL injuries were more common. In contrast to the ACL injuries, no significant association between the stage of the menstrual cycle and the likelihood of injury was found in teenage athletes aged 12 to 15 years (Sommerfield et al., 2020). Such mixed findings suggest a more complex explanation is required for injury risk beyond the timing of menstrual phase.

4.6 Rationale

Considering the increased participation of women in sports, it becomes necessary to understand the effects that are induced by the cyclical hormonal changes on the properties of skeletal muscles. So far, the evidence is limited, and studies are inconsistent. In addition, despite the increasing pool of female athletes, particularly at high school (14 to 18 years) and collegiate levels (>18), there remains few reports concerning the effects of psychology and hormones on performance and risk of injury (Tanaka, Jones and Forman, 2020; Cairo et al., 2021). Muscle strength, the capacity to produce force, is an important characteristic on intermittent team sports, hence, there are compelling attributes to research concerning physical performance and injuries. Adequate knee flexor, hip adductor and abductor muscle strength is important for sprinting, jumping, and kicking movements, which are integral to soccer. Hip adductor and abductor muscles perform important roles to pelvic stability and to the alignment of the lower limb during dynamic tasks; and knee flexors, where it has been indicated that the hamstring forces reduce ACL strain against the quadriceps (Renström et al., 1986; Ireland, 2003; Shimokochi and Shultz, 2008; Power, 2010; Souza et al., 2010). Potential changes of muscle strength may alter joint kinematics increasing the risk for injury during a specific menstrual phase. Thus, given that muscle strength is required in soccer players and significantly influences athletic performance and injury risk, it is prudent to elucidate how it varies across the menstrual cycle. Therefore, the aim of this study was: 1. to investigate the effect of the menstrual cycle on a battery of lower limb muscle strength measures associated with common injuries in football (i.e., hip, groin and knee flexors) and; 2. to evaluate the effects of the menstrual cycle on mood in female soccer players. Thus, the research questions posed for this study were as follows:

1. Does the menstrual cycle phase influence functional lower extremity muscle strength in female soccer players?
2. Does the menstrual cycle phase affect the mood in female soccer players?

4.7 Methods

4.7.1 Participants

Sixteen (n=16) national soccer players volunteered to participate in this study. Participants were included if they were playing national level soccer with a body mass index (BMI) equal to or less than 30, a non-smoker, with a consistent menstrual cycle, with no history of pregnancy, and no lower limb injury or experiencing any pain during the period of testing. Soccer players with amenorrhea (absence of menstrual cycles) or using birth control contraception other than oral contraception were excluded. A consistent cycle was defined as a menstrual cycle no less than 21 days and no more than 35 days (Creinin, Keverline and Meyn, 2004; Oyelowo, 2007; Bull et al., 2019). Seven soccer players from the 16 who agreed to take part were excluded due to history of irregular menstrual cycles leaving nine players (N=9) aged 18-31 years.

4.7.2 Procedure

The study was approved by the University of South Wales research ethics committee (approval number: 18SA1101HR). Prior to commencing data collection, permission from a member of the national team management was obtained to contact the soccer players from the squad to invite them to consider volunteering for the study. Once permission to approach potential soccer players had been obtained in writing, the physiotherapist of a women's national soccer team was contacted and asked to distribute the information sheet (Appendix 3). Players over the age of 18 years were invited to take part in the study. Consent forms (Appendix 3) were supplied via email in advance of the initial testing commencing.

Data collection was obtained three times during the pre-season period in August 2019 (Figure 4.7.2a outlines the study design). Soccer players performed three identical experimental sessions during self-reported menstrual cycle that took place in random order during the menstrual cycle: one session performed during the follicular (days 1-9), one during ovulatory (days 10-14), and the other during the luteal phase (day 15-end of cycle) based on the Wojtys et al. (1998) method. Day 1 is defined as from the time of the onset of menses.

Specifically, the players were tested on three occasions. The first test session was in the follicular phase, day 2-4 of the menstrual cycle, the second test session was during days 11-13 from the start of the menstrual cycle (ovulation) and the third test session was 6-7 days after ovulation (luteal).

At the first testing day, consent forms were collected, and two questionnaires were provided to the soccer players: 1) the menstrual and previous injury history questionnaire, and 2) the Menstrual Distress questionnaire (MDQ).

Prior the testing procedure, the soccer players' anthropometric (stature and body mass) characteristics were measured using a digital scale and a portable stadiometer. Body mass, using a digital scale (Seca 813, Hamburg, Germany) and stature using portable stadiometer (Seca 213, Hamburg, Germany) were measured; athletes were then assessed using a suite of field-based tests for isometric hip adductor and abductor strength, eccentric Nordic hamstring exercise (NHE) strength and a single leg jump task.

The soccer players completed the menstrual distress questionnaire and performed the testing procedure two more occasions during one menstrual cycle. Therefore, in total, the menstrual distress questionnaire and testing procedure were taking during three sessions.

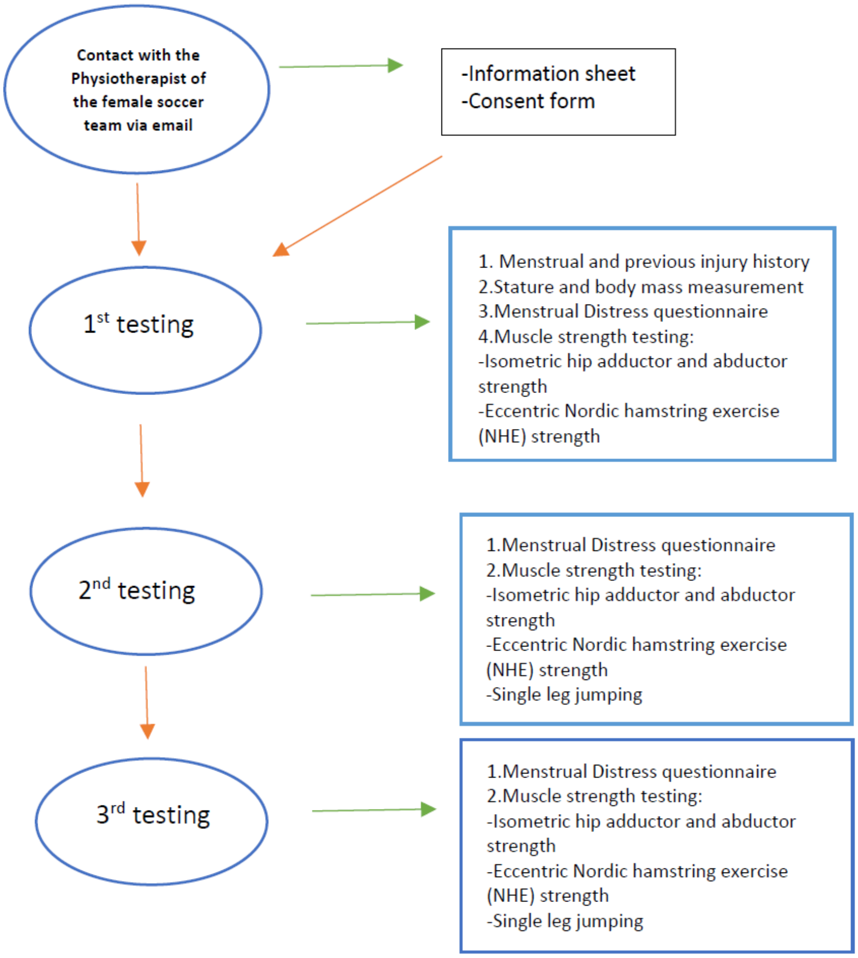


Figure 4.7.2a: Study Design.

4.7.3 Questionnaires

Menstrual and previous injury questionnaire

The menstrual and previous injury questionnaire was completed by each participant once, it consisted of four parts that asked for information on the following:

5) Soccer players physical and sports characteristics (age, stature, body mass, preferred kicking limb, years playing their sport)

6) Family ACL history (whether a family member had an ACL injury)

7) Participant's injury history (previous injury in the last 12 months, location, diagnosis, treatment, contact/no contact injury, surface that occurred, and time loss)
8) Menstrual and oral contraception history (date of last menstrual cycle, menstrual cycle regularity, length, age of menarche, and use of oral contraception).

In addition to the menstrual history questionnaire where the days of the last menstrual cycle was reported, a menstrual history of the previous four months was provided by each player based on their period tracking applications to confirm the regularity of the cycle. Clinical guidelines state that a woman's median cycle length is 28 days (21-35 days) (Popat et al., 2008). Therefore, the athletes should follow this standardized length to be defined their cycles as regular. A menstrual cycle of <21 days or >35 days reported in the previous four months was defined as irregular.

Menstrual Distress questionnaire

Menstrual Distress questionnaire (MDQ) is a 47 item self-report inventory for use in the assessment of premenstrual and menstrual symptoms. The MDQ can distinguish changes in physical symptoms, mood and behaviour, and arousal and it identifies the type and intensity of symptoms women experience during each phase of the menstrual cycle (Moos, 1968). The MDQ has eight scales labelled: Pain, Water Retention, Autonomic Reactions, Negative Affect, Impaired Concentration, Behaviour Change, Arousal, and Control. This is derived from factor analysis and is scored on a five-point Likert-type scale (0-4) (0=not at all; 1=small degree; 2=moderate degree; 3=great degree; 4=high degree). Higher scores indicated higher perceived levels of menstrual stress. Previous work (Boyle, 1991; Boyle, 1992; Boyle and Grant, 1992; Aganoff and Boyle, 1994) has shown this to be a reliable and valid instrument to gather information about the symptoms of menstruation (Boyle, 1992). Specifically, the MDQ has been found to have Cronbach's alphas subscales ranging from .64 to .88 (Moos, cited in Sigmon et al., 2000).

4.7.4 Strength measures

The testing procedure for strength has been described in detail before in the cohort study (section 2.5.4).

4.7.5 Statistics

Statistical analysis was conducted using the statistical software package SPSS version 26 (IBM Corporation, Chicago, IL). Descriptive statistics included means, standard deviations for all variables. To describe the dataset: mean and standard deviations (SD) of age, stature, body mass, years of playing, first menstrual period, eccentric knee-flexor strength for the left and right limb and between-limb imbalance (%), isometric hip abductor strength at 60° (N), and at 90^{o} for the left and right limb and between-limb imbalance (%), isometric hip adductor strength at 60^{o} and 90^{o} for the left and right limb and between-limb imbalance (%) and jump height for the left and right limb and between imbalance (%) were reported.

Shapiro–Wilks tests were used to test the muscle strength data for normality of distribution ($p > 0.05$). In the case where the normality assumption was not met, the log10 data transform for correcting the non-normal distributions was applied successfully.

The differences in strength and menstrual distress questionnaire between the three phases of the menstrual cycle were analysed using one-way repeated-measures analysis of variance (ANOVA). Greenhouse-Geisser adjustment was applied when the assumption of sphericity was violated ($p<0.05$ for Mauchly's test of sphericity). The Friedman test was used to compare the menstrual distress questionnaire factors (pain, concentration, behavioural change, autonomic reactions, water retention, negative effect, arousal, and control). Bonferroni corrections for ANOVA were applied to correct for the multiple comparisons. The significance level was set in 5% ($p<0.05$). Partial eta-squared

(η^2) was reported to demonstrate the effect size in the repeated-measures ANOVA tests. Cohen (1988) suggested benchmarks to define small (η^2=0.01), medium (η^2=0.06), and large (η^2=0.14) effects.

Power Calculation

Based on previous reported study, for the estimation of explosive strength, when the sample size is 10, the test at the 0.05 significance level in a one-way repeated measures analysis of variance with 3 levels will have 97% power to detect a difference of 10% between phases (Fridén et al., 2003a). For the functional explosive muscle strength such as single leg jump, when sample size is 10, it will have 98% power to detect a difference of 10% between phases (Fridén et al., 2003a). Therefore, the power with seven soccer players was 67.9%.

4.8 Results

Out of the 16 elite female footballers who volunteered for this study, nine female footballers (Mean age: 24.9(5) years; Mean body mass: 63.7(7.7) kg; and Mean stature: 163.9(6.8) cm) fulfilled the inclusion criteria. However, two athletes were excluded due to quadriceps and hamstring injuries at the follicular and the ovulatory phases, respectively, and only seven successfully completed all three phases of testing.

