Analysis of Lower Limb Injury Prevention Programmes in Relation to Hamstring and Anterior Cruciate Ligament Risk Factors in Team Sport Athletes

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A thesis submitted in partial fulfilment of the

requirements of the University of Greenwich

for the Degree of Doctor of Philosophy

August 2017

DECLARATION

I certify that the work contained in this thesis, or any part of it, has not been accepted in substance for any previous degree awarded to me, and is not concurrently being submitted for any degree other than that of Doctor of Philosophy being studied at the University of Greenwich. I also declare that this work is the result of my own investigations, except where otherwise identified by references and that the contents are not the outcome of any form of research misconduct.”

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ACKNOWLEDGEMENT

This work would not have been possible without the support of my family, supervisors, University of Greenwich staff and friends.

Firstly, I would like to thank my supervisory team, Dr Fernando Naclerio and Dr Mark Goss-Sampson, for their support and scientific guidance throughout the work reported in this doctoral thesis. Particular thanks to Dr Fernando Naclerio for his time and amazing untiring efforts, precise supervision and his fundamental role in my doctoral work. Furthermore, I would like to thank Dr Eneko Lamrube-Zabala for his guidance and support on statistical analysis and scientific writing. Special thanks to all the participants who volunteered to take part in this studies reported herein, without whom this project would not have been possible.

Additionally, I would like to thank the entire Sport Science department especially Ms Kelly Cooper.

A big thank you also goes to Mr. Jagdeep Matharoo for his generous time for proof reading.

Finally, I would like to take this opportunity to express a personal thanks to my amazing family. I am eternally grateful for all my parents, Ali and Monir, have done to support me emotionally and financially. Their support and dedication have been invaluable and will never be forgotten. I am deeply thankful to my wonderful wife, Yasaman, for her support, encouragement and patience. Without her sacrifices this thesis would never have been written.

ABSTRACT

Hamstring and anterior cruciate ligament injuries are, respectively, the most prevalent and serious non-contact occurring injuries in team sports. Several biomechanical and neuromuscular risk factors have been suggested to be associated with these injuries. Consequently, preventative programmes including different exercise modality have been proposed to modify the injury risk factors. However, there is still a lack of uniform criteria regarding the design of an ideal protocol for effective protection against the two aforementioned injuries in team sport athletes.

The preliminary study (study 1) was carried out to evaluate the effect of two different preventative programmes on hamstring strength and torque angle relationship. The results revealed that although both programmes increased hamstring strength, the effect of interventions on knee flexors torque-angle relationship was significantly different. Therefore, a systematic review of literature (study 2) was conducted to clarify the effect of different preventive strategies to modify ACL and hamstring risk factors. Study 2 revealed that multifaceted programmes are the most successful to positively modify the ACL risk factors. Moreover, resistance exercises demonstrated to be an effective component of injury prevention programmes to produce adaptation for preventing hamstring injury in athletes. Furthermore, two observational studies aimed to analyse lower extremity muscle activation pattern during five common preventative exercises were conducted.

Findings from the preliminary, systematic review and the two observational studies highlighted the importance of designing new innovative protocols aimed to produce positive changes in injury risk factors. Based on recent evidence supporting the effectiveness of isoinertial technology in attenuating the rate of injuries in athletes, the last study was conducted to compare the effect of isoinertial technology-based versus traditional bodyweight training on ACL and hamstring risk factors. Results indicated that a 20-minute multifaceted program, involving 6 exercises performed with isoinertial technology, implemented twice a week during a period of 6 weeks is effective to enhance tuck jump assessment, hamstring muscle strength and repeated shuttle sprint ability.

In conclusion, injury prevention protocols using a combination of different exercises modalities, including the use of isoinertial-technology and technical feedback appears to be

effective to positively modify the associated hamstring and ACL risk factors in uninjured team sport athletes.

ADDENDUM

Peer reviewed Publications

Monajati, A., Larumbe-Zabala, E., Goss-Sampson, M. and Naclerio, F., 2017. Analysis of the hamstring muscle activation during two injury prevention exercises. *Journal of Human Kinetics*.

Monajati, A., Larumbe-Zabala, E., Goss-Sampson, M. and Naclerio, F., 2016. The effectiveness of injury prevention programs to modify risk factors for non-contact anterior cruciate ligament and hamstring injuries in uninjured team sports athletes: a systematic review. *PloS one*, *11*(5), p.e0155272.

Naclerio, F., Larumbe-Zabala, E., **Monajati, A**. and Goss-Sampson, M., 2015. Effects of two different injury prevention resistance exercise protocols on the hamstring torque-angle relationship: a randomized controlled trial. *Research in Sports Medicine*, *23*(4), pp.379-393.

Conference Communication

Monajati, A., Larumbe-Zabala, E., Goss-Sampson, M. and Naclerio, F. (July 2016) : Analysis of the hamstring muscle activation during two injury prevention exercises. 21st Annual congress of the European College of sport science, Vienna; oral presentation.

Abbreviations

ACL= Anterior Cruciate Ligament

BF= Biceps Femoris

ST= Semitendinosus

SM= Semimembranosus

VL= Vastus Lateralis

VM= Vastus Medialis

H:Q= Hamstring to Quadriceps

MVIC= Maximum Voluntary Isometric Contraction

ECC= Eccentric

UNS= Unstable

ICC= Intra-class Correlation Coefficients

DVJ= Drop Vertical Jump

VJ= Vertical Jump

SLD= Single Leg Drop

DLSJ= Double Leg Stop Jump

NC= Nordic Curl

BLC= Ball Leg Curl

HEE= Hamstring Eccentric exercise

EMG= Electromyography

RMS= Root Mean Square

FY= Flywheel

GT= Gravity Dependent

TJA= Tuck Jump Assessment

RSSA= Repeated Shuttle Sprint Ability

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Chapter 1

GENERAL INTRODUCTION:

1.1. Overview

Despite many studies involving, enhanced training, developments of injury prevention programmes and new technologies during the last few decades, athletic injuries still occur, and in some cases have increased, in both males and females in many sports (Chandran et al., 2016, Hootman et al., 2007). Several factors such as lower age of entry to sport, raised frequency, duration and intensity of both training and competition contribute to increasing the occurrence of athletic injuries (Council and Youth, 2014).

Epidemiological studies on collegiate athletes conducted between 1989 and 2015 (Hootman et al., 2007, Roos et al., 2017, Chandran et al., 2016) demonstrated that more than half of injuries involved the lower limbs, whilst knee injuries accounted for the highest rate of severe injuries (>21days time lost). There is evidence that anterior cruciate ligament (ACL) and hamstring injuries are the most frequent and severe, respectively, affecting team athletes (Hootman et al., 2007). Within those, rugby and football players showed the highest rate of injury for both males and females. The epidemiology of injuries in professional athletes also revealed similar results. Injury record of the men's English professional football demonstrated that more that 41% of injuries occur in thigh and knee, and 56% of total injuries accounted for muscle strain and ligament sprain (Woods et al., 2002). Furthermore, investigations on female professional football player also revealed that the knee is the most common location of injury (32%) (Giza et al., 2005). Moreover, injury records of English professional rugby players demonstrated that ACL and hamstring injuries had the highest proportion of days absents from training compared to all other type of injuries, and hamstring injury counted the most common injury in training and the second most common during matches (Brooks et al., 2005a, Brooks et al., 2005b). Current literature reports female athletes have 2 to 6 times higher risk of knee and ACL injuries compared to their male counterparts (Giza et al., 2005, Walden et al., 2011, Hewett et al., 2005).

Both ACL and hamstring injuries may impose serious physical and financial burdens on athletes and clubs and result in prolonged time lost from training and competition (Swenson et al., 2013, Woods et al., 2002). Consequently, numerous preventive strategies have been proposed to attenuate the incidence of these injuries. However, only a few of those proposed strategies have strong evidence based on their effectiveness in reducing injury rate (Stevenson et al., 2015). Based on the mechanism of the injuries, several biomechanical and neuromuscular risk factors, such as muscle strength and coordination, knee abduction angle, hip internal rotation etc., have been proposed (Hewett et al., 1996, Alentorn-Geli et al., 2009a, Alentorn-Geli et al., 2009b). The effectiveness of a preventive protocol can be assessed by either its capacity to modify the biomechanical and neuromuscular risk factors, or its ability to reduce the injury rate. The latter can only be accomplished through long prospective studies. Consequently, the majority of prevention programmes are evaluated based on their effectiveness to modify the risk factors. Nonetheless, the effectiveness of injury prevention protocols to alter hamstring and ACL risk factors are in some cases contradictory.