4.8.1 Participant characteristics

Seven nulliparous national female soccer players (N=7) aged between 18 and 31 years were included in the final analyse. Based on the reported time and duration of menstruation and the responses in the oral contraception history, none of the soccer players were taking oral contraception during the period of study. All soccer players were right dominant leg (i.e., preferred to kick with their right leg), did not compete to any other sport, and four of them had a lower limb injury past 12 months. Descriptive statistics for the study soccer players are shown in Table 4.8.1a.

Table 4.8.1a Demographic and anthropometric characteristics of the study soccer players (N=7); Data are expressed as mean ± standard deviation for continuous variables with normal distribution; *median (Interquartile range (IQR)) for variables with non-normal distribution; kg=kilogram, cm=centimetres.

Soccer players' characteristics	Mean (SD)	Range
Age (years)	24.6 (5.6)	18 to 31
Body Mass (kg)	60.8 (5.9)	52 to 68
Stature (cm)	161.7 (5.2)	155 to 168
BMI	23.2 (1.8)	22 to 26
Age started sport (years)	8.9 (2.8)	6 to 13
Years of playing experience (years)	15.3 (6.4)	5 to 24
Duration menstrual bleeding (days)	5.0 (3)*	4 to 7
Length of menstrual cycle (days)	28.0 (5)*	21 to 30
Age first menarche (years)	13.9 (0.7)	13 to 15

4.8.2 Lower limb strength

All muscle strength and imbalance variables across menstrual phases are presented in Table 4.8.2a. Only hip adductor strength at 60° changed significantly across menstrual cycle. Specifically, it was found that the athletes had stronger hip adductors at 60° during follicular phase compared to ovulatory and luteal phases (Tables 4.8.2a, 4.8.2b, and Figure 4.8.2a).

Table 4.8.2a. All strength (two limb average) and imbalance (between-limb) variables for the three menstrual phases. FMP: Follicular menstrual phase, OVMP: ovulatory menstrual phase, LMP: luteal menstrual phase. *$p<0.05$, **$p<0.01$ [a]: after transforming data to normality; N=Newtons, cm=centimetres.

	FMP Mean (SD)	OVMP Mean (SD)	LMP Mean (SD)	Df	F	Partial Eta Squared	*p*
Mean Single leg jumping (cm)	11.2 (1.9)	12.9 (5.3)	12.4 (3.12)	2	0.64	0.10	0.545
Single leg jumping-Imbalance (%) - Between-limb	9.2 (6.1)	16.6 (16.8)	7.7 (4.6)	1	1.54	0.20	0.261
Mean Eccentric hamstring strength (N)	232 (59)	222 (61)	218 (55)	1	0.46	0.07	0.550

Eccentric hamstring - Imbalance (%)[a] - Between-limb	0.8 (0.5)	1.0 (0.5)	1.0 (0.6)	2	0.41	0.06	0.672
Mean Isometric hip adductor 90° (N)	284 (49)	275 (79)	249 (76)	2	0.86	0.13	0.447
Isometric hip adductor 90°- Imbalance (%) - Between-limb	3.4 (3.3)	4.2 (2.6)	7.0 (6.4)	2	2.17	0.27	0.157
Mean Isometric hip abductor 90°-	205 (49)	224 (52)	233 (84)	2	1.16	0.16	0.347
Isometric hip abductor 90° Imbalance (%) - Between-limb	12.8 (10.0)	9.5 (4.8)	9 (8.0)	2	0.84	0.12	0.457
Mean Isometric hip adductor 60°	340 (59)	301 (62)	301 (65)	2	8.22	0.58	0.006**
Isometric hip adductor 60° Imbalance (%)[a] - Between-limb	0.3 (0.5)	0.3 (0.4)	0.7 (0.4)	2	1.81	0.27	0.213
Mean Isometric hip abductor 60°	272 (81)	263 (69)	290 (70)	2	2.01	0.25	0.176
Isometric hip abductor 60 ° Imbalance (%)[a] - Between-limb	0.4 (0.4)	0.6 (0.5)	0.4 (0.7)	1	0.47	0.07	0.542

Table 4.8.2b. Statistical differences between three different phases at isometric hip adductor 60°. FMP: Follicular menstrual phase, OVMP: ovulatory menstrual phase, LMP: luteal menstrual phase. *p<0.05, **p<0.01

Isometric Hip adductors at 60°	Mean difference (N)	95%CI (N)	p
FMP vs OVMP	40	10 to 69	0.014*
OVMP vs LMP	0	-46 to 46	>0.999
FMP vs LMP	39	6 to 73	0.024*

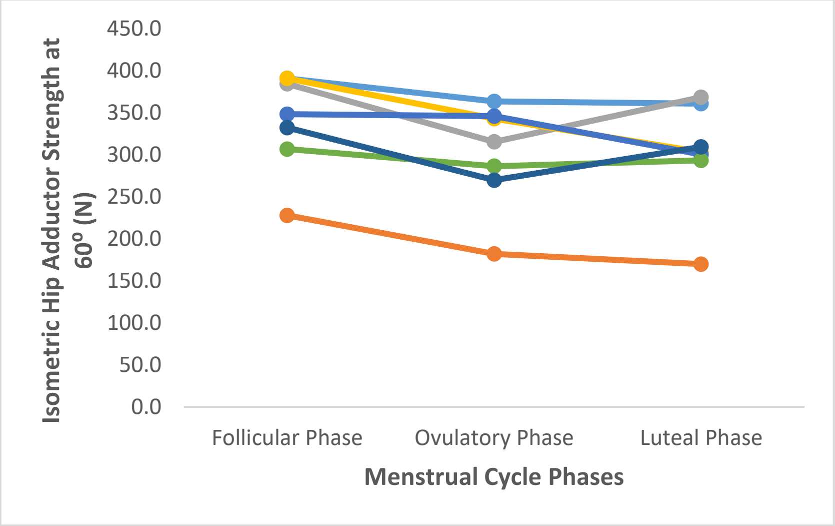


Figure 4.8.a: Mean isometric hip adductors strength at 60°during the menstrual cycle phases for each participant.

4.8.3 Menstrual Distress

Comparison results for all menstrual distress categories between the three menstrual phases are presented in Table 4.8.3a. The number of indefinite complaints was highest in the follicular phase, followed by the luteal phase, with the fewest complaints occurring in the ovulatory phase. The results indicated that symptoms were differed significantly across menstrual cycle for the pain, concentration, behavioural change, water retention, negative effect, and arousal factors.

Table 4.8.3a Menstrual Distress Questionnaire (MDQ) scores in follicular, ovulatory, and luteal phases. * The mean difference is significant at the .05 level; ** The mean difference is significant at the .01 level.

Mean (SD)	Follicular	Ovulatory	Luteal	*p*	Chi-Square
Pain	8.5 (4.1)	2.17 (2.7)	9.7 (3.6)	0.009**	9.3
Concentration	2.5 (2.2)	0	2 (1.4)	0.003**	11.7
Behavioural change	6 (3)	0.7 (1.2)	6.2 (2.7)	0.009**	9.5
Autonomic reactions	4.3 (2.6)	1.0 (1.2)	4.0 (2.6)	0.223	3.0
Water retention	3.8 (2.2)	0.5 (1.0)	2.8 (2.1)	0.039*	6.5
Negative effect	5.5 (3.9)	0.3 (0.7)	4.4 (3.9)	0.001**	14.0
Arousal	2.4 (1.7)	0	2.8 (1.5)	0.022*	7.6
Control	2.3 (1.2)	0.3 (0.8)	1.0 (0)	0.055	5.8
Total	29.9 (35.1)	3.9 (4.6)	27.6 (26.7)	0.080	5.0

The results of post-hoc tests (Table 4.8.3b) showed that during the luteal phase soccer players reported higher scores for pain factors, such as headache, lumbago, hypogastric pain, and physical listlessness; and arousal factors, that athletes had more affectionate, orderliness, excitement, feelings of wellbeing and burst of energy/activity compared to the follicular phase. During the follicular phase, athletes reported significantly more water retentions factors such as weight gain, skin disorders, painful breast, swelling than the ovulatory and luteal phases.

At both follicular and luteal menstrual phases soccer players reported to experience impaired concentration symptoms (insomnia, forgetfulness, confusion, lowered judgement, difficulty concentrating, distractible, accidents and lowered motor coordination), and changes in behaviour such as lowered school or work performance, take naps or stay in bed, stay at home (absenteeism), avoid social activities, decreased efficiency, and change in eating habits / craving for sweets), and negative feelings (crying, loneliness, anxiety, restlessness, irritability, mood swings, depression, tension) when compared to ovulatory phase.

Table 4.8.3b. Subcategories of the menstrual Distress questionnaire between menstrual phases. FMP: Follicular menstrual phase, OVMP: ovulatory menstrual phase, LMP: luteal menstrual phase. *. The mean difference is significant at the .05 level; ** The mean difference is significant at the .01 level.

	Follicular vs Ovulatory Mean Difference	**Follicular vs Ovulatory *p***	**Ovulatory vs Luteal Mean Difference**	**Ovulatory vs Luteal *p***	**Follicular vs Luteal Mean Difference**	**Follicular vsLuteal *p***
Pain	6.3	0.081	-7.50	0.015*	-1.17	0.985
Concentration	2.5	0.045*	-2.50	0.016*	0.50	>0.999
Behavioural change	5.3	0.003**	-5.5	0.002**	-0.17	>0.999
Autonomic reactions	3.3	0.353	-3.00	0.491	0.25	>0.999
Water retention	3.25	0.042*	-2.25	0.294	1.00	>0.999
Negative effect	5.25	0.010**	1.13	0.040*	-4.13	>0.999
Arousal	2.40	0.098	-2.89	0.013*	-0.40	0.717
Control	2.00	0.123	-0.67	0.306	1.33	0.129
Total	26.00	0.211	-23.71	0.119	2.29	>0.999

4.9 Discussion

In chapter 4, one-way repeated measures analysis of variance (ANOVA) was used to determine differences in strength and menstrual distress symptoms across the three menstrual cycle phases. Further Friedman test analysis was used to detect differences in menstrual distress questionnaire factors across the three menstrual phases.

The major findings of this study were that eumenorrheic nulliparous national female soccer players had greater hip adductor strength while indicating signs of menstrual distress symptoms during the follicular phase. Specifically, during the follicular phase, female soccer players experienced greater impaired concentration, water retention, and negative feelings. As reflected in Table 4.8.2a, value from the partial eta squared for hip adductor strength at 60^o was higher than 0.14, which indicates high effect of menstrual cycle on hip adductors strength.

Study 3 identified hip adductor strength as a risk factor for lower limb injuries in female athletes. Considering the hip adductors provide stability for the lower extremity during sporting movements such as sprinting and change of direction, an abnormal performance of hip adductor strength may alter the distribution of forces across the joint, affecting the athlete's performance. Therefore, variation in muscle strength across menstrual cycle phases may affect joint stability which, during sporting activities, increases the risk for injury.

Given that hip adductor muscle strength is greater during the follicular phase, it could be assumed that the lower limb is protected from injuries during this phase. However, menstrual distress symptoms such as mood and behavioural changes may affect the athlete's performance on the pitch and offset this benefit increasing the risk for injury.

No cyclic fluctuations were found for any other strength measures. To the best of our knowledge, this is the first study that investigates the relationship between menstrual cycle in hip and groin strength in national soccer players. Although previous studies have examined the effects of hormonal variations of the menstrual cycle on muscle strength, the results are conflicted and the number of studies pertaining to sportswomen is limited. The current study demonstrated that hip adductor strength was greater during the follicular phase than at the other two menstrual phases. This finding supports earlier small studies exploring the effects of the menstrual cycle on muscle strength. Specifically, in a study involving 10 rowers, it found a 10% increase in strength measured by means of maximum voluntary force (MVF) in the adductor pollicis during the follicular phase, which was followed by a reciprocal drop at the time of ovulation (Philips et al., 1996). More recently, Rodrigues, Correira and Wharton (2019) reported 17kg greater maximal voluntary contraction on leg press at 45° during the follicular phase compared to the luteal phase.

The current study also measured muscle strength during the ovulatory phase suggesting that it was greater during the follicular phase than in the ovulatory phase. In contrast Rodrigues, Correira and Wharton (2019) ovulation testing was missed during the phase where estrogen levels are highest (ovulatory), which meant failure to detect important changes in muscle strength due to hormonal concentrations.