Some studies (Pollard et al., 2006, Nagano et al., 2011) reported no differences in injury risk factors (i.e., hip internal rotation and flexion angle) after implementation of preventive protocols, whilst, others (Herrington, 2010, Kato et al., 2008, Chappell and Limpisvasti, 2008) showed significant improvement in the risk factors (i.e., knee valgus). The observed conflicting results might be in part due to the type of exercise protocol (i.e., strength, balance, plyometric and etc.), participants' level of performance (non-athletes, recreational or professional athletes), assessment tools and duration of the intervention programmes. In order to have a better understanding of the effectiveness of the injury prevention programmes a systematic review of the literature (Chapter 3) has been carried out. Systematic review of literature is a process to collate all empirical evidence according to eligibility criteria and involves describing the process, defining the key words, registering the protocol, comprehensive literature search, reading titles, abstracts, and the full texts to select relevant studies. Overall, this process could demand 18 months. During the early stages (first 6 months) of a comprehensive literature search the most common mode of exercises, eccentric and unstable, utilised in the review papers to prevent ACL and hamstring injuries were identified. The different effects of these two exercise modalities, eccentric vs. unstable, on injury risk factors were examined and presented as a preliminary study.

Studies in this thesis are presented according to their completion date. Consequently, the preliminary study that started after initiating the systematic review is presented as the first completed intervention.

Furthermore, in order to critically analyse the hamstring and ACL injury prevention protocols, understanding the mechanism underlying injuries would be beneficial.

1.1.1. Anterior Cruciate Ligament (ACL)

1.1.1.1. Anatomy

Four ligaments support the knee joint; lateral, medial, posterior cruciate and anterior cruciate ligament (Watkins, 2010). These ligaments have important role to stabilize the knee motions, and each participates in different type of stability. The ACL originates from the anterior intercondylar area of the tibia, and run superiorly, laterally and posteriorly to attach posteromedial aspect of the lateral femoral condyle (Markatos et al., 2013), and its role is to prevent anterior, anterio-lateral and valgus instability (Matsumoto et al., 2001), figure1. Clinically, valgus is described as an opening in knee medial joint space, and in experimental studies described by an increase in the valgus rotation angle (i.e., the angle between the long axes of the femur and tibia) (Matsumoto et al., 2001).

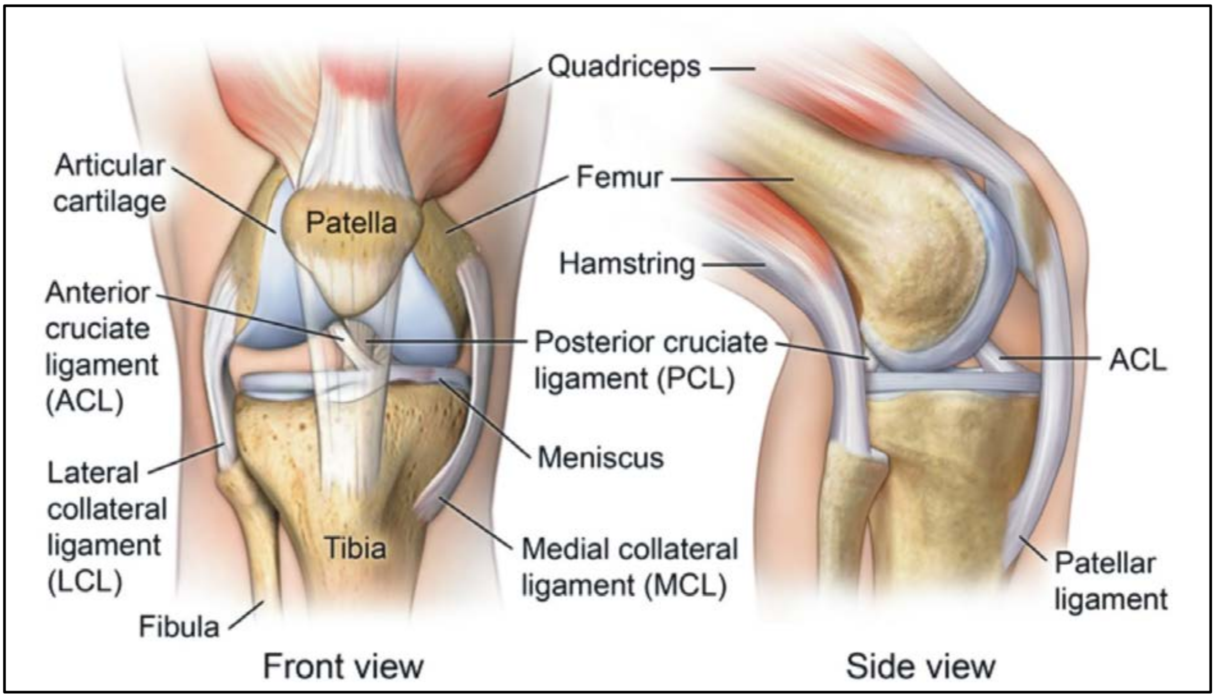

***Figure 1**, Knee joint frontal and sagittal view (FloridaKnee, n.d)*

1.1.1.2. Injury mechanism

Almost two thirds of ACL injuries are non-contact and potentially preventable. Different approaches such as athletes' interview, laboratory and clinical research, cadaver and mathematical studies, and video analysis have been utilized to clarify the mechanism of ACL injuries (Krosshaug et al., 2005). According to these investigations, unilateral landing involving exaggerated knee abduction (valgus) has been identified as one of the most frequent actions associated with the incidence of ACL injuries (Ireland, 1999, Boden et al., 2000). Indeed, similar body position with the knee close to full extension along with an external rotation of the tibia and foot planted have been identified as a common knee valgus mechanism (Olsen et al., 2004, Boden et al., 2000, Krosshaug et al., 2007). A number of investigations have focused on anthropometric and anatomical measurement and suggested that factors such as height, thigh length, femoral width etc. are contributing to ACL injury. In addition, several anatomical differences between males and females such as intercondylar notch, posterior tibial slope, structure and function of the ACL and quadriceps angle have been associated to the higher rate of the ACL injury in females (Makovitch and Blauwet, 2016). However, these factors are non-modifiable by nature (Hewett et al., 2005). Moreover, there is evidence that hormonal factors also are associated with ACL injury, however, the level of contribution, and the extent to which these contributions are modifiable has remained unclear (Hewett et al., 2005). There is increasing evidence in the literature suggesting that neuromuscular deficits, muscle activation strategy and poor muscle coordination during high risk manoeuvres (i.e., unilateral landing, cutting and deceleration) can cause exaggerated valgus and consequently increase the risk of ACL injury (Hewett et al., 2005, Myer et al., 2005a, Ford et al., 2003).

1.1.2. Hamstring

1.1.2.1. Anatomy

The hamstring, comprising of biceps femoris long (BF) and short head (BFsh), semitendinosus (ST) and semimembranosus (SM), figure 2, compose a bi-articular muscle group crossing the hip and knee joint that acts synergistically in extending the hip and flexing the knee during sprint related activities (Opar et al., 2012). The biceps femoris long head arising from the medial facet of the ischial tuberosity and the short head arising from the middle third of the linea aspera and the lateral supracondylar ridge of the femur. The insertion of both long and short head include the styloid process of the head of the fibula, lateral collateral ligament, and lateral tibial condyle. Therefore, only the long head crosses the two joints (Beltran et al., 2012). The semitendinosus muscle originates from the inferomedial aspect of the ischial tuberosity and inserted into the upper part of the medial surface of the body of tibia (Beltran et al., 2012). Finally, the semimembranosus muscle arises from the superolateral aspect of the ischial tuberosity and inserted to the superior aspect of the lateral condyle of femur and tibial condyle (Beltran et al., 2012).