Estrogen is clearly beneficial for muscle mass and strength and it has been demonstrated that estrogen insufficiency affects muscle strength at least in animal models (Kitajima and Ono, 2016). It has been found that after 24 weeks of estrogen deficiency there was a 10% decrease in strength and an 18% decrease in cross-sectional area (Kitajima and Ono, 2016). Similarly, it may be possible that estrogen has a positive effect on skeletal muscle but not immediately, and takes some hours or days leading to a delayed onset strengthening effect; and therefore, the force of contraction continues to rise while estrogen levels have begun to fall (Phillips et al., 1996). This delayed effect of estrogen on muscle strength could explain the current findings.

Conversely, recent work by Shahraki et al. (2020) using hand-held dynamometer on the dominant hand found greater strength in shoulder abduction and internal and external rotation during the ovulatory phase than the luteal and follicular phases suggesting that it may be possible that progesterone is inhibitory to the strength enhancing effects of estrogen, causing muscles to be weaker in the luteal phase and that estrogen is the hormone with the highest effect on increased strength. However, a prior study in women undergoing in vitro fertilization (IVF) when progesterone levels were supressed and estogen levels changed from hypo- to hyper-estrogen levels did not show any effect in first dorsal interosseus muscle strength (Greeves et al., 1997).

The current study used a different testing method to measure muscle strength than the prior studies. GroinBar is a system that has been developed to assess hip adductor strength bilaterally with greater measurement precision in comparison to the dynamometry method (Ryan et al., 2019). The greater hip adductor muscle strength during the follicular phase found exclusively at 60^{o}, and not at the position of 90^{o} may be of interest. The two positions were used since they should evaluate different adductor muscles, with 60^{o} position likely examining the adductor longus muscle, and 90^{o} examining predominantly the pectineus and adductor brevis muscles.

However, the value at 90^{o} was higher during the follicular phase, but no significant difference was found. On further inspection, it may be that the magnitude of scores obtained from the two positions could be the reason for lack of difference observed at 90^{o}. At 60^{o} the values are greater and this is confirmed by the normative data that is presented in study 2. Moreover, based on the normative data presented in study 2, female soccer players were comparatively weak for strength measures were obtained from the 90^{o} position, and with such baseline strength values from outset this may explain the lack of change in strength levels across phases (i.e., they had little strength to lose at 90^{o}).

Single leg jumping has not been examined for cyclic differences previously. Previous works examined double counter movement jumps (Julian et al., 2017) and squat jumps (Giacomoni et al., 2000) for cyclic variations and found no differences. However, the current study tested whether or not single leg jumping and between-limb imbalance is affected throughout menstrual cycle. Most of the tasks of soccer players on the pitch are single-legged (running, jumping, receiving a pass). Therefore, evaluation of single leg strength would be more meaningful than double-leg jumping which may not fully represent the neuromuscular strategies that are utilized during high-risk activities (Taylor et al., 2016). Additionally, compared to the current study, both previous works examined participants only in the follicular and luteal phases and may have missed changes with the comparison to the high estrogen phase (ovulatory). Also, it found that soccer players in the Julian et al. (2017) study had lower hormone concentrations than the general population and this could have affected the chance to identify cyclic changes. However, lower hormone concentration in female athletes has been previously reported and for this reason comparison with prior studies that included non-athletic women would be unwise (Genç et al., 2019).

To the best of our knowledge, there is no menstrual distress data for female soccer players or for other athletic populations across menstrual cycle phases. The current study found greater menstrual distress total scores in the follicular phase. However, differences between luteal and ovulatory phases were clearly demonstrated. Specifically, pain score was greater in the luteal phase compared to the follicular and ovulatory. This finding supports an earlier small study involving eight Japanese ambulance paramedics who reported more pain during the luteal phase compared to the follicular (Suzuki et al., 2016). Although the reasons for the menstrual differences in pain response remain unclear, hypotheses have been proposed. It has been suggested that a decrease in the production of progesterone late in the luteal phase induces an increase of prostaglandin E2 and prostaglandin F2a that induce contractions of the uterine muscle and reinforce egestion of the desquamated endometrial membrane, which might lower the pain threshold (Jabbour et al., 2006). Also, it may be possible that a decline of beta–endorphin levels and mood variation in the late luteal phase might affect the pain perception (Viana, da Silva and de Sousa, 2005). Therefore, it is hypothesized that the fluctuation of gonadal hormone secretion influences the emotional and endogenous pain modulation system contributing to pain aggravation during the luteal phase (Kakeda et al., 2019). This pain distress feeling may also affect changes in behaviour factors such as preference to stay home and avoid social activities as players in the current study reported a greater score for the behavioural change during the luteal phase.

Water retention was found to be greater during the follicular phase which agrees with prior studies (Lahmeyer, Miller and Deleon-Jones, 1982; Cockerill, Wormington and Nevill, 1994). However, a prior work by Ramcharan et al. (1992) found higher scores in water retention at the luteal phase. Increased progesterone levels at the luteal phase could lead to fluid retention due to the complex interaction of the aldosterone and progesterone (Lebrun, 1993). Specifically, it has been proposed that progesterone independently stimulates aldosterone production, and then volume retention may occur (Szmuilowicz et al., 2006). The variability of fluid degree retention among women may be associated with the differences in progesterone production and adrenal sensitivity to progesterone (Szmuilowicz et al., 2006). However, it is suggested that fluid redistribution, rather than water retention, is responsible for symptoms like bloatedness (Tollan et al., 1993).

Finally, players reported more negative feelings and impaired concentration during the follicular phase. It is common belief that mood symptoms depend on the phase of the menstrual cycle. It has been suggested that decreased progesterone levels and through that, decreased levels of neuroactive progesterone metabolites such as allopregnanolone, influence mood and behaviour (Andréen et al., 2009). Therefore, lower levels of progesterone coincide with the higher intensity of aggressive behaviour and fatigue during this phase (Ziomkiewicz et al., 2012). Progesterone, or rather its neuroactive metabolite allopregnanolone, modulates amygdala activity and as a result influences anxiety, cognition such as memory, by reducing the recruitment of those brain regions that support memory formation and retrieval (Van Wingen et al., 2007). Progesterone and its metabolite allopregnanolone levels are also associated with arousal. Specifically, levels of progesterone and its metabolite allopregnanolone were found to correlate negatively with arousal in the luteal phase (De Wit and Rukstalis, 1997). However, players reported higher scores for arousal during the luteal phase where the progesterone levels peak.

The current study identified lower MDQ scores compared to prior works (Lahmeyer, Miller and Deleon-Jones, 1982; Tada et al., 2017). This could be explained by the fact that the current study included athletes rather than the nonathletic populations used in previous studies. One earlier study that examined the effects of exercise on mood states and menstrual cycle symptoms found that exercisers have significantly lower scores than the non-exercisers on negative affect, impaired concentration, behaviour change, and pain (Aganoff and Boyle, 1994). It seems that exercise improves a negative mood state, and this may be due to endorphin production while exercising, which influences the mood and pain (Fremont and Craighead, 1987). Raised endorphin levels have been associated with significant reductions in headache and depression (Balchin et al., 2016; Amin et al., 2018). Beta-endorphin is an endogenous opioid produced by the anterior pituitary and produces analgesia by binding to pre- and postsynaptic opioid receptors (mainly mu receptors) (Schwarz and Kindermann, 1989). It is increased after exercise when anaerobic threshold is exceeded or if an exercise at a lower threshold is prolonged for about 50 min (McMurray et al., 1987; Langenfeld, Hart and Kao, 1987; Rahkila et al., 1988; Goldfarb et al., 1990). Additionally, exercise acts as an improvement to body image and self-efficacy which may have an effect on self-conception and self-esteem, decreasing the psychosomatic complaints (Alfermann and Stoll, 2000).

Premenstrual and menstrual discomfort has been previously associated with injury risk suggesting that the symptoms increase the risk for suffering an injury in female athletes than in those athletes without symptoms (Möller-Nielsen and Hammar, 1989). Specifically, it has been found that athletes with symptoms of irritability, swelling in the breasts, and in the abdomen have higher risk for injury. It may be possible that the premenstrual and menstrual symptoms start to affect the decision-making during the sporting activities negatively, resulting in a profound effect on injury risk. Although most studies are mainly focused on premenstrual symptoms, it seems that symptoms also occur during the early follicular phase.

There are limitations in the current study that are worth noting to interpret these findings properly. Firstly, similarly to previous work, the sample size was small to achieve traditional statistical benchmarks such as a power of 80% at alpha 0.05. Based on previous reported study, for the estimation of explosive strength, when the sample size is 10, the test at the 0.05 significance level in a one-way repeated measures analysis of variance with 3 levels will have 97% power to detect a difference of 10% between phases (Fridén et al., 2003a). For the functional explosive muscle strength such as single leg jump, when sample size is 10, it will have 98% power to detect a difference of 10% between phases (Fridén et al., 2003a). Therefore, the power with seven soccer players was 67.9%.

Insufficient statistical power could lead to increased risk that statistically significant results will actually be falsely positive (Christley, 2010). With the inclusion criteria being rigid in terms of menstrual regularity, our participants were limited to only nine women, as it was difficult to identify athletes with regular menstrual cycles. Small sample size is a common challenge in sport and exercise science, investigating women with regular menstrual cycle (Friden et al., 2003a; Shahraki et al., 2020). Moreover, the small sample size restricts the generalizability of the findings, thus, it is recommended that the findings be confirmed by larger studies in the future (Tipton et al., 2017).

In this study, eumenorrheic nulliparous national female soccer players during the follicular phase displayed greater isometric hip adductor strength and symptoms of menstrual distress when compared to the other menstrual phases. Hip adductor strength was greater during follicular menstrual cycle phase, but significant difference was only found at 60°. This could be explained by the fact that 60° is in a more mechanically advantageous position compared to the positions of 90° and therefore more likely to be more sensitive to detect changes compared to the weaker 90° position (Lovell, Blanch and Barnes, 2012; Kato et al., 2019). Finally, multiple testing corrections was not done and adjustments to alpha given the exploratory nature of the testing using a novel devices (Feise, 2002).

To confirm the regularity of the cycle in the current study, a menstrual history of the previous four months was provided. Based on the literature amenorrhea/oligomenorrhea is more prevalent among athletes than in the general population (Goodman and Warren, 2005). Menstrual dysfunction is one of the three clinical entities of the female athlete triad with the low energy availability and decreased bone mineral density (Nazem and Ackerman, 2012). Menstrual cycle problems can be caused from the suppression of the pulsatile secretion of hypothalamic gonadotrophin-releasing hormone (GnRH), which leads to a decreased secretion of luteinizing hormone (LH) and follicle stimulating hormone (FSH), thus preventing ovarian stimulation, and causing a decline in estrogen and progesterone levels (Roupas and Georgopoulos, 2011; Márquez and Molinero, 2013).

Furthermore, test occasions were determined only by counting days in the menstrual cycle based on the method of previous study (Wojtys et al., 1998). All soccer players attended the three testing sessions on planned days for each menstrual cycle phase. Although, a menstrual history of the previous four months was provided to ensure cycle regularity, the current study did not use sex hormones measurements to determine the menstrual cycle phases. The ideal menstrual cycle is 28 days long, with ovulation being at the 14th day; however, the range of a normal cycle length is between

21 and 35 days and the length of the follicular phase and luteal phase can range of 12-17 days and 12-16 days respectively (Bakos et al., 1994; Frase et al., 2011; Bull et al., 2019). Variability in menstrual-cycle length, as well as the length of each phase and the hormonal fluctuations within each menstrual phase are already well known facts. Regular cycle length can range from 21 to 35 days. Length of menstrual phases can vary, for follicular from 10 to 23 (means = 13 to 15), and for luteal phases from 8 to 17 (means = 13 to 14) (Harlow and Ephross, 1995). The major cause of cycle length variability is attributable to the follicular phase. Menstrual cycle variability is less present within women than between women, however, variations between cycles exist (Shultz et al., 2004). Menstrual-cycle length variation relies on when the follicle begins to develop (producing predominantly estradiol) and the viability of the corpus luteum (which produces the peak of progesterone) (Allen et al., 2016). Due to the fixed scheduling of testing days (to coincide with training schedule), it may be possible that the days when muscle strength was at its maximum or minimum may have been missed, or the days in the cycle when these points occur are different between soccer players due to differing time frames and magnitudes of response to hormone fluctuations (Burgess et al., 2009).