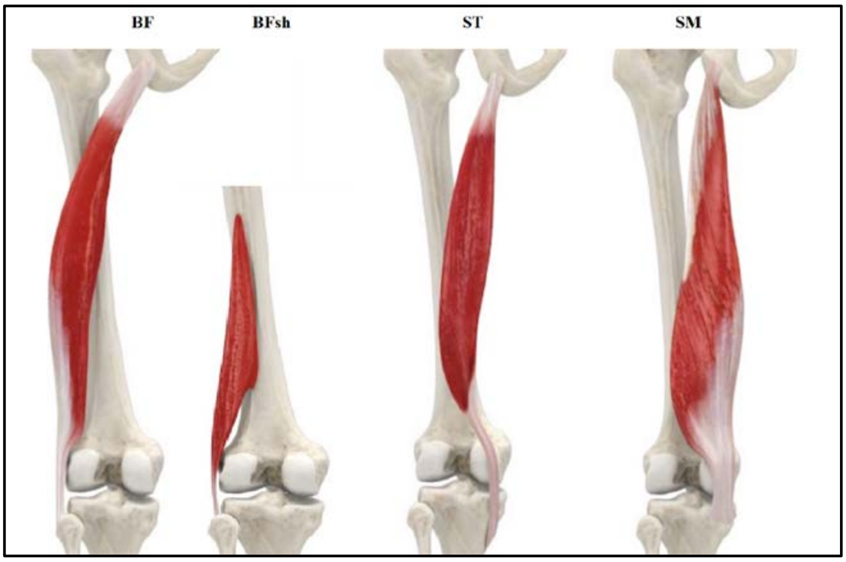

Figure 2*, Posterior view of the hamstring muscles (3D4medical, Dublin, Ireland)*
Biceps femoris long (BF) and short head (BFsh), Semitendinosus (ST) and Semimembranosus (SM)(REF)

The main role of hamstring muscles is flexing and extending the knee and hip, respectively, and in some movements (i.e., running) knee flexion and hip extension occur simultaneously with opposite effect on hamstring length. In addition, hamstring muscles are contracting eccentrically during running or change of direction to decelerate the tibia forward movement. These muscles also contribute to dynamic stabilization of the knee. Coactivation of the hamstring and quadriceps muscles during different movement, such as landing or changing direction, can decrease the ground reaction force and potentially decrease the load on ACL (Hewett et al., 2010). Moreover, when the hamstrings are considered within a functional kinetic chain, this muscle group appears to be associated with both upper body (pelvis, spine, shoulder and skull) and the lower limb alignment and stabilisation (Naclerio and Goss-Sampson, 2013).

1.1.1.2. Injury Mechanism:

Hamstring muscles are highly activated in sports involving deceleration, acceleration and jumping (Arnason et al., 2008). Despite the complex aetiology, the occurrence of hamstring injury is associated with rapid actions involving hip flexion and knee extension, and injury takes place during eccentric muscle action where the contracting muscle is lengthened to decelerate a movement and hamstring muscle-tendon length is beyond its upright length (knee and hip angle ~ 0°). During eccentric contractions, sarcomeres are overstretched and microscopic damages are likely (Opar et al., 2012). In sprinting, hamstring injury occurs when hamstrings are actively lengthened and contract to decelerate the thigh and the lower leg to an angle of approximately 30° (knee anatomical angle) before extending the knee during the last half of the swing phase (Ditroilo et al., 2013, Heiderscheit et al., 2005). It is widely suggested that the repetition of fast eccentric muscle actions toward open knee angles results into accumulated microscopic muscle damage that may develop into an injury (Timmins et al., 2015). In sports involving sprint, acceleration and deceleration, biceps femoris is the most common hamstring injured muscle. This might be due to the fact that BF lengthens to a greater extent than the other hamstring muscles (ST and SM) during eccentric contraction (Dolman et al., 2014). Heiderscheit et al. (2005) monitored hamstring musculotendon lengths during the late swing phase of sprint (estimated period of injury) and reported that BF stretched (12%) beyond its upright length more than that in ST (9.8%) and SM (10.4%).

1.1.3. Agonist action of hamstring and ACL

The ACL and hamstring muscles are both quadriceps antagonist during knee extension and together help to stabilize the knee. The hamstring eccentric contraction during knee extension decelerates the forward movement of the tibia and help ACL to prevent anterior tibia translation. When quadriceps muscle is relatively stronger than hamstring (low hamstring to quadriceps ratio – H:Q) both hamstring and ACL are more prone to injury (Holcomb et al., 2007). Li et al. (1996) proposed H:Q ratio closer to 1 decrease the anterior tibial translation and may reduce the load on ACL. Since hamstring muscles and ACL work as agonists, any deficit or injury in one of them may negatively affect the other, therefore it is important to integrate both hamstring and ACL injury prevention exercises in a protocol.

1.2. Rational for the current research project

In spite of recommendation and extensive use of ACL and hamstring injury prevention programmes, the rate of these injuries remained unchanged (Ekstrand et al., 2013) or in some cases increased within athletes (Ekstrand et al., 2016, Myklebust et al., 2013). The results obtained from college (Hootman et al., 2007) and professional (Engebretsen et al., 2013) team sport athletes indicate that lower extremity non-contact injuries have the highest rate of injury, while hamstring and ACL injuries are the most common. Although numerous controlled studies showed promising effects of injury prevention exercises to reduce the risk and rate of hamstring and ACL injuries, follow up studies demonstrate unchanged or increased rate of the aforementioned injuries. The latest UEFA elite club injury survey indicated that between 2001 and 2014 the rate of hamstring injuries increased by 4% annually in men’s professional football players (Ekstrand et al., 2016). In addition, a follow-up study of Norwegian professional handball players showed an increased ACL injury rate despite implementation of injury prevention programmes (Myklebust et al., 2013). Both hamstring and ACL injuries are multi risk factorial injuries. However, the majority of the controlled studies reported desired effect of intervention on one or a few risk factors but they did not measure or report changes in all other risk factors. Several injury prevention programmes involving jumps (Herrington, 2010), strength (Cochrane et al., 2010, Herman et al., 2009, Herman et al., 2008, Holcomb et al., 2007), unstable (Donnelly et al., 2012, Myer et al., 2005b), or a combination of different exercises modes (Barendrecht et al., 2011, Lim et al., 2009, Myer et al., 2006b, Noyes et al., 2005) have been proposed to prevent both ACL and hamstring injuries. However, there is still a lack of uniform criteria regarding the design of an ideal protocol for effective protection against the two aforementioned injuries in team sport athletes. Indeed, there is no consensus about how to integrate ACL and hamstring preventive exercises within an optimal injury prevention protocol in team sports. Furthermore, the majority of the proposed preventive protocols are multifaceted which includes different type of exercises. However, the effect of each component of the preventive programme solely or in combination with other exercises is still unclear.

Therefore, to standardise guidelines and design an effective injury prevention programme, there is a need to 1) systematic review of the documented effects of the different proposed injury prevention protocols on ACL and/or HAM risk factors in uninjured team sport athletes; 2) analyse the muscle activation patterns of components of injury prevention protocols to understand how each component may affect the risk factors.

Results from the systematic review, focusing on the effectiveness of injury prevention protocols, and the analysis of the most commonly used preventative exercises will provide important information to standardise and design a novel and effective preventive programme.

1.3. Aims

The aim of the current project was to analyse the effect of different intervention protocols on hamstring and ACL modifiable injury risk factors in uninjured team sport athletes.

In order to achieve the proposed aim, one review, 2 observational and 2 intervention studies were conducted.

The first study aimed to compare the effect of two different protocols: hamstring eccentric vs. squatting-unstable exercises on hamstring strength and knee flexors torque-angle relationship.

The second study conducted a systematic review of literature aimed to summarise the effect of currently used injury prevention programmes on team athletes. The study also highlights the most successful preventive strategies to modify biomechanical and neuromuscular risk factors associated with the incidence of ACL and hamstring.

The third study aimed to analyse the pattern of muscular activation of two exercises commonly used for protecting athletes from hamstring injuries: Nordic Curl and Ball leg Curl.

The forth study aimed to analyse the pattern of muscular activation the three exercises commonly used for protecting athletes from ACL injuries: Double Leg Squat, Double Leg Squat on Bossu and Single Leg Squat on Bench.

The last investigation involved an intervention study, aimed to compare the effect of a new designed injury prevention programme using isoinertial technology versus a traditional body weight exercise protocol on modifiable hamstring and ACL injury risk factors and performance in team sport athletes.