Additionally, anovulatory cycles may occur in spite of normal menstrual cycle, affecting hormonal levels (Prior et al., 2015). A limitation to the study, was that data collection was restricted to within a single cycle for each participant. This increases the likelihood of including data with an anovulatory cycle, where hormone levels differ compared to the ovulatory cycle. This may mask the potential effects of the hormones on lower limb muscle strength. The only way to have truly determined the cycle phases and length would have been to measure hormone concentrations by blood sampling for 3 months (before, during, and after), which was beyond the scope of this study and would have been an unacceptable inconvenience to the players and coaches (Shultz et al., 2004).

Although the players were tested on the specific range of days for each menstrual cycle phase as has been defined by Wojtys et al., 1998, the hormonal variations within phases across players may have affected the results (Allen et al., 2016). These hormonal variations across testing days could be distinguished only by using blood sampling to determine the specific level of hormones at that stage of the menstrual cycle phase on each player. Such invasive testing, was beyond the scope of this field-based study and could be considered for future. Finally, individual differences in emotion regulation within soccer players could affect the muscle strength testing result. Prior work in male participants showed that static handgrip endurance (percent change in force throughout the 30-s hold) changed by up to 20% between testing periods, without fluctuations in hormone levels adding to this variance (Nicolay et al., 2008). The present study found changes in both strength and menstrual distress at the follicular phase. Menstrual distress symptoms such as irritability may be positively associated with the observed greater hip adductor strength at the follicular menstrual phase. This is supported by a prior study conducted on physical performance and anger, proposing that anger facilitated performance of the peak force task (Davis, Woodman and Callow, 2010). Therefore, based on these limitations, our findings should be interpreted with caution.

Since the findings suggest that muscle strength is affected by the menstrual cycle phases, future studies need to clarify the underlying mechanisms behind this effect, but also to determine whether the mechanisms are physiologically or psychologically related with the menstrual distress symptoms. Future studies should consider the potential effect of confounding factors such as the presence of ovulatory vs. anovulatory cycles, training, diet and whether the menstrual cycle phases affect the sporting performance and if this leads to an increased risk of injury.

Given the role that hip muscle strength plays in stabilizing the pelvis, an abnormal performance of the muscles of the hip may alter the distribution of forces across the joint, affecting performance and predisposing the athlete to injury. Therefore, fluctuations in muscle strength across menstrual cycle phases may result in changes of joint stability which during sporting activities may result in an increased susceptibility to injury in female athletes. Practitioners working with female athletes need to consider the menstrual cycle and be aware of the fluctuations across the cycle whereby exercise performance might be enhanced (follicular phase) or reduced (ovulatory and luteal phases). But this approach should be informed by the individual athlete. Athletes should be supported on these issues which can be achieved through conversations initiated by staff, in particular since athletes may not feel confident to raise these concerns. Additionally, sports medicine professionals should be aware of the menstrual distress symptoms, providing education for athletes and staff to improve symptom management, protecting athletes from the negative effects on athletic performance and thus of injury occurrence.

Conclusion

In conclusion, the current study reported that female soccer players with a regular menstrual cycle had greater hip adductor strength and menstrual distress symptoms during the follicular phase. This indicates that hormonal fluctuations throughout the menstrual cycle do affect muscle strength and distress. The underlying hormone effects, especially of oestrogen on muscle strength is not known; however, it may be possible that the effects of estrogen on skeletal muscle are positive, but not immediate, and may take some hours or days leading to a delayed onset strengthening effect. Hip strength provides stability, therefore, the variation in muscle strength and distress symptoms during menstrual cycle phases may have an impact on sporting performance leading to increased sports injuries in female athletes. Although increased muscle strength of the hip adductors could protect soccer players from lower limb injuries at the follicular phase, menstrual distress symptoms may offset this muscle strength advantage, affecting the players sports performance. As a consequence, the risk for injury may be increased. Considering this, soccer players may be at a constant risk for lower limb injury. Further exploration is required to clarify the interaction of muscle strength and menstrual distress effects in relation to hormonal variations during the menstrual cycle. Future studies with a greater number of female players, whose menstrual cycle phases would be determined by sex hormone measurements may establish the effects on and relationship with muscle strength and lead to more precise and concrete conclusions.

Chapter 5 – General discussion and conclusions

The purpose of this final chapter is to draw together the main findings and to discuss the implications of this research programme. The chapter is organized into six sections that present: 1) a recapitulation of the purposes and main findings from each study; 2) the methodological and theoretical implications that emerged from this thesis; 3) a discussion of the practical implications of the findings of this research; 4) the limitations of this research programme; 5) recommendations for future research; and 6) conclusions that summarize the most important findings of the thesis.

This programme of research is comprised of four studies, the first of which was a systematic review of the risk factors for ACL injuries in female athletes. Anterior cruciate ligament (ACL) rupture is one of the most common injuries in female athletes who are 2-3 times more likely to have a rupture than their male counterparts. Therefore, awareness of the risk factors for ACL injuries in female athletes is an important component of developing injury risk management strategies. Hence the first study aimed to systematically review studies investigating the risk factors for ACL injuries in female athletes. The review suggested that the strongest supported risk factors for ACL injury in female athletes were small intercondylar notch width and prior history of ACL injury. Conflicting and limited evidence was found for the following reported predisposing factors for ACL injury in athletes: knee hyperextension; family history; Body Mass Index; playing surface; tibial slope; muscular strength, flexibility and coordination; psychological factors; sex hormones.

It was unclear as to the mechanism by which the small femoral notch predisposes the ligament to greater injury risk; but a small intercondylar width may produce a bony impingement against the small ACL, which predisposes the ligament to a higher risk of rupture (Simon et al., 2010). A prior history of

ACL injury seems to affect the anatomical structure of the knee increasing the risk for reinjury. Deficits in movement mechanics and compensatory movement patterns can often develop after an ACL injury that over the long-term may lead to maladaptations and ACL re-injury (Souryal and Freeman, 1993). This finding may reflect the inadequate levels of rehabilitation, or the premature return to sporting activity after an ACL injury, increasing the subsequent risk of reinjury. Inadequate rehabilitation following an ACL injury may lead the athlete to return to sporting activity with neuromuscular deficits increasing the risk for ACL reinjury or other lower limb injuries. Muscle strength deficiency has been shown as a risk factor for a variety of lower limb injuries, however, evidence is mainly focused on male athletes (Finoff et al., 2011; Power et al., 2017).

Given the importance of appropriate muscular strength in the lower limb, regular measurement of these variables is warranted to allow for the continuing evaluation of injury risk management programmes and guidance of return-to-play decisions after injury. To date, hip adductor/abductor and knee flexor (Nordic) strength normative values for female athlete populations are sparse. While Nordbord has been established since the prototype data was published in 2012 (Opar et al., 2012), ForceFrame was a recently developed device to allow fast and reliable measures of hip and groin strength to be obtained in the field. Therefore, the second study involved a secondary analysis of data of normative values for eccentric knee flexor and isometric hip adduction and abduction muscle strength reported. In addition, relationships between muscle strength measurements and anthropometrical data were assessed; and the association between adduction and abduction variables at each position and between Nordbord testing positions in healthy, female athletes.

Strong positive correlations (range of r= 0.55 to 0.90) between adductors (ADD) and abductors (ABD) were obtained for each position. Also, body mass was correlated with eccentric knee flexor, and hip adductor and abductor strength at 60^0, suggesting the influence of body mass in the force-generating capacity of muscles. Additionally, hip adductor and abductor muscle strength at 60^0 was also found to be associated with an athletes' stature suggesting that body size influences muscle strength.

Muscle strength of the lower extremities was also one fitness component identified from the systematic review that can be specifically targeted and changed by training. In addition, psychological factors have also been suggested to predispose athletes to injury given the associated stress. The third study with an expanded scope beyond ACL injury, investigated retrospectively and prospectively the association between lower extremity muscle strength and the risk for lower limb injuries, and the potential relationship between life events and lower limb injuries in female athletes. The main findings from the second study were that a history of negative life events was associated with a risk of future non-contact lower limb injury in female athletes. The theoretical underpinning for study 3 originated from Williams and Andersen's (1998) "stress-injury model" which divides psychological risk factors into three main categories: personality factors, history of stressors, and coping resources. The model suggests a positive relationship between life-event stress and injury risk (Williams and Andersen, 1998). It was hypothesized that negative life events may affect the stress responses (physical/physiological or psychological/attentional changes) in athletes, increasing the risk for injury (Williams and Andersen, 1998). Therefore, negative life events require both adaptive and coping skills on the part of the athlete to meet the situational demands and thus, protecting the athlete from injury risk (Sarason, Johnson and Siegal, 1978; Williams and Andersen, 1998).

Furthermore, it was found that the group with the highest proportion of athletes who reported having irregular menstrual cycles, were in the cluster that had high levels of negative life events. The exact underlying mechanism for the association between stress and menstrual dysfunction is unclear. However, it has been suggested that the dysregulation of the hypothalamic–pituitary–adrenal (HPA) axis and the glucocorticoids negative feedback have reciprocal interactions with ovarian hormones, which influence a woman's menstrual cycle regulation (Chrousos, Torpy and Gold, 1998; Saunders and

Bruce, 1999). This could propose a link between stress, menstrual cycle regularity and injury risk. Given this, a plan focusing on targeted support and counselling to help athletes cope better with feelings and stress may be a worthwhile investment into the prevention of injuries.

Findings from the third study also revealed new potential non-contact lower limb injury risk factors related to decreased muscular strength. Specifically, weak hip adductor strength, and between-limb adductor and abductor strength imbalances were associated with a risk of future non-contact lower limb injury. The hip adductor and abductors play a central role to the execution of rapid and forceful movement tasks involved in team sports such as running, jumping and change of direction.

Hip abductors also have a role in controlling the lateral pelvic tilt and foot placement during the swing phase of gait (MacKinnon and Winter, 1993; Friel et al., 2006). Interestingly, athletes from study 3 with a history of ankle injury were found to be at increased risk of lower limb injury. If strength of the hip abductor muscles have altered following an ankle injury, the position of the foot at initial contact may be more adducted than normal, and the risk for reinjury is increased (MacKinnon and Winter, 1993; Friel et al., 2006). Before this work, there was a paucity about the role of hip adductor strength on lower limb injuries and prior work was dominated by a male athlete focus and therefore, generalizations couldn't be made since gender differences in lower extremity muscle activation have been shown previously (Zazulak et al., 2005; Hanson et al., 2008; Brophy et al., 2010).

Other potential risk factors for lower limb injuries also emerged from study 3, these were familial history of ACL injury and oral contraception use. Athletes with a familial predisposition to ACL injury were four times more likely to sustain an ACL injury. Familial predisposition towards ACL injury has been linked with genetic factors. Specifically, it has been found that specific genes related to collagen with different polymorphism were associated with ACL tears (Posthumus et al., 2009; Posthumus et al., 2010; John et al., 2016). In addition, gender differences between females and males in the expression of three genes (ACAN, FMOD, and WISP2) related to the structure and integrity of ligaments have been found.

Gender differences in relation to ligament integrity may also be due to female hormones. Female hormones seem to be linked with musculoskeletal injuries. Specifically, athletes who reported use of oral contraception were found to have less injuries in study 3, suggesting that female hormones have an impact on the mechanical ligament structure and physical properties. However, further analysis is needed to determine the full impact of hormones on ligaments, tendons, and muscles.

Based on study 1 and supported by the results from study 3, it was important to further explore the impact of female hormones on athletes' potential markers of injury risk. During the menstrual cycle, there are well established hormonal variations characteristic to each phase. However, based on the previous literature it remained unclear whether these cyclic changes may affect the force producing capabilities (i.e., strength) of the hip adductors and abductors and thus, impact on the athlete's injury risk status. Therefore, fourth study aimed to investigate the effect of the menstrual cycle on a battery of lower limb muscle strength measures associated with lower limb injuries in football and evaluated the effects of the menstrual cycle on mood in female soccer players. Female soccer players were tested throughout three different menstrual phases (follicular, ovulatory, and luteal) and it was found that hip adductor strength and menstrual distress peaked during the follicular phase. It may be possible that menstrual distress symptoms such as irritability as well as the positive correlation observed in greater hip adductor strength during the follicular menstrual phase, could protect against non-contact lower limb injury.

Based on the findings of third study in which hip adductor strength was associated with lower limb injuries, the conclusion can be made that athletes may be protected from injuries at the follicular phase, where the hip adductors were found to be stronger. However, it may be more complex than that as menstrual distress symptoms, such as anger could offset this benefit on increased strength, and as a consequence, the risk for injury may be increased. This means that female athletes may be at a constant risk of injury, but the underpinning causes may change.

Methodological and theoretical implications

Several methodological and theoretical implications have emerged from this research programme. Given that a prior history of ACL injury is the strongest predictor for ACL reinjury, it begs the question what the procedure should be for the rehabilitation and return-to-sport criteria. Although clinicians follow specific steps at the time of rehabilitation based on several clinical and impairment-based criteria, ACL reinjury is still occurs. This may be because rehabilitation programmes are varied, the return-to-sport criteria are not standardized, and therefore experts disagree on the key criteria that should be met, before return to sports (Makhni et al., 2016; de Mille and Osmak, 2017).

As a result, the high incidence of ACL reinjury and the low rates of successful return to sport clearly imply that more work is needed. Research studies have focused on identifying the battery of tests that will best indicate the optimal return-to-sport as well as expanding the return-to-sport decision-making process. However, the return-to-sport decision making is made at the ‘theoretical end’ of the rehabilitation process, while the criteria for the ′′return-to-sport′′ mainly focuses on impairments of the injured knee joint (Dingenen and Gokeler, 2017). To address this issue, perhaps it is time to move away from a binary return to sport decision making process and re-frame the pathway after ACL reconstruction to an “optimized return to sport approach” which involves shared decision-making with a broad spectrum of individual sensorimotor, psychological, and biomechanical outcomes (Dingenen and Gokeler, 2017; de Mille and Osmak, 2017). It has been suggested that ACL injury should be considered not as a simple musculoskeletal injury with only local mechanical or motor dysfunctions, but as a neurophysiological injury, highlighting potential neurophysiological alterations after ACL injury that may require a different rehabilitation approach (Kapreli and Athanasopoulos, 2006). However, return-to-sport batteries do not focus on enhancing the injured athlete’s ability to handle neurocognitive overload and fail to comprehensively address the interaction of the injured athletes with the task and environmental constraints (Dingenen and Gokeler, 2017). Furthermore, return-to-sport criteria are mainly focused on the recovery in a physical capacity, focusing on coping with the physical demands of a specific sport and maximizing performance, but ignoring the psychological factors such as readiness to return to sport or other psychological stressors (e.g., personality, history of stressors). The results from the third study showed a positive relationship between life-event stress and injury; hence, early recognition of maladaptive or dysfunctional psychological responses during rehabilitation can be addressed with targeted interventions before return-to-sport. It seems that ongoing communication between all members of the return to sport team (surgeon, physical therapist, fitness professional, athletic trainer, sport psychologist, coach) is required to provide the missing link in the transition from rehabilitation to successful return to sport performance.

Study 3 was underpinned by Williams and Andersen’s (1998) ‘’stress-injury model’’. This model supports the role of several psychological variables such as life event stress and personality characteristics associated with injury occurrence. Although this model has been widely used in previous studies, limitations have been noted. While the model focuses on cognitive response, other factors such as environmental and sociocultural (e.g., team norms) that also affect injury occurrence (Ivarsson et al., 2017), were not included. The inclusion of these factors may lead to a better design of intervention programmes (Appaneal and Perna, 2014). To deal with these limitations, the biopsychosocial model of stress athletic injury and health (BMSAIH) was proposed by Appaneal and Perna’s (2014). The BMSAIH expands the Andersen and Williams model of ‘’stress and injury’’ including other behavioural, environmental and physiological factors that are also associated with injury occurrence. Specifically, BMSAIH suggests that the combination of both physiological (e.g., attentional perturbation) and psychological stress (e.g., negative life events) will intensify the stress response predisposing an athlete to injury. However, not much attention has been given to the BMSAIH, and since this work was beyond the scope of the current research programme, further work is warranted. Given the consistent relationship between hip muscle weakness and lower limb injuries, the question remains as to whether lower limb injury can be successfully reduced if the treatment is limited to only one aspect. For example, it is questionable if a treatment strategy focused solely on hip strengthening is adequate to achieve successful outcomes. The persistent display of altered hip motion during activities in athletes with a history of injury may suggest that movement re-education may not be an essential aspect of care. However, abnormal hip motion may cause a problem to recur leading to musculoskeletal pathology, suggesting that strength may not always be a prerequisite for movement re-education. This issue utilized findings from the study that used a combination of strength training and movement education (video-assisted feedback programme) to achieve maximal efficacy (Herman et al., 2009).

Distress symptoms such as anger are able to facilitate performance of a task (Davis, Woodman, and Callow, 2010). This begs the question whether the muscle strength that was found to be increased was caused by distress symptoms or due to hormonal variations. If menstrual symptoms influence muscle strength, the potential management techniques to address the symptoms may then, decrease muscle strength. As a consequence, this may affect the relationship between strength and injury, negatively. However, menstrual distress symptoms and its impact on performance and sports injuries has received very little attention. Furthermore, symptoms may also be provoked when certain tasks or demands are required, such as testing maximal muscle strength force. Or they could be enhanced by other factors such as caffeine, diet, age or personality traits. Either way, women suffering from menstrual distress are more predisposed to depression, anxiety and somatization (Granot et al., 2001; Alonso and Coe, 2001). A theory of ‘’illness behaviour’’ by Osterweis et al. (1987) suggests a conceptual framework for the changes in perception, attribution, expression, and control experienced by women with menstrual distress. Specifically, a woman's reactions to the bodily sensations depends on her psychological makeup and also on her expectations based on social and cultural context. Furthermore, reporting menstrual distress symptoms is related to cultural attitudes and beliefs regarding menstruation (Sveinsdottir, 1998).

Practical implications

Several practical implications have emerged from this research programme with relevance for female athletes, sports medicine staff, coaches, athletic trainers and researchers interested in sports injury. Study one demonstrated the lack of evidence supporting risk factors that could be modified by training interventions. Although anatomical factors cannot be modified, the impact of prior history of ACL injury could be reduced. Return to sporting activity after ACL injury is ultimately characterized by achievement of the preinjury level of sport. Therefore, progressive optimal postoperative physical rehabilitation, physical conditioning and proprioceptive training may lead to a reduction in the risk of ACL re-injury. Each ACL injury case must be assessed individually taking into account the time considerations with respect to the biology of ACL graft tissue healing and the neuromuscular function recovery. Additionally, the identified association between prior history of ACL injury and ACL reinjury may imply that there is a need to improve return-to-sport guidelines so that female athletes can more safely reintegrate back into sport with a reduced risk for reinjury. Although there has been development of return to sport guidelines over the past years, there is a lack of scientific consensus on the return-to-sport criteria used to allow an athlete to return to sporting activity (unrestricted) after ACL reconstruction (Gokele et al., 2020).

Functional impairment testing has been typically used in sports injury rehabilitation (Manske and Reiman, 2013). However, a frame of reference values was not established for female athletes regarding hip strength. Therefore, findings from study 2 could help clinicians to set treatments goals and help coaches to evaluate for a potential strength deficiency. Increasing hip strength is multifaceted in terms of benefiting the entire lower extremity. And based on the findings of study 3 may be able to decrease the risk of injury. Normative muscle strength data can be useful for sports coaches, trainers, medicine physicians, physiotherapists and others who are responsible for an athletes' health, but also for return-to-sport criteria.

Despite this, most studies are focused mainly on neuromuscular factors where the experience of negative life events can increase the risk for injury. Study three demonstrated how the history of negative life events can increase the probability of lower limb injury in female athletes. As such, there is a need for a holistic approach, incorporating psychological training programmes into other injury risk management programmes that athletes can follow to reduce the risk for injury.

In addition to training programmes, the monitoring of psychological status in combination with training loads and performance will be critical for the coach to determine a female athlete's physiological status and psychological status. This may help athletes with negative life events experience to follow an adjusted training programme focused on coping with the additional stress they are experiencing. Furthermore, athletes should be encouraged by coaches to report potential feelings such as stress to help them cope with the diverse demanding status. One way to achieve this is the coaches' education in relation of the different challenges, barriers and demands that athletes are faced with, that could influence the injury occurrence. In view of the negative consequences that can be caused by stress, specific intervention programmes to develop coping resources is re required. Stress management programmes could be useful to teach the athlete relaxation and cognitive skills enabling them to adapt to stressors (Perna et al., 2003). This could be applied individually through a sports psychology consultation or group intervention. Many athletes don't ask for help from a sport psychologist on an individual level, due to the fear of stigma of getting professional mental help

(Bauman, 2016). However, group intervention programmes and coach encouragement may help athletes seek out professional counselling.

Although there is attention paid to knee flexor and extensor strength factors in female athletes, the presumed association between hip strength deficits and lower limb injuries has been suggested from study 3. Hip adductors strength and between-limb hip adduction and abduction in athletes, may cause abnormal kinematics, increasing the odds of suffering a future lower limb injury. These Imbalances may persist in athletes for a number of reasons. This may be due to repetitive, asymmetrical, sport-specific demands (kick, changes of direction), previous injury, pain or incomplete recovery (Rahnama, Lees and Bambaecichi, 2005; Schiltz et al., 2009; Castanharo et al., 2011; Fulton et al., 2014; Fort-Vanmeerhaeghe et al., 2016). Based on these new findings, clinicians should consider including exercises that focus on strengthening hip adductor and abductor strength as part of their training programme. Strength training targeted towards the hip adductors should be a major component in injury risk management programme . Additionally, regular muscle strength and asymmetry evaluation may help to identify potential malalignment early so that individual-specific strength prevention programmes can be applied.

Additionally, EMG studies have shown the role of adductor magnus (working in concert with the hamstrings) as a hip extensor as well as a hip adductor and internal rotator during functional activities such as sprinting (Ko et al., 2017). Specifically, when the hip is flexed, adductor magnus has a positional leverage to act as a hip extensor, and vice versa when the hip is in extension (Neumann, 2010; Mansfield and Neumann, 2018). Therefore, clinicians should consider the hip position when seeking to screen for injury risk and focus on improving the strength of the hip extensors.

The relationship between the menstrual cycle, associated hormonal fluctuations, menstrual distress and sporting performance is complex (Findlay et al., 2020). More than 90% of female athletes report menstrual cycle-related symptoms (Findlay et al., 2020). Study 4 identified high menstrual distress symptoms at the follicular phase. Symptoms such as menstrual pain and menstrual attitude can influence daily activity and may impair sporting performance. Thus, there is a need for sports medical teams to initiate conversations with female athletes surrounding the menstrual cycle and distress symptoms, especially due to the male-dominated environments. This may minimise any negative impact of distress symptoms and maximise health and performance. Sports medical teams should be aware of and able to understand menstrual cycle dysfunctions and menstrual symptoms along with the appropriate available treatments. Therefore, education should be provided to the sports medical teams who work with female athletes in regard to the above. This will comfort athletes and hopefully encourage rather than discourage them to discuss menstrual cycle concerns and issues with male staff members. Additionally, since menstrual distress and muscle strength has been found to be increased during follicular phase, athletes should be educated on management techniques to address symptoms such as headache, cramps, back pain etc.

Limitations

The findings from this programme of study include a range of strengths and limitations. The systematic review evaluated a comprehensive range of risk factors utilising a variety of databases. However, a meta-analysis was not conducted for study 1, which could be able to provide more objective information. This was unable to be completed due to the high variability in the data, and the different statistical variables that the studies used (OR, RR, and IRR). A second limitation was that the review did not include any study outside the English language, which may have limited the risk factors identified. A third methodological limitation was that the included studies examined athletes through the season, but athletes were tested for outcome measures (e.g., muscle strength) only once during the season. Athletes muscle strength and flexibility may have changed during the season affected by different factors such as injury, or fatigue. A fourth limitation is that some of the studies were case-control studies with potential bias (e.g., recall bias, selection bias). Future research is required to focus on confirming the less supported ACL injury risk factors in female athletes. This may be achieved by compiling objective and functional outcome measures as part of a testing procedure in female athletes. This would be of particular importance for female athletes, based on the incidence of ACL injuries highlighted previously.

Study 2 established normative values based on high numbers of female participants with a wide range of ages, the variation of sports played and the use of commonly used testing positions, ensuring the findings could be generalised. However, the conditions of how the tests were performed are unknown.