Chapter 2:

Study 1- Effects of Two Different Injury Prevention Resistance Exercise Protocols on The Hamstring Torque-angle Relationship: A Randomized Controlled Trial

2.1. Abstract

The effects of two different six-week lower body injury prevention programmes on knee muscle torque–angle relationship were examined in soccer players. Thirty-two men were randomly assigned to three groups: hamstring-eccentric (n=11), unstable-squatting (n=11) or control (n=10). Intervention groups performed 3 training sessions per week using only 3 hamstring-eccentric or unstable-squatting exercises respectively. Maximal peak knee flexion torque was measured at 35°; 45°; 60°: 80°; 90° and 100°, pre and post intervention. Pairwise comparisons between pre-test and post-test measures across groups showed no significant differences for control group, whereas the intervention groups showed opposite changes. Peak torque increased at 35º (P=0.034, d=0.67) and 45º (P=0.004, d=0.96) in the hamstring-eccentric group, and at 60º (P=0.024, d=1.16), 80º (P=0.018, d=1.21), and 90º (P=0.001, d=1.38) in the unstable-squatting group. As these specific modifications might respectively and differentially protect athletes against hamstring and knee-joint injuries, the integration of both types of exercises should be considered when designing injury prevention programmes for soccer players.

2.2. Introduction

Hamstring strength is one of the main requirements for protecting athletes against both hamstring strain (Schache et al., 2012) and anterior cruciate ligament (ACL) (Lloyd et al., 2005) injuries. Several injury prevention protocols including eccentric exercises such as the Nordic Curl, (Gabbe et al., 2006, Petersen et al., 2011) double-leg dead lift, (Holcomb et al., 2007) or leg curl using a flywheel machine (Askling et al., 2003b) have shown to successfully attenuate the incidence of hamstring injuries (Opar et al., 2012). These protective effects have been associated with some specific muscular adaptations such as increased isometric (Kilgallon et al., 2007) or dynamic (Mjølsnes et al., 2004) hamstring strength and a shift of the optimal knee flexion peak torque toward a more open angle position (Brughelli and Cronin, 2007, Clark et al., 2005). Additionally, unstable exercises such as single leg squats (Cochrane et al., 2010) or lunges (Heiderscheit et al., 2010) have also been recommended to improve knee stabilization for varus/valgus moments and external/internal rotation moments that occur when athletes perform repeated jumps, sprints and changes of direction in team sports (Lloyd et al., 2005). As the aforementioned biomechanical variables have been associated with the incidence of noncontact ACL injury (Myer et al., 2012), different training strategies involving unstable squatting exercises aiming to improve the ability of the hamstring to rapidly stabilize and control the knee have been proposed as effective intervention (Myer et al., 2012). Furthermore, systematic review of literature (Chapter 3) also demonstrate that hamstring eccentric exercises and unstable training are the two common proposed exercise modalities to prevent hamstring and ACL injuries, respectively. Even though hamstring strength and optimal peak torque localization have been considered as useful criteria to identify athletes at risk of injury, to our knowledge, only a few studies have examined the effects of combining both predominantly hamstring-eccentric and unstable-squatting exercises on these injury-predictors factors. Brughelli et al. (2010) reported a shift in maximal peak torque localization toward a more open knee angle position during both isokinetic flexion (+4º) and extension (+6.5º) tests after a 4-week injury prevention programme involving different open and closed kinetic chain exercises in soccer players. More recently Naclerio et al. (2013) observed significant increases in maximal isometric force at both closed (80°) and open (35°) knee angles after a 4 weeks intervention programme involving two predominantly hamstring-eccentric and one unstable-squatting exercises. It would appear that some exercises used to protect against both injuries would lead to an opposite, although compatible, modification of the knee flexion-length-tension relationship. Nevertheless, both hamstring-eccentric and unstable-squatting exercises have shown to positively reduce the incidence of hamstring strain (Chumanov et al., 2011, Heiderscheit et al., 2010), knee, ankle, or trunk postural related injuries (Hübscher et al., 2010). The effects of different injury prevention protocols on the knee angle–torque relationship could be manipulated depending on the specific characteristics of the selected exercises as well as the technique of execution. The aim of the current investigation was to compare the effects of two different 6-week resistance training protocols, involving only predominantly hamstring-eccentric (ECC) or unstable-squatting (UNS) exercises on the hamstring strength and the torque-angle relationship of the knee flexors in recreationally trained football players. We hypothesized that the ECC programme would emphasize strength improvement over the most open angles, while the UNS protocol would mainly strengthen the closer positions.

2.3. Methods

Thirty-two healthy, recreationally-trained football players (22.2±2.6 years, mass 75.9±7.3 kg; height 178.9±7.7 cm) were recruited from the university's population and randomly assigned to one of three groups: hamstring-eccentric exercise group (ECC, n=11); unstable squatting exercise group (UNS, n=11); or control (C, n=10). Participants were excluded if they had undertaken a lower body resistance-training programme in the 6 preceding months, or if they reported a previous lower limb injury. All were instructed to maintain their normal diet and exercise routine during the experimental period. Compliance with these guidelines was monitored through frequent contact and verbal questioning. Before participating in this study, all participants read and signed an informed consent. The study was carried out in accordance with the guidelines contained in the Declaration of Helsinki, and was approved by the university Institutional Review Board. As summarized in figure 3, after assessing for eligibility, all recruited participants completed all aspects of the study (n=11 ECC, n=11 UNS, and n=10 C).

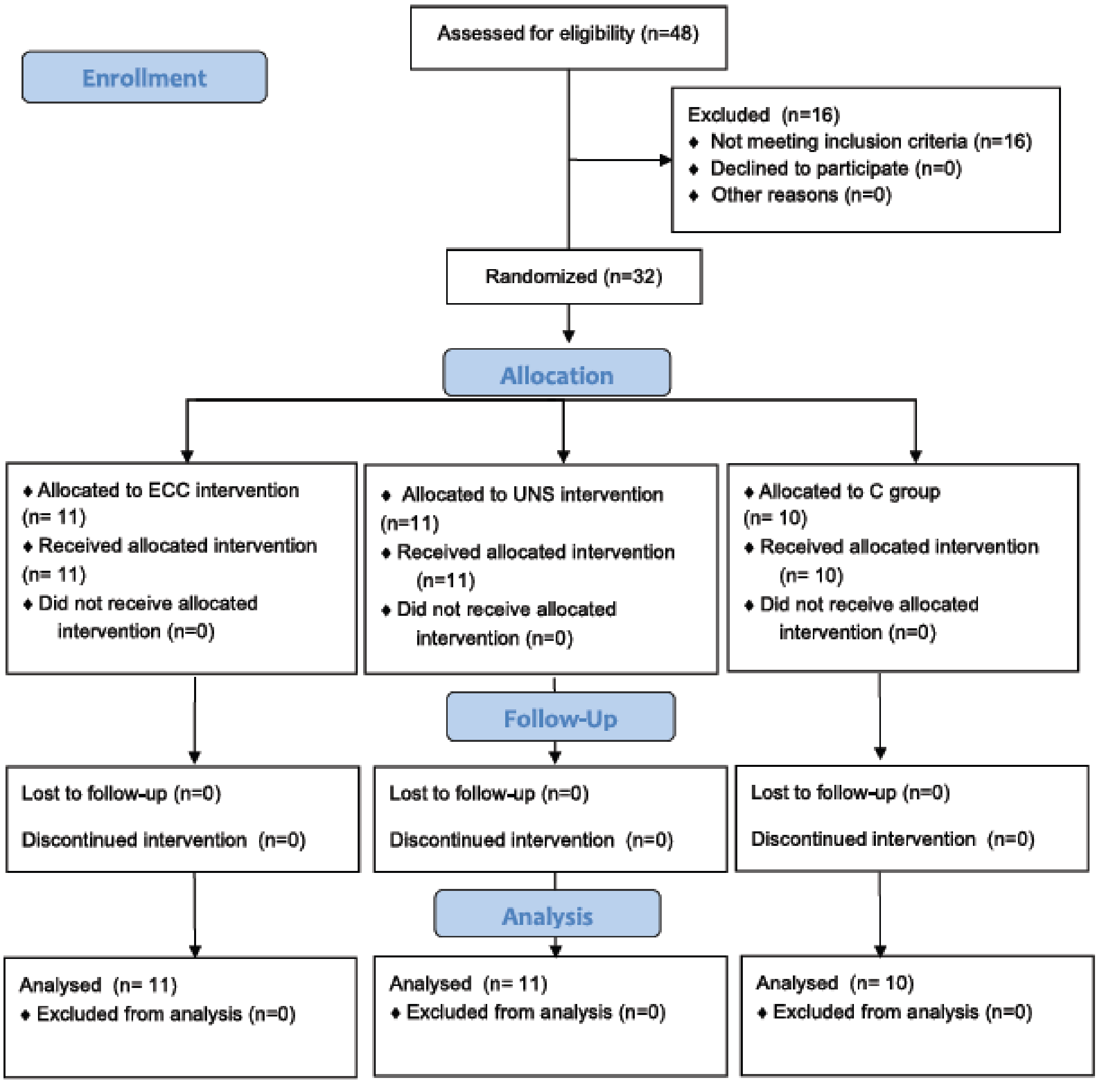

***Figure 3**, Flow diagram of participants throughout the course of the study.*

ECC: hamstring-eccentric exercise group, UNS: unstable squatting exercise group, C: control group.