Although, cohort study 3 used a valid tool for measuring the life events, the athletes who were less than 18 years of age could not use the LESCA questionnaire because LESCA includes items not suitable for children. These include: such as: death of a close family member; breaking up with partner; marriage; failing an important exam or course. Unfortunately, a suitable validated alternative was not available and censoring the inappropriate questions would have rendered the questionnaire invalid. Additionally, as the questionnaire reflected possible life events that athletes may have experienced in the previous 12 months, problems of memory recall or biased recall may have occurred. Finally, the lack of an athlete's season exposure data and injury severity information did not allow for the determination of injury incidence relative to their exposure to training and match play. Unfortunately, in study 3 detailed injury data was not made available, therefore the IOC recommendation for the format of incidence reporting (i.e., per 1000 playing hours) was not possible. Additionally, study 3 used novel reliable testing devices to measure hip muscle strength and knee flexor strength when investigating the effect of muscle strength to injury. Although the sample size was large, the limited number of specific injuries (hamstring, ACL) did not allow for subgroup analysis. This means that potential associations between certain risk factors related solely to specific types of injury may have been masked. Finally, while study 3 included female athletes from different sports, findings can not be generalized to male athletes.

The tests selected are field-based measures used to screen groups of individuals and inform practice they are based on exercises used as part of physical preparation and rehabilitation and supported by research that shows an association with injury risk across a wide range of sports and injuries. Eccentric muscle contraction is mainly associated with injuries due to excess tension compared to concentric or isometric contractions (Frizziero et al., 2014). Although the current study measured the knee flexors eccentrically, which is the specific contraction responsible for hamstring injuries (e.g. terminal swing phase of running), hip adductors and abductors were measured isometrically (Heiderscheit et al., 2005; Chumanov et al., 2011). The hip adductor longus muscle is stressed during kicking, where the adductor muscles are exposed to large eccentric forces (from hip extension to hip flexion movement) which results in adductor muscle injury (Charnock et al., 2009). Although injuries mainly occurred during the eccentric contraction, isometric contraction is valuable for training as well as being an evaluation tool of a muscle group (Lee et al., 2018; Moreno-Pérez et al., 2019; Markovic et al., 2020). Isometric hip adductor and abductor muscle weaknesses have been established as risk factors for future development of groin injuries, ankle injuries and knee pain in athletes (Ryan et al., 2014; Luedke et al., 2015; Delahunt et al., 2017; Powers et al., 2017). In study 3, two different testing positions were used for hip muscle strength. Different testing positions also provide evaluation of other primary hip adductors. For example, Pectineus muscle has its greatest activation at 90^0 hip flexion with Adductor brevis (Lovell, Blanch and Barnes, 2012). It has been suggested that training isometrically at different angles produced significantly greater gains in isometric strength across a range of angles (Folland et al., 2005). This means that isometric measurements at different angles could also be useful for the evaluation of the hip muscle strength during the season. Future studies should include isometric strength measurement at angles between or outside of the training angles of each sport movements.

Additionally, although neuromuscular performance deficits in relation to balance, stability, lower limb power, and strength have been considered as potential modifiable risk factors for lower limb injuries, studies 3 and 4 were limited as they only measured the lower limb muscle strength (Bahr and Holme, 2003; Myer et al., 2011; Lehr et al., 2017; Faude et al., 2017). Neuromuscular performance refers to the ability to produce controlled movement through coordinated muscle activity (Hamilton and Luttgens, 2001; Maxey and Magnusson, 2013). However, the measure of muscle activity is time-consuming procedure for the sports field and requires professionals with the education and proper training (Pilkar et al., 2020). Muscle strength training of the lower limb alone may not be sufficient to improve the neuromuscular control of the hip and knee joints, particularly if movement quality and speed of force production are being overlooked. Therefore, further future studies are needed to evaluate lower limb performance using a multimodal testing approach.With respect to the strengths and limitations of study 4, athletes did not know their menstrual phase at each specific time of the testing and therefore, subject attrition was avoided. However, the sample size was small. This is consistent with previous report because amenorrhea/oligomenorrhea is more prevalent among athletes than in the general population (Goodman and Warren, 2005). Therefore, the current results should be interpreted with caution because of the low sample size. Secondly, test occasions were determined using the menstrual history based on the method used in previous study (Wojtys et al., 1998). Accuracy in determining the specific menstrual cycle phase is via analysis of the serum levels of estrogen/progesterone ratio in the urine, saliva or blood. However, to confirm the regularity of the cycle in study 4, a menstrual history of the previous four months was provided. Furthermore, larger studies are needed that should examine the hormones at the day of the testing.

Future recommendations

In addition to the points that have been already referenced above, several future recommendations can be made. Although anatomically, a small intercondylar notch is identified as a risk factor in suffering a sports-related injury, it cannot be altered. Therefore, further research is warranted to investigate those risk factors (e.g., BMI, muscle strength, psychological factors) that can be modified in order to improve prevention strategies. Body mass index (BMI) is another parameter that has been considered to be associated with lower extremity injuries (Nilstad et al., 2014). Knee injuries may be more likely to happen in athletes with high BMI during tasks that require changing direction and momentum, challenging knee stability (Amoako, Nassim, and Keller, 2017). Unfortunately, thus far, studies have been small with a reduced number of injuries, reducing the statistical power for the subgroup analyses (Östenberg and Roos, 2000; Nilstad et al., 2014). Therefore, further studies are needed on BMI and ACL injuries to investigate whether reduction in body mass is able to reduce ACL injuries in female athletes.

Muscle strength and co-activation of hamstrings and quadriceps muscles may be critical to knee stabilization protecting the ACL from injury (Steffen et al., 2016). Thus, a potential deficit in hamstring strength may increase ACL injury risk in female athletes (Steffen et al., 2016). However, the literature is limited, and findings so far conflicting (Myer et al., 2009; Steffen et al., 2016). Therefore, further work needs to be done on lower limb muscle strength and functional movement task screening, which may contribute to the development of better injury risk management programmes.

In a competitive sport situation, psychological factors can influence the athletes' performance, and affect the incidence of injury. However, few studies have investigated the impact of psychological factors on sports injuries, especially ACL injuries in female athletes where the findings are limited (Kosaka et al., 2016). Further studies are needed, focusing on the impact of psychological factors on ACL injuries and whether management could help in reducing the injury rates.

Although the LESCA remains the most widely used measure of life event stress within the athletic population, it was unable to be used on athletes less than 18 years old due to the type of questions.

Consequently, the development of an alternative scale that can capture the life events in athletes less than 18 years old would be desirable. This will provide the opportunity for future studies to examine this relationship of life events and injury occurrence in athletes less than 18 years old.

Williams and Andersen's (1998) ''stress model'' proposes that personality characteristics could also affect what situations an athlete considers as stressful. The role of personality variables in the stress injury model is associated to cognitive appraisal. Personality traits such as trait-anxiety and low self-confidence may affect the athlete's ability to perceive situations and events, such that they experience more stress and become more susceptible to the effects of the stressors, than would otherwise have been the case (Petrie, 1993). Additionally, Williams and Andersen's (1998) ''stress model'' has also proposed coping resources (e.g., coping behaviours, social support systems and stress management) as effective ways to influence the stress response and lower the likelihood of injury occurrence in female athletes. However, the current study only measured the life events and did not explore the effects of coping resources on the severity and frequency of injuries. Future studies should consider a more comprehensive treatment to Andersen and Williams's model including personality variables and coping resources.

Cohort study 3 also demonstrated association between hip adductor strength, between-limb adductor and abductor strength imbalances and the risk of future non-contact lower limb injury. Hip control affects movement patterns in the leg. Potential hip asymmetries may alter the movement patterns during sporting tasks, increasing the risk for lower limb injury. Further studies are warranted to assess the effectiveness of hip strength prevention protocols in the prevention of lower limb injuries.

Although athletes in study 4 demonstrated stronger hip adductor muscle strength at the follicular phase, the cause of this difference in relation to hormones but also to menstrual distress, needs further exploration. It may be possible that this rise in muscle strength at the follicular phase is caused by the symptoms of distress rather than hormonal fluctuations. Therefore, future and larger studies are needed to evaluate the relationship between muscle strength and distress in female athletes and whether menstrual distress symptoms affect the sporting performance and injury occurrence.

Although study 2 established normative data and that can be applied in the clinical setting, it is unknown whether it can predict future injuries. Therefore, further research is warranted to demonstrate whether this information is useful in injury prediction and to contribute to the development of injury risk management programmes. Additionally, due to the biomechanical and training differences between sports, future studies should establish normative values for specific sporting populations.

Conclusion

In conclusion, findings from this programme of research have demonstrated that the history of negative life events is a significant risk factor for lower limb injuries in female athletes. In addition, hormonal fluctuations throughout the menstrual cycle do affect muscle strength and distress at the follicular phase and may have an impact on sporting performance, leading to increased sports injuries in female athletes. Finally, reference ranges have been established for strength of the hip adductor and abductor muscles and knee flexor strength in female athletes.

Chapter 6 -References

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Chapter 7-Appendices

Appendix 1: Systematic Review-Data extraction form

Authors year	N	Study design	Age	Country	Type of sport	Assessment methods	Risk factors	Response rate	Key findings	Quality score

Appendix 2: Study 3

Study 3: Letter to participants and consent forms

Participation information sheet

Risk factors for lower limb injuries in National level female footballers in Wales.

Introduction

I am a PhD student and I would like to invite you to take part in my research study. Before you decide you need to understand why the research is being done and what it would involve for you. Please take time to read the following information carefully. Ask questions if anything you read is not clear or would like more information. Take time to decide whether or not to take part.

What is the purpose of the study?

The aims of this study is to identify the risk factors which are associated with lower limb injuries in the female athletes in Wales. The information that you will provide is anticipated to help us to understand which female athletes are at risk of lower limb injuries. Furthermore, the findings of this study will contribute to design prevention strategies in the future since an improved understanding of what risk factors may lead to injury is expected.

Why have I been invited?

You have been invited because you are a female athlete who plays national level in Wales.

Do I have to take part?

It is up to you to decide. Before you make a decision, we will describe the study and go through this information sheet, which we have provided. You may read through the information sheet for as long as you need and feel free to ask any questions. If you decide to take part, then you will be asked to sign a consent form to show you agreed to take part. Please note: that you are free to withdraw at any time, without giving a reason.

If you participate, you will be asked to complete risk factor questionnaires that provide background on your physical and sports training characteristics, menstrual and oral contraception history, history of any previous injury, family history regarding ACL injury and the level of stress you have experienced.

In addition, you will be asked to take part in a series of tests on two occasions over a season. All testing will take place at your Club's training facility. The tests are non-invasive assessments that are relatively safe and less physically demanding than what you are exposed to when playing football. The tests include: height, weight, strength measurements of hip, groin and leg.

Hip and groin tests: For the hip and groin tests, we will use a GroinBar™ or handheld dynamometer, where you will be asked to adopt various positions while lying down and squeeze then push against specialised pads that measure force.

Single leg jump: Another test that you will be asked to perform is a single leg jump. Standing on one leg you will be asked to jump as high as you can and land on the same spot on the platform that measures the pushing and landing forces.

Eccentric hamstring strength measurement: We will also use a Nordbord ™ to measure eccentric hamstring strength. For that test you will be asked to kneel on a specialised device with braces to secure your ankles that will record your pulling forces. Then as slowly and as smoothly as possible, lean forward so that your chest will approach the ground.

Expenses and payments

No expenses or payments will be available if you participate to our study.

What will I have to do?

You have to fill in our questionnaires online over the season and participate in the testing procedure.

What are the possible disadvantages and risks of taking part?

With all physical tests such as the ones you will be asked to perform there is some risk of injury. However, the volume (amount) of one exercise you will be asked to complete during the data collection is much lower than that typically used during a training season. Therefore, the risk in taking part is low.

What are the possible benefits of taking part?

We cannot promise the study will help you but the information we get from the study will help to increase the understanding of the incidence of lower limb injuries in female football players and so, prevention strategies could be developed in future.

What if there is a problem?

If you have a concern about any aspect of this study, you should ask to speak to the researcher Sania who will do her best to answer your questions. If you have questions regarding other problems, they will be referred to Dr Morgan Williams via email morgan.williams@southwales.ac.uk or Prof Rich Mullen rich.mullen@southwales.ac.uk who they supervised this research study.

If you remain unhappy you can contact the research governance officer Mr Jonathan Sinfield on (01443) 484518 or via email jonathan.sinfield@southwales.ac.uk .

Will my taking part in the study be kept confidential?

All information that will be collected about you during the research study will be kept strictly confidential, and any information with your name and address will be removed so that you cannot be recognised.