2.3.1. Experimental design

This study utilized a three parallel-groups randomized controlled design, where 3 between-participant conditions, ECC, UNS and C, were tested. Once considered eligible for the study, all participants were familiarized with the testing procedures. Participants attended the laboratory for a pre-training test session, where body mass, height and muscle functional parameters were recorded. Two days after their pre-test, participants enrolled in ECC or UNS started a 6-weeks (18 sessions) training program, while the control group did not perform any type of resistance training. Nevertheless, during the 6-week intervention period all three groups continued with their normal football training, consisting of 2 sessions per week and a friendly match. Two days after the end of the intervention period, muscle function was re-tested and the intra-class correlation coefficients (ICCs) between tests were calculated.

All participants attended one-familiarization session, aimed to determine the optimal positioning for torque-angle analysis (e.g., lever arm height and length, lying angle) and to acquaint them with the testing procedure. Additionally, in order to minimize risks related with the training intervention, participants in both ECC and UNS groups completed two additional familiarization sessions intended to correct and improve the exercises technique.

2.3.2. Testing procedure

Before and after a 6-week training period (pre and post training respectively), all participants performed a series of maximal voluntary isometric contraction (MVIC) test. The isometric torque-angle relationship of the knee flexors was determined using a load cell, with a maximum force load of 5000 N and I Metric v. 8.32 software (Globus, Italy). The same investigators conducted all of the tests. Participants were placed in a fully prone position and performed a series of MVICs against a lever arm, which was set at six angular positions: 35º, 45º, 60º, 80º, 90º, and 100º from anatomical zero (knee angle of 0º, in full extension, with lower limbs in horizontal position). Markers were placed on the lateral epicondyle of the knee, lateral malleolus of the ankle, and in line with the greater trochanter. Each participant's angular position was recorded using a digital video camera (JVC GR-D721) positioned perpendicular to the hip placed on the tripod at a standardized height (0.80 m) and distance (1 m). Joint angles were analysed using Dartfish software (Version 4.06.0–A04). The order in which knee angles were tested was randomized both pre- and post-test. All testing was performed on the dominant side of the body (determined according to the preferred kicking leg).

In order to isolate the hamstrings, the lower back of each participant was strapped down to the testing platform to prevent lifting of the pelvis (figure 4). Participants performed three MVICs at each angle. Verbal encouragement was provided in a consistent manner during all tests. Rest periods between MVICs and angular position were 1 and 2 min, respectively (Kilgallon et al., 2007). If a subject was deemed to have shifted their test position (i.e. elevated hips to allow synergistic gluteal activity) data were discarded and they were required to perform an additional repetition. The maximal peak torque at each angle was recorded, after correction for gravity and the knee angle at which maximal torque occurred was determined.

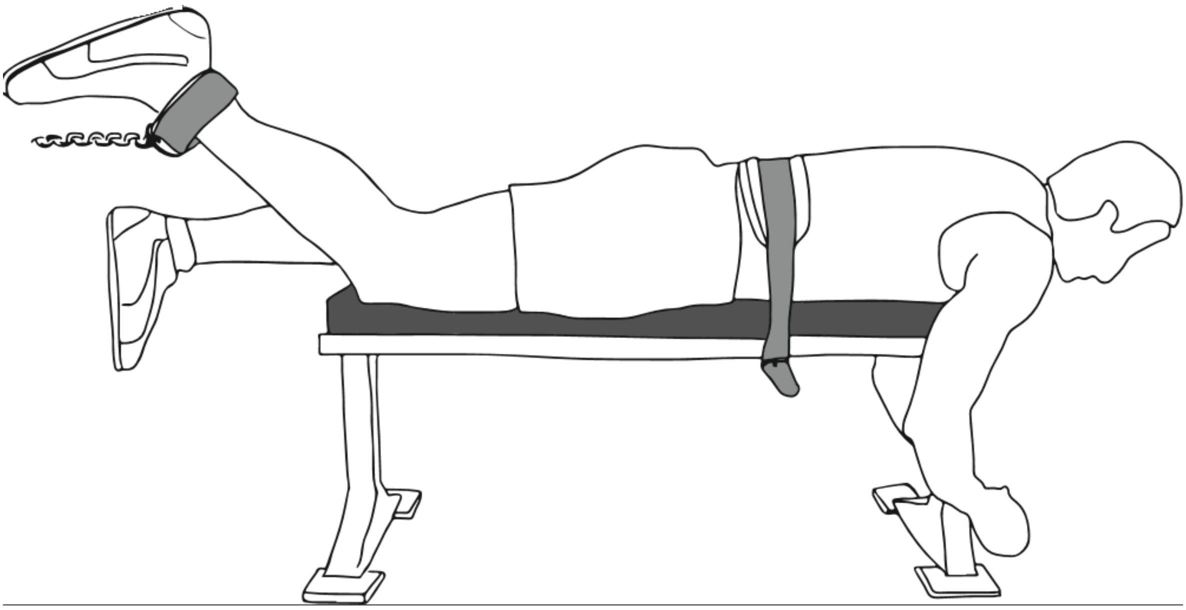

Figure 4, *Participant position during the maximal voluntary isometric contraction test*

2.3.3. Training

Participants in both intervention groups, ECC and UNS, trained 3 times per week on non-consecutive days for 6 weeks, for a total of 18 training sessions. Each session lasted about 20 minutes and was performed in the morning on the days alternating with the regular football training or a friendly match. Participants included in C group did not undergo any resistance training.

ECC training involved the following three predominantly eccentric hamstring exercises (figure 5): i) Assisted Nordic Curl: Kneeling on the ground with ankles fixed by a partner, participant lowering the trunk to the ground by eccentrically contracting the hamstrings. This exercise was focused on increasing the hamstring strength at the more open knee angles (45º to 0º anatomical position). Figure 5a shows the coach and band-assisted performance in order to facilitate a better control of the overload that allow athletes to maximally activate hamstring during the last part of the range of motion (Myer et al., 2005b). Band resistance was specifically determined in order to provide a pulling force of about 20% of the participant's body mass during the later phase of the downward movement (45°). ii) Eccentric single stiff-legged dead lift: From standing position with the arm crossing over the chest, participant lowering the body toward the ground by flexing the hip joint without bending the support leg knee and raising the other leg until form an straight line with the trunk (Brughelli and Cronin, 2008) iii) Eccentric double stiff-legged dead lift: From standing position with the arm crossing over the chest, participant lowering the body toward the ground by flexing the hip joint without bending the knees until the body parallel with the floor.

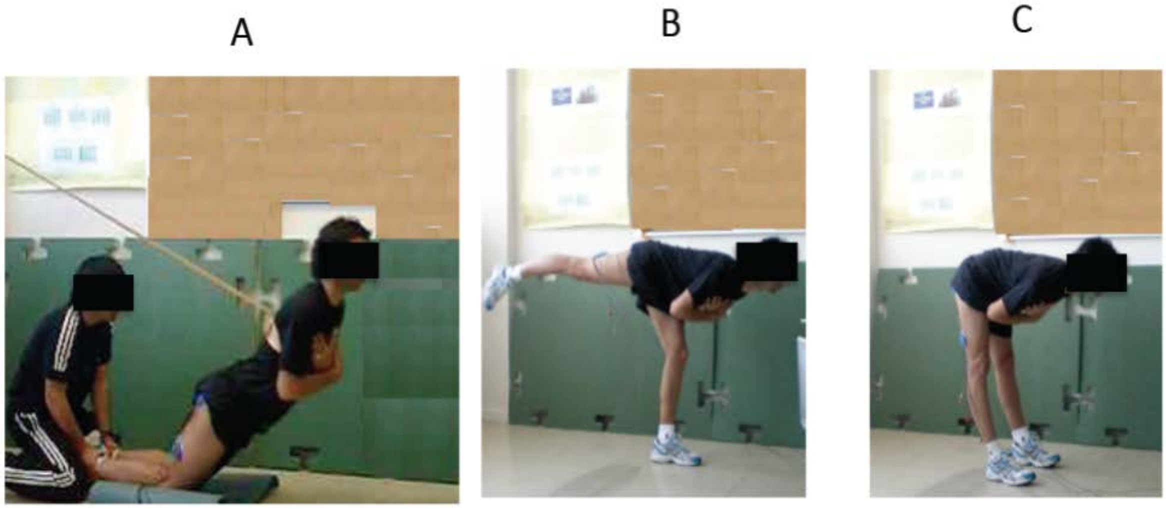

***Figure 5**, Eccentric hamstring exercises*

(A) Assisted Nordic curl, (B) Eccentric single stiff-legged dead lift, and (C) Eccentric double stiff-legged dead lift.