What will happen if I don’ t carry on with the study?

If you withdraw from the study, we will destroy all your identifiable data, but if you are happy for us to keep the data up to your withdrawal, we would like to use the data in the final analysis.

What will happen to the results of the research study?

The results of the studies will be written up as a part of a PhD thesis. Also, we hope to share the results to a wider audience by publishing a paper in an academic journal. Please note: the publication will not include any confidential data or names of the participants.

Who is organising or sponsoring the research?

This study is organized and funded by the University of South Wales.

Further information and contact details:

Sania Almousa, PT, M.Sc.

PhD student

Faculty of Life Sciences and Education

University of South Wales

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Thank you for taking the time to read this Information Sheet.

Study 3: Consent form

STUDY CONSENT FORM

Title of Project: **Risk factors for anterior cruciate ligament injuries in National level female footballers in Wales.**

Name of Researcher: Ms **Sania Almousa**

Name of supervisor: **Prof Richard Mullen, Mr Craig Gill, Dr Morgan Williams**

Please **(initial)** all boxes

1. I confirm that I have read and understand the information sheet Version 1. 11/05/2017 for the above study. I have had the opportunity to consider the information, ask questions and have had these answered satisfactorily. ☐

2. I understand that my participation is voluntary and that I am free to withdraw at any time without giving any reason, without any consequence to myself. ☐

3. I agree to:

    a. Having my physical characteristics measured (i.e., height, weight). ☐

    b. Provide information regarding my characteristics as a football player (position, dominant leg) (once). ☐

    c. Complete the injury history questionnaires and the club to report details of any injuries I sustain during training or competitive match play. ☐

    d. Provide information regarding my menstrual and oral contraceptive history and my family history for any potential anterior cruciate ligament injury. ☐

    e. Provide information regarding my stress status. ☐

    f. Perform the following tests: hip and groin, single leg jump, and the Eccentric hamstring strength measurement ☐

4. I agree to my anonymised data being used in study specific reports and subsequent articles that will appear in academic journals. ☐

5. I agree to take part in the above study. ☐

____________________	____________________	____________________
Name of Participant	Date	Signature
____________________	____________________	____________________
Name of person - taking consent.	Date	Signature

Study 3: Parent/Guardian Consent Form

University of South Wales
Prifysgol De Cymru

Parent/Guardian Consent Form

Title of Project: **Risk factors for anterior cruciate ligament injuries in National level female footballers in Wales.**

Name of Researcher: **Sania Almousa**

Name of supervisor: **Richard Mullen, Craig Gill, Morgan Williams**

Please **initial** all boxes

6. I confirm that I have read and understand the information sheet Version 1. 11/05/2017 for the above study. I have had the opportunity to consider the information, ask questions and have had these answered satisfactorily. ☐

7. I understand that my child's participation in this study is voluntary and that I am free to withdraw my child at any time without giving any reason, without any consequence to myself or my child. ☐

8. I agree to my child's anonymised data being used in study specific reports and subsequent articles that will appear in academic journals. ☐

9. I agree my child to provide ahthropometric data (height, and weight), menstrual history, histroy of previous injuries, stress history and family history for any potential anterior cruciate ligament injury. ☐

10. I agree my child to perform the following tests: hip and groin, single leg jump, and the eccentric hamstring strenght measurement. ☐

11. I agree to allow my child to take part in the above study. ☐

Name of Participant

____

Name of Parent/Guardian Date Signature

____

Name of person - Date Signature

taking consent.

____

Study 3: Assent form (*under* the age of *18 years*)

University of
South Wales
Prifysgol
De Cymru

STUDY ASSENT FORM (under 18 year-olds)

Title of Project: **Risk factors for anterior cruciate ligament injuries in National level female footballers in Wales**

Name of Researcher: **Sania Almousa**

Name of supervisor: **Richard Mullen, Craig Gill, Morgan Williams**

Please **initial** all boxes

1. I confirm that I have read and understand the information sheet Version 1. 11/05/2017 for the above study. I have had the opportunity to consider the information, ask questions and have had these answered satisfactorily. ☐
2. I understand that my participation is voluntary and that I am free to withdraw at any time without giving any reason, without any consequence to myself. ☐
3. I agree to my anonymised data being used in study specific reports and subsequent articles that will appear in academic journals. ☐
4. I agree to:

a. Having my physical characteristics measured (i.e., height, weight). ☐

b. Provide information regarding my characteristics as a football player (position, dominant leg) (once). ☐

c. Complete the injury history questionnaires and the club to report details of any injuries I sustain during training or competitive match play. ☐

d. Provide information regarding my menstrual cycle and my family history for any potential anterior cruciate ligament injury. ☐

e. Provide information regarding my stress status. ☐

f. Perform the following tests: hip and groin, single leg jump, and the eccentric hamstring strength measurement. ☐

5. I agree to take part in the above study. ☐

______________________	______________________	______________________
Name of Participant	Date	Signature
______________________	______________________	______________________
Name of person - taking assent.	Date	Signature

Study 3: The Life Events *Survey* for Collegiate Athletes (LESCA)

Instructions: Listed below are 69 events that sometimes occur in the lives of college athletes. These events often produce change within an individual's life that require some adjustment by the individual. For each event that you have experienced within the last year (12 months), indicate what kind of effect it had on your life when the event occurred. A rating of -4 would indicate that the event had an extremely negative effect on you. A rating of +4 would indicate that the event had an extremely positive effect on you. For those events that have happened more than once, indicate the average effect across all occurrences. If you have not experienced an event within the last year, leave that item blank. The events are listed in no particular order, and there are no right or wrong answers. Please respond to each event honestly as applies to you.

<u>If you have NOT experienced an event listed below (e.g., Marriage) in the past 24 months, leave that item blank. ONLY respond to items you have experienced</u>

Extremely Negative
Moderately Somewhat Somewhat Moderately Positive Extremely

Negative Negative
Negative Positive Positive Positive

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--

1. Marriage -4 -3 -2 -1 +1 +2 +3 +4

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2. Death of mate (boyfriend, girlfriend, spouse, significant other) -4 -3 -2 -1
+1 +2 +3 +4

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--

3. Major change in sleeping habits (increase or

decrease in amount of sleep) -4 -3 -2 -1 +1 +2 +3 +4

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--

4. Death of a close family member(s)

Father -4 -3 -2 -1 +1 +2 +3 +4

Mother -4 -3 -2 -1 +1 +2 +3 +4

Brother -4 -3 -2 -1 +1 +2 +3 +4

Sister -4 -3 -2 -1 +1 +2 +3 +4

Grandfather -4 -3 -2 -1 +1 +2 +3 +4

Grandmother -4 -3 -2 -1 +1 +2 +3 +4

Other -4 -3 -2 -1 +1 +2 +3 +4

----

5. Major change in eating habits (increase of decrease in food intake) -4 -3 -2 -1 +1 +2 +3 +4

----

6. Death of close friend(s) -4 -3 -2 -1 +1 +2 +3 +4

----

7. Outstanding personal achievement -4 -3 -2 -1 +1 +2 +3 +4

----

8. Male: mate pregnant -4 -3 -2 -1 +1 +2 +3 +4

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9. Female: becoming pregnant -4 -3 -2 -1 +1 +2 +3 +4

----

10. Sexual difficulties -4 -3 -2 -1 +1 +2 +3 +4

----

11. Being fired from job -4 -3 -2 -1 +1 +2 +3 +4

----

12. Being apart from mate (boy/girlfriend, spouse, etc) due to sport -4 -3 -2 -1 +1 +2 +3 +4

----

13. Serious injury or illness to close family member(s)

Father	**-4**	**-3**	**-2**	**-1**	**+1**	**+2**	**+3**	**+4**
Mother	**-4**	**-3**	**-2**	**-1**	**+1**	**+2**	**+3**	**+4**
Brother	**-4**	**-3**	**-2**	**-1**	**+1**	**+2**	**+3**	**+4**
Sister	**-4**	**-3**	**-2**	**-1**	**+1**	**+2**	**+3**	**+4**

Extremely Negative
Moderately Somewhat Somewhat Moderately Positive Extremely

Negative Negative
Negative Positive Positive Positive

Grandfather -4 -3 -2 -1 +1 +2 +3 +4

Grandmother -4 -3 -2 -1 +1 +2 +3 +4

Other -4 -3 -2 -1 +1 +2 +3 +4

----

14. Major change in the number (more/less) of arguments with mate -4 -3 -2 -1 +1 +2 +3 +4

----

15. Major personal injury or illness -4 -3 -2 -1 +1 +2 +3 +4

----

16. Major change in the frequency (increased or decreased) of social

activities due to participation in sport -4 -3 -2 -1 +1 +2 +3 +4

----

17. Serious injury or illness to close friend -4 -3 -2 -1 +1 +2 +3 +4

----

18. Breaking up with mate (boy/girlfriend, etc) -4 -3 -2 -1 +1 +2 +3 +4

----

19. Beginning a new school experience

(beginning college, transferring college etc) -4 -3 -2 -1 +1 +2 +3 +4

----

20. Engagement -4 -3 -2 -1 +1 +2 +3 +4

----

21. Academic probation/ineligibility -4 -3 -2 -1 +1 +2 +3 +4

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22. Being dismissed from dorm or other residence -4 -3 -2 -1 +1 +2 +3 +4

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23. Failing an important exam -4 -3 -2 -1 +1 +2 +3 +4

----

24. Major change in relationship with coach (better or worse) -4 -3 -2 -1 +1 +2 +3 +4

----

25. Failing a course -4 -3 -2 -1 +1 +2 +3 +4

----

26. Major change in the length and/or conditions of practice/training

(better or worse) -4 -3 -2 -1 +1 +2 +3 +4

----

27. Financial problems concerning school -4 -3 -2 -1 +1 +2 +3 +4

----

28. Major change in relationship with family

member(s) (better or worse) -4 -3 -2 -1 +1 +2 +3 +4

----

29. Conflict with roommate -4 -3 -2 -1 +1 +2 +3 +4

----

30. Male: mate having an abortion -4 -3 -2 -1 +1 +2 +3 +4

----

31. Female: having an abortion -4 -3 -2 -1 +1 +2 +3 +4

Extremely Negative
Moderately Somewhat Somewhat Moderately Positive Extremely
Negative Negative
Negative Positive Positive Positive

---

32. Major change in the amount (more or less) of academic
activity (home work, class time, etc) -4 -3 -2 -1 +1 +2 +3
+4

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33. Pressure to gain/lose weight-due to participation in sport -4 -3 -2 -1
+1 +2 +3 +4

---

34. Discrimination from teammates/coaches -4 -3 -2 -1 +1 +2
+3 +4

---

35. Major change in relationship(s) with team-mate(s) (better /worse) -4 -3 -2
-1 +1 +2 +3 +4

---

36. Suspended from team for non-academic reasons -4 -3 -2 -1 +1
+2 +3 +4

---

37. Trouble with academic counsellor -4 -3 -2 -1 +1 +2 +3
+4

---

38. Major change in use of alcohol/drugs (increased or decreased) -4 -3 -2 -1
+1 +2 +3 +4

---

39. Beginning sexual activity -4 -3 -2 -1 +1 +2 +3 +4

----

40. Major change in relationship(s) with friend(s) (better or worse) -4 -3 -2 -1
+1 +2 +3 +4

----

41. Recovery from illness/injury/operation -4 -3 -2 -1 +1 +2 +3
+4

----

42. Major change in level of athletic performance in actual

competition (better or worse) -4 -3 -2 -1 +1 +2 +3 +4

----

43. Divorce or separation of your parents -4 -3 -2 -1 +1 +2 +3
+4

----

44. Major change in level of responsibility on team

(increased/decreased) -4 -3 -2 -1 +1 +2 +3 +4

----

45. Receiving an athletic scholarship -4 -3 -2 -1 +1 +2 +3
+4

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46. Not attaining personal goals in sport -4 -3 -2 -1 +1 +2 +3
+4

----

47. Major change in playing status on team -4 -3 -2 -1 +1 +2
+3 +4

----

48. Injury to team-mates -4 -3 -2 -1 +1 +2 +3 +4

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49. Being absent from school (classes) because

of participation in sport -4 -3 -2 -1 +1 +2 +3 +4

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50. Troubles with athletic association and/or athletic director -4 -3 -2 -1 +1 +2 +3 +4

----

51. Difficulties with trainer/physician -4 -3 -2 -1 +1 +2 +3 +4

Extremely Negative
Moderately Somewhat Somewhat Moderately Positive Extremely

Negative Negative
Negative Positive Positive Positive

----

52. Major change in playing time (playing more or less)

– due to injury -4 -3 -2 -1 +1 +2 +3 +4

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53. Major errors/mistakes in actual competition -4 -3 -2 -1 +1 +2
+3 +4

--**54.**
Losing your athletic scholarship-4 -3 -2 -1 +1 +2 +3 +4

----

55. No recognition/praise of accomplishments from

coaching staff -4 -3 -2 -1 +1 +2 +3 +4

----

56. Pressure from family to perform well -4 -3 -2 -1 +1 +2 +3
+4

----

57. Loss of confidence due to injury -4 -3 -2 -1 +1 +2 +3
+4

--**58.**
Unable to find a job -4 -3 -2 -1 +1 +2 +3 +4

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59. Change in coaching staff -4 -3 -2 -1 +1 +2 +3 +4

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--60.