UNS training consisted in the following three unstable-squatting exercises (figure 6): i) Single leg squat: Standing on the floor on one leg only and squat down until knee flexed to 90^0 and press back up with just that single leg. ii) Single leg Squat on Bosu® balance trainer: Standing on the Bosu® balance trainer on one leg only and squat down until supporting leg knee flexes to 90^0 before returning upright. iii) Forward lunges on a Bosu® balance trainer: position the forward leg on the Bosu® balance trainer and lunging with the forward leg to 90^0 before returning to the initial position. In order to guarantee correct technique and to avoid loss of balance during both single leg squatting exercises, each participant was assisted during these movements (figure 6).

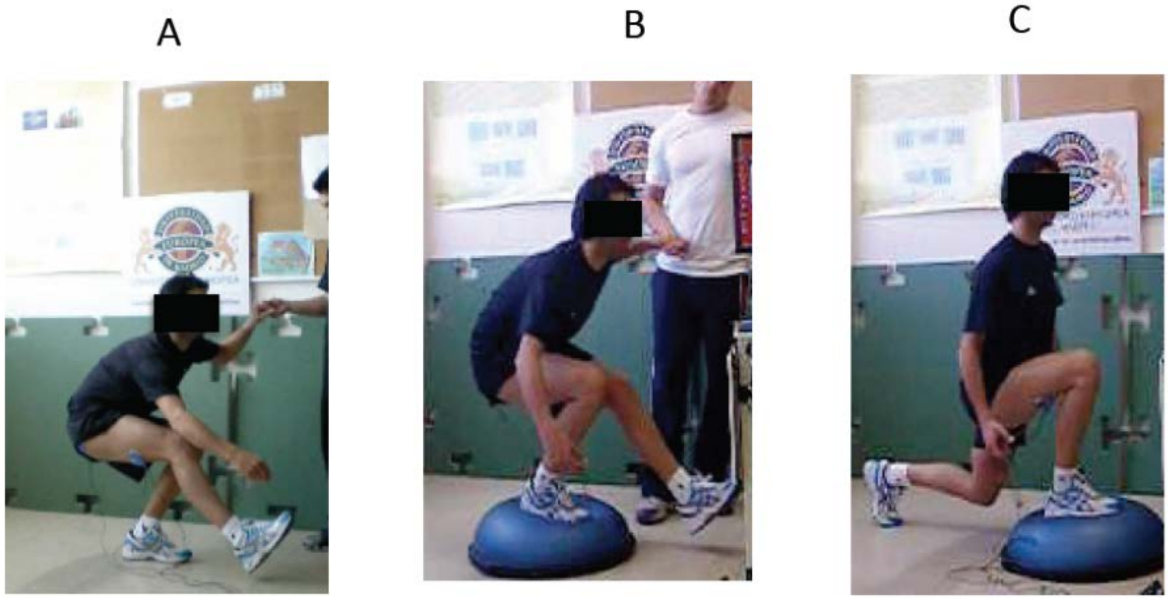

***Figure 6**, Unstable-squatting exercises*

A) Single leg squat B) Single leg Squat on Bosu® balance Trainer C) Forward lunges on a Bosu® Balance Trainer

Participants were instructed to maintain the proper technique performing each repetition against the resistance offered by their own body weight (with no external load). Each training session involved the three eccentric exercises or unstable for the ECC or UNS group respectively. Three sets of 8 repetitions with 1 minute of rest between sets and 2 minutes between exercises were performed. The exercise order was as follows ECC group: assisted Nordic curl, eccentric single stiff-legged dead lift and finally the eccentric double stiff-legged dead lift. UNS group: single leg squat, single leg Squat on Bosu® balance trainer and finally forward lunges on a Bosu® balance trainer. In order to ensure proper technique, tempo, full range of motion, and consistency between participants, a qualified Certified Strength and Conditioning Specialist (CSCS) supervised all training sessions (2:1 participant to instructor ratio).

2.3.4. Statistical Analysis

Data showed to be normally distributed by Kolmogorov-Smirnov and Shapiro-Wilk tests, and descriptive analysis was subsequently performed with data being presented as mean±1SD. A 3×6×2 mixed model analysis of variance (ANOVA) was carried out to compare groups (three, ECC, UNS and C) by angle (six repeated measures, 35º, 45º, 60º, 80º, 90º, and 100º) by time (two repeated measures, pre-test vs. post-test). Pairwise comparisons were used to determine differences between each tested angles. Cohen´s d values and Omega squared (ω^2) were reported to provide an estimate of effect size: small d = 0.2, ω^2= 0.01; moderate d = 0.5, ω^2 = 0.06; and large d = 0.8, ω^2 = 0.14 (Ellis, 2010). The alpha level was set at $P \leq 0.05$ and adjusted using the Bonferroni method for all ANOVA pairwise comparisons. Test-retest reliability coefficients (ICCs) for the day-to-day reproducibility of each of the dependent performance measures were recorded at ICCs = 0.90 during the familiarization period. The coefficients of variation ranged from 1.0% to 2.5%, indicating a high reliability of the testing procedures (Wojtowicz et al., 2012).

2.4. Results

Mixed ANOVA indicated two significant interaction effects. First, an interaction was found between the main group effect and the difference between pre and post measures, $F(2,29)=4.953$, $P=0.014$, $\omega^2=0.006$. Additionally, performance of the groups showed significant interaction effect with the angle, $F(10,145)=4.311$, $P=0.001$, $\omega^2=0.026$.

No significant between-group differences were observed for body mass (ECC=75.2±6.2 kg; UNS=77.2±6.2 kg; C=75.1±9.8 kg) or height (ECC=178.4±8.22 cm; UNS=181±7.3 cm C =176±7.7 cm). Pre-test comparison of maximal torques at each angle indicated no significant between-group differences, ($F(2,29)=2.767$, $P=0.079$, $\omega^2=0.003$). All three groups reached a highest peak torque value between 45º and 80º, with no differences between them (C vs UNS P=0.215; C vs ECC P=0.392; UNS vs ECC P= 0.634). However, these values were significantly different ($P<0.05$) from those attained at 35º and 100º for ECC and UNS groups, and from 35º, 90º and 100º for C groups.

Post-test comparison of maximal torques showed no changes for C group. ECC group showed the highest peak torque at 45º that was significantly different ($P<0.05$) from those achieved at 35º, 90º and 100º, while UNS reached the highest peak torque at 80º that was significantly different ($P<0.05$) from those achieved at 35º and 100º. Pre and post-test peak torque data at each knee flexion angle with respective Cohen's d values are presented in table 1.

***Table 1**, Peak Torque (Nm) measured pre (before) and post (after) training intervention for the three tested groups.*

Angle position	ECC training group (n=11)			UNS training group (n=11)			C non-training group (n=10)		
	Pre N.m	Post N.m	*d*	Pre N.m	Post N.m	*d*	Pre N.m	Post N.m	*d*
35 º	129.39 (55.7)	141.23* (57.4)	0.67	122.69 (63.2)	119.69 (56.8)	-0.17	113.73 (54.6)	119.71 (61.9)	0.34
45 º	294.08 (101.1)	371.18** (67.6)	0.96	392.33 (154.0)	371.75 (128.7)	-0.26	227.02 (82.3)	240.18 (93.5)	0.16
60 º	372.08 (115.1)	359.10 (126.0)	-0.19	397.68 (132.5)	435.09** (159.6)	1.16	323.45 (132.1)	325.29 (128.6)	0.03
80 º	312.52 (76.9)	292.86 (114.3)	-0.44	378.03 (113.1)	449.92** (155.5)	1.21	308.80 (108.8)	307.41 (133.5)	-0.01
90 º	282.22 (104.9)	242.62 (111.9)	-0.52	242.96 (80.0)	315.66** (116.4)	1.38	230.82 (88.5)	235.42 (75.9)	0.07
100 º	180.55 (80.4)	169.18 (72.5)	-0.16	213.80 (77.4)	246.17 (119.4)	0.46	151.22 (67.8)	169.62 (82.3)	0.26

Data are presented as means ± standard deviation, and Effect Size value (d)

*Significant differences at *p<0.05 and **p<0.01*

Pairwise comparisons between pre-test and post-test measures across groups showed no significant differences for C group, whereas the intervention groups showed opposite changes. ECC increased peak torque at 35º (t(29)=2.227, P=0.034, d=0.67) and 45º (t(29)=3.177, P=0.004, d=0.96), see figure 7. Alternatively UNS produced significant higher peak torque values at 60º (t(29)=3.836, P =0.024, d=1.16); 80º (t(29)=4.027, P=0.018 d=1.21) and 90º (t(29)=4.567, P=0.001 d=1.38), see figure 8. No other significant differences were found.

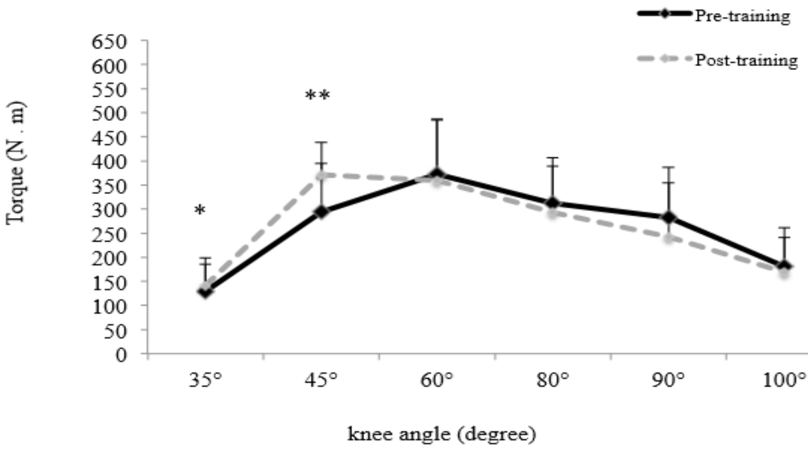

***Figure 7**, Hamstrings isometric knee torque-angle relationship assessed in ECC training group pre (before) and post (after) 6 weeks of training intervention (M±SD)*

*∗P< 0.05 and ** P=0.004*

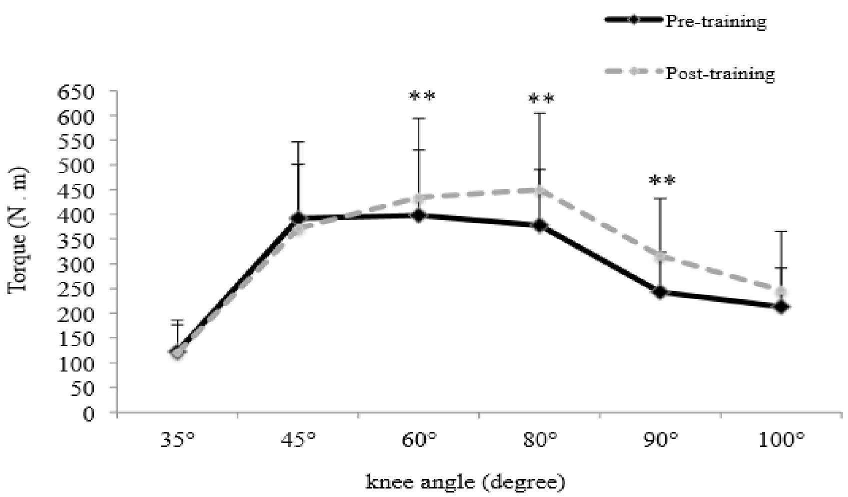

***Figure 8**, Hamstrings isometric knee torque-angle relationship assessed in UNS training group pre (before) and post (after) 6 weeks of training intervention (M±SD)*

**P<0.001

2.5. Discussion

The major finding of the present study was that different injury prevention protocols involving mainly hamstring-eccentric or unstable-squatting exercises elicited differential changes over the knee flexion angle-torque relationship. The ECC group increased the peak torques at the two most opened knee flexion angles (35º and 45º, figure 7), whereas the UNS group improved at closer knee positions (60º; 80º and 90º, figure 8). These results confirm our hypothesis (the ECC programme would emphasize strength improvement over the most open angles while the UNS protocol would mainly strengthen the more closed positions). In addition, when considering the effect sizes (*d*) obtained after comparing pre and post isometric torque values for each of the 6 measured angles, it seems that hamstring muscle strength did not improve or even tended to decrease at the closer knee angles for ECC group or at the longer position for the UNS group (table 1). A possible explanation for our findings could be based on the characteristics of training protocols that involve systematic attempts to overload the hamstring musculature on different lengths and mode of muscle contractions. The ECC group emphasized the application of force toward the more open knee position, whereas the UNS group used unstable-squatting exercises where the hamstrings were required to counteract anterior tibial shear forces pulling on the tibia while exercising at a shorter muscle length (Bahr and Holme, 2003). Differential angular torque productions in response to different training intervention have been previously reported. Kilgallon et al. (2007) observed significant increases in the isometric hamstring peak torque at more open knee angles (from 40º to 10º) with no increase at more closed positions (50º to 80º) after 3 weeks of a progressive training involving two eccentric hamstring exercises (stiff-legged deadlifts and leg curls). Conversely, another group that performed the same exercises using only concentric contractions, increased hamstring peak torque at both flexed and extended knee angles. Mjølsnes et al. (2004) also reported different training outcomes after performing 4 weeks of two different training protocols involving one eccentric (Nordic curl) or one concentric (traditional knee-curl) exercise in soccer players. The eccentric Nordic curl was more effective in developing dynamic eccentric and isometric hamstring peak torque measured at 30º 60º and 90º of knee flexion. In addition, the eccentric exercises lead to a greater increase of the isometric peak torque at more open angles (30º and 60º) compared to the improvement observed at 90º.

Opposed to our study, Orishimo and McHugh (2014) observed significant increase in hamstring strength with no specific angle effect after performing 4 weeks of a three eccentric hamstring exercise program. Perhaps, differences in the exercises execution could explain the discrepancy. In the current study, participants in ECC group were continuously encouraged to increase the level of hamstring strength as the trunk approached the horizontal position, toward the end of the descending movement. On the other hand, participants in UNS group where instructed to perform a slower controlled descending phase and maximally accelerate during upward part of the exercise. The controlled-slower descending phase during unstable squatting exercises would require a near-isometric hamstring activation that could have caused the observed differential changes at the knee flexor-torque angle relationship for the UNS compared to the ECC group.

Hamstrings muscles act within a functional kinetic chain associated with both upper body (pelvis, spine, shoulder and skull) and the lower-limb alignment and stabilization (Hoskins and Pollard, 2005). Unstable squatting exercises that emphasize hamstring-quadriceps co-contraction together with a simultaneous and coordinated activation of the core and lower body musculature would therefore be a suitable approach for improving hamstring knee stabilization and help to protect athletes from ligament injuries (Myer et al., 2005b, Opar et al., 2012). To our knowledge, only the study by Naclerio et al. (2013) combined eccentric hamstring lengthening with unbalance-squatting exercises along a 4-week injury prevention program. Results from this investigation showed a marked increase of the hamstring strength extended from 35° to 80° with no optimal peak torque observed over the knee range of motion. It seems that combining exercises of different nature aimed to protect athletes from different types of injuries would be an effective method to prevent injury in athletes. However, the most appropriate and effective exercises dosage (sets and repetitions) and combination still remain to be elucidated. In conclusion, six weeks of a lower body injury prevention protocol including only eccentric-hamstring or unstable-squatting exercises improved hamstring strength. However, the eccentric-hamstring protocol increased peak torques at more open angles (35º and 45º) with no effect on the more closed positions, meanwhile, the unstable-squatting intervention resulted in an improvement of the hamstring strength at middle to closed knee angles (60º; 80º and 90º) with no effect on the more open positions.

In order to guarantee higher participant compliance and correct technique execution this programme used no external load other than body weight. Although exercising with no external resistance makes the programme easier to follow, a more intense stimulus could be obtained through a progressive resistance protocol that adds weight using dumbbells or weight vest.