Female: menstrual period/PMS -4 -3 -2 -1 +1 +2 +3 +4

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--61.

Major change in level of academic

performance (doing better or worse) -4 -3 -2 -1 +1 +2 +3
+4

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62. Making career decisions (applying to

graduate school, interviewing for jobs, etc) -4 -3 -2 -1 +1 +2
+3 +4

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63. Being cut/dropped from the team -4 -3 -2 -1 +1 +2 +3
+4

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64. Continual poor performance of team -4 -3 -2 -1 +1 +2 +3
+4

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--

65. Change in graduation schedule -4 -3 -2 -1 +1 +2 +3 +4

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--66.

Major change in family finances (increased or decreased) -4 -3 -2 -1
+1 +2 +3 +4

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67. Major change in attitude toward sport (like/enjoy more or less) -4 -3 -2
-1 +1 +2 +3 +4

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68. Victim of harassment/abuse (sexual, emotional, physical) -4 -3 -2 -1 +1 +2 +3 +4

---69.
Victim of personal attack (rape, robbery, assault, etc) -4 -3 -2 -1 +1 +2 +3 +4

Other events might have occurred to you in the past year (and affected you in a positive or negative manner) but were not included in this list. If there were such events, please list them below.

70. ____________________________ -4 -3 -2 -1 +1 +2 +3 +4

71. ____________________________ -4 -3 -2 -1 +1 +2 +3 +4

71. ____________________________ -4 -3 -2 -1 +1 +2 +3 +4

Appendix 3: Study 4

Participation information sheet

1. Study Title

Effects of menstrual cycle on muscular strength in female athletes.

2. Invitation paragraph

I am a PhD student studying at University of South Wales and I would like to invite you to take part in a research study. Before you decide, you need to understand why the research is being done and what it would involve. Please take time to read the following information carefully. Ask questions if anything you read is not clear or if would like more information. Once you have sufficient information regarding the research study please consider whether or not you would like to volunteer to take part.

3. What is the purpose of the study?

The aim of the study is to investigate the effect of the menstrual cycle on lower limb muscle strength in female athletes. Currently, the expected changes in strength over the menstrual cycle and how it influences Anterior Cruciate Ligament (ACL) injury are unclear. It is therefore anticipated that by using a battery of assessments, will provide new insights into leg strength changes at given times of the menstrual cycle in female athletes. It is also anticipated that coaches could use this new information to plan ahead and structure training and competition with the aim to maximise performance and minimise ACL injury risk.

4. Why have I been invited?

You have been invited because you: are a female athlete over 18; are a non-smoker; have a body mass index (BMI) equal to or less than 30; have a consistent menstrual cycle (26 to 32 days); have no history of pregnancy; and have no current knee injury.

You will perform three identical experimental sessions during different phases of your menstrual cycle. One session will be performed during the follicular phase (days 1-9), one during the ovulatory phase (days 10-14), and the other during the luteal phase (days 15-end of cycle). Day 1 is defined as from the time of the onset of menses. Each session will take no longer than 30 mins.

However, if your menstrual cycle is not regular (longer than 32 days), or you have a current knee injury, then you will not be able to take part in this study.

5. Do I have to take part?

You do not have to take part in this study. It is up to you to decide. Before you make a decision, this information sheet and the study will be explained to you. You may read through the information sheet for as long as you need and please feel free to ask any questions.

6. What will happen to me if I take part?

If you do decide to take part, you will be asked to sign a consent form to show you understand what participation in the study involves and that you have agreed to take part. Please note: you are free to withdraw at any time, without giving a reason and that this will have no impact on your involvement with the team/club you compete for.

If you participate, you will be asked to complete two questionnaires. One questionnaire will be about your menstrual and oral contraception history, physical and training characteristics, any previous injury, and any family history regarding ACL injury. The other questionnaire, (Menstrual Distress Questionnaire) will be about your physical and emotional menstrual symptoms and will need to be completed on three separate occasions over one menstrual cycle.

At the same time that you complete the Menstrual Distress Questionnaire, you will be asked to take part in a series of strength assessments on three separate occasions over one menstrual cycle. All assessments will take place at the University of South Wales, Sport Park, Treforest Industrial Estate, Pontypridd CF37 5UP. The strength assessments are non-invasive. The risk of injury, pain or soreness as a result of the assessments is expected to be lower than that when training or participating in your chosen sport. However, the risk of soreness up to 72 hours post assessment is heightened if you do not usually perform the exercises involved. The strength assessments will be performed under the supervision of an experienced member of the research team and are designed to be less physically demanding than what you would ordinarily be exposed to when playing your sport. The assessments include: height, weight, and strength measurements of hip, groin and leg.

<u>Hip and groin tests</u>: For the hip and groin tests, we will use a GroinBar™, where you will be asked to adopt two positions. The first test will involve lying down, feet on the ground and knees bent at 60° (as shown below in Figure 1). In this position you will squeeze and hold for about 3 – 5 seconds, and repeat three times. Then you will be asked to push against the specialised pads and hold for 3 -5 seconds. This will be repeated three times. The second test will involve a similar procedure while lying down, but adopting a slightly different position so the hip and knee are at right angles and the feet are elevated. Again, force data for three squeezes and three pushes will be collected.

Figure 1. Isometric adductor squeeze at 60^{o}.

<u>Eccentric hamstring strength measurement</u>: We will also use a Nordbord ™ to measure eccentric hamstring strength while you perform the Nordic Hamstring Exercise (Figure 2). For this test you will be asked to kneel on a specialised device with braces to secure your ankles that will record your pulling forces. Then as slowly and as smoothly as possible, lean forward so that your chest will approach the ground. A warm-up followed by three attempts will be allowed.

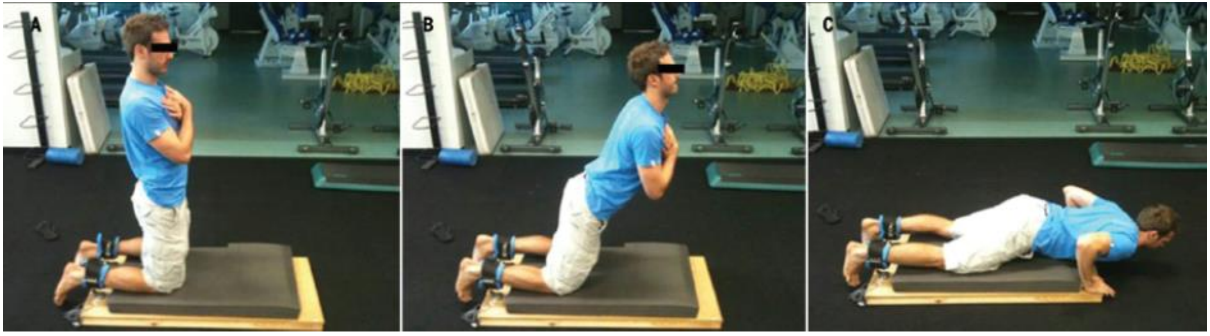

Figure 2: Eccentric Hamstring strength measurement (modified by Opar et al., 2013).

<u>Single leg jump test:</u> Another test that you will be asked to perform is a single leg jump (as shown in Figure 3). Standing on one leg you will be asked to jump as high as you can and land on the same spot on the platform that measures the pushing and landing forces. You will be asked to perform between 3 and 5 jumps for each leg.

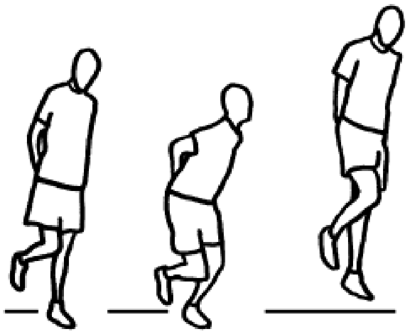

Figure 3. Single leg jump (modified by Gustavsson et al., 2006).

7. Expenses and payments

No expenses or payments will be available if you participate in this study.

8. What will I have to do?

You will complete one questionnaire at the outset of your participation. You will complete another questionnaire three times over a one month period, at the same time as a strength assessment.

9. **What are the possible disadvantages and risks of taking part?**

   As with all physical tests, there is some risk of injury. However, the volume (amount) of the exercises you will be asked to complete during the data collection is much lower than that typically used during a training session, reducing the risk of injury.

10. **What are the possible benefits of taking part?**

    We cannot promise the study will help you directly, but the information we get from the study is proposed to increase understanding of the effect of menstrual cycle phases on muscle strength, which may be connected to the high incidence of ACL injuries in female athletes. It is hoped that this could lead to development of prevention strategies.

11. **What if there is a problem?**

    If you have a concern about any aspect of this study, you may ask to speak to the researcher, Sania Almousa, in the first instance. If you have further concerns or questions you may contact the supervisors of this study, Dr Morgan Williams (morgan.williams@southwales.ac.uk) or Prof Rich Mullen(rich.mullen@southwales.ac.uk).
    If you remain concerned you can contact the research governance officer Mr Jonathan Sinfield on (01443) 484518 or via email jonathan.sinfield@southwales.ac.uk .

12. **Will my taking part in the study be kept confidential?**

All information that will be collected about you during the research study will be kept strictly confidential, and your name and address will be removed from any information about you, so that you cannot be identified.

13. **What will happen if I don’t carry on with the study?**

If you withdraw from the study, we will destroy all your data, but if you are happy for us to keep the data up to your withdrawal, we would like to use the data in the final analysis.

14. **What will happen to the results of the research study?**

The results of the studies will be written up as a part of a PhD thesis. Also, we hope to share the results to a wider audience by publishing a paper in an academic journal. Please note: the publication will not include any confidential data or names of the participants.

15. **Who is organising or sponsoring the research?**

This study is organized and funded by the University of South Wales.

16. Further information and contact details:

Sania Almousa, PT, M.Sc.
PhD student
Faculty of Life Sciences and Education
University of South Wales

Study 4: Study consent form

University of
South Wales
Prifysgol
De Cymru

STUDY CONSENT FORM

Title of Project: **Effects of menstrual cycle on muscular strength in female athletes.**

Name of Researcher: **Ms Sania Almousa**

Name of supervisor: **Prof Richard Mullen, and Dr Morgan Williams**

Please **(initial)** all boxes

12. I confirm that I have read and understand the information sheet Version 1. 11/05/2017 for the above study. I have had the opportunity to consider the information, ask questions and have had these answered satisfactorily. ☐

13. I understand that my participation is voluntary and that I am free to withdraw at any time without giving any reason, without any consequence to myself. ☐

14. I agree to:
    - a. having my physical characteristics measured (i.e., height, weight); ☐
    - b. complete the injury history questionnaire of any injuries I have sustained during training or competitive match play; ☐
    - c. complete the menstrual distress questionnaire at three occasions that details any symptoms I experience during the study; ☐
    - d. provide information regarding my menstrual and oral contraceptive history and my family history for any potential anterior cruciate ligament injury; ☐
    - e. perform the following tests: hip and groin, jump and the Eccentric hamstring strength measurement (three times over a month). ☐

15. I agree to my anonymised data being used in study specific reports and subsequent articles that will appear in academic journals. ☐

16. I understand that all the information I provide will be held securely and treated confidentially in accordance with the Data Protection Act 1998 (up until 24th May 2018) and the General Data Protection Regulation 2016 (GDPR). ☐

17. I am free from injury and agree to take part in the above study. ☐

Name of Participant	Date	Signature
Name of person - taking consent.	Date	Signature