The effect size analysis suggests that performing only eccentric-hamstring or unstable-squatting exercises would produce positive specific adaptations to attenuate hamstring or ACL injury respectively but at the same time would increase the risk to suffer from other injury (see negative values in table 1).

2.6. Practical application

As team sport players need to be protected from both types of injuries, coaches are advised to consider both types of exercises and their potential specific angle adaptations when designing injury prevention protocols. The consequences of the observed adaptation in the angle–torque relationship may be of critical importance for athletes engaged in sports that demand high hamstring force application at specific knee angles.

Chapter 3

Study 2- The effectiveness of injury prevention programmes to modify risk factors for non-contact anterior cruciate ligament and hamstring injuries in uninjured team sports athletes: A systematic review

3.1. Abstract

Background: Hamstring and anterior cruciate ligament injuries are, respectively, the most prevalent and serious non-contact occurring injuries in team sports. Specific biomechanical and neuromuscular variables have been used to estimate the risk of incurring a non-contact injury in athletes.

Objective: The aim of this study was to systematically review the evidences for the effectiveness of injury prevention protocols to modify biomechanical and neuromuscular anterior cruciate and/or hamstring injuries associated risk factors in uninjured team sport athletes.

Data Sources: PubMed, Science Direct, Web of Science, Cochrane Libraries, U.S. National Institutes of Health clinicaltrials.gov, Sport Discuss and Google Scholar databases were searched for relevant journal articles published until March 2015. A manual review of relevant articles, authors, and journals, including bibliographies was performed from identified articles.

Main Results: Nineteen studies were included in this review. Four assessment categories: i) landing, ii) side cutting, iii) stop-jump, and iv) muscle strength outcomes, were used to analyse the effectiveness of the preventive protocols. Eight studies using multifaceted interventions supported by video and/or technical feedback showed improvement in landing and/or stop-jump biomechanics, while no effects were observed on side-cutting manoeuvre. Additionally, multifaceted programmes including hamstring eccentric exercises increased hamstring strength, hamstring to quadriceps functional ratio and/or promoted a shift of optimal knee flexion peak torque toward a more open angle position.

Conclusions: multifaceted programmes, supported by proper video and/or technical feedback, including eccentric hamstring exercises would positively modify the biomechanical and or neuromuscular anterior cruciate and/or hamstring injury risk factors.

3.2. Introduction

Hamstring and anterior cruciate ligament (ACL) injuries are, respectively, the most prevalent (Opar et al., 2012) and serious (Stevenson et al., 2015) non-contact occurring injuries in team sports and therefore preventive programmes aiming to protect athletes from both types of injury should be integrated. Several injury prevention programmes involving jumps (Herrington, 2010), strength (Cochrane et al., 2010, Herman et al., 2009, Herman et al., 2008, Holcomb et al., 2007), unstable (Donnelly et al., 2012, Myer et al., 2005b), or a combination of different exercises modes (Barendrecht et al., 2011, Lim et al., 2009, Myer et al., 2006b, Noyes et al., 2005) have been proposed to prevent both ACL and hamstring injuries. However, there is still a lack of uniform criteria regarding the design of an ideal protocol for effective protection against the two aforementioned injuries in team sport athletes. Indeed, to the authors' knowledge there is no consensus about how to integrate ACL and hamstring preventive exercises within an optimal injury prevention protocol in team sports. A recently published systematic review highlights the lack of enough evidence to support the effect of neuromuscular training programmes to reduce ACL injuries in athletes (Stevenson et al., 2015). Additionally, it seems that multifaceted programmes involving strength, plyometric, balance, agility, core, and flexibility exercises would be the most effective intervention to prevent from ACL injuries (Stevenson et al., 2015). Similarly, effective strategies to reduce the incidence of hamstring injuries may also include a combination of different types of muscular actions including both active lengthening eccentric and co-contracting knee stabilizer exercises (Naclerio and Goss-Sampson, 2013, Opar et al., 2012).

In previously uninjured athletes the protective effects of different prevention protocols have been assessed by their capacity to modify biomechanical (posture, trunk, or lower limb alignments) and neuromuscular (strength deficits or balance) risk factors, rather than to reduce injury rates (the latter require more time and also only can be accomplished through a prospective study). For example, knee valgus or varus moment and open knee flexion angle during landing, exaggerated hip internal rotation and adduction, and/or an uncontrolled trunk motion including lateral displacement during jumping (Myer et al., 2011, Myer et al., 2006b), or cutting manoeuvres (Havens and Sigward, 2015) have been associated with an increased ACL injury risk in females athletes. On the other hand, the angle at which the optimal knee flexor peak torque occurred has been used to assess the risk of hamstring injury

(Brockett et al., 2004). Furthermore both ACL and hamstring injuries have been associated with hamstring strength, hamstring to quadriceps (H:Q) strength ratio or hamstring bilateral ratio (Croisier et al., 2008). Even though the above-mentioned variables have been the focus of several trials (Ter Stege et al., 2014, Opar et al., 2012, Stevenson et al., 2015), there is still a lack of consensus about how these factors would respond to different training interventions. For example, when strength training exercises were used alone, including closed-chain hip rotation, bands, machine and free weight lower body exercises, studies reported no change (Herman et al., 2009) to significant modifications (Snyder et al., 2009) in the hip internal rotation, and knee abduction moment during running or cut and jump actions. Furthermore, significant increases in isometric hamstring strength in response to similar eccentric exercise protocols have been produced with (Kilgallon et al., 2007) or without (Orishimo and McHugh, 2014) a concomitant displacement of the optimal knee flexion peak torque toward a more open angle position.

To the authors' knowledge there are still no standardized guidelines for designing an effective lower limb injury prevention protocol in terms of exercise modes (stable, balance, open or closed chain, using eccentric or concentric actions), sets, repetitions and relative overload in team sport athletes. Therefore, the aim of the current review is to examine the documented effects of the different proposed injury prevention protocols on the following modifiable ACL and/or HAM risk factors in uninjured team sport athletes: i) knee valgus/varus angle and moment; ii) hip adduction/abduction angle and moment; iii) knee and hip rotation angle; iv) knee and hip flexion angle; v) hamstring and quadriceps muscle strength; vi) hamstring to quadriceps (H:Q) conventional and functional strength ratios; and vii) the angle at which the optimal knee flexor peak torque occurred.

3.3. Method

A systematic review of the literature was conducted in accordance with the PRISMA guidelines (Liberati et al., 2009, Moher et al., 2009) with procedures defined a priori. Search of literature was performed by using PubMed, Science Direct, Web of Science, Cochrane Libraries, U.S. National Institutes of Health clinicaltrials.gov, Sport Discuss and Google Scholar, from the start date of the representative database through the last week of March 2015. English-language publications in human populations were identified as being eligible for review. Articles were included if they were published in peer reviewed journals and full text was accessible. Commentaries, reviews, or duplicate publications from the same study were removed. Manual searches of personal files were conducted, along with screening of reference lists of previous reviews and identified articles, for inclusion. Combinations of the following keywords were used as search terms: “Anterior cruciate ligament or ACL and injury”; “hamstring and injury or strain”, together with the markers “exercise”, “intervention”, “training”, “protocol” “prevention” “muscle”, “biomechanics”, “kinetic”, and “kinematic”.

The selection criteria were applied independently by two reviewers (AM and FN). Potentially relevant articles were selected by: 1) screening the titles; 2) screening the abstracts; and 3) if abstracts did not provide sufficient data, the entire article was retrieved and screened to determine whether it met the inclusion criteria depicted in table 2.

Table 2*, Study Criteria for Inclusion in the Review*

• Intervention studies
• Duration of at least 4 weeks involving minimum of 8 training sessions no longer than 35 minutes
• Examined at least one of the previously defined lower extremity injury risk factors
• Involves male and/or female athletes (an athlete was defined as a person who performs minimum of two organized training sessions per week).
• Participants: ≥14 years old, team sport athletes,
• Without history of an ACL and/or hamstring injury, not engaged in any injury prevention programme over the last 12 months prior to the intervention

The abstracts of the search results were reviewed. Reference lists of relevant studies were also reviewed to identify publications not found through the electronic search. Only studies examining the effect of injury prevention protocols on some of the previously identified HAM and/or ACL injury risk markers were considered. When data were not accurately presented (only available from figures or graphs) authors were contacted and requested to provide the appropriate range of values.

The following qualitative and quantitative information was extracted from each included study: authors; publication year; baseline population characteristics; intervention and control procedures; study duration; sample size per group; training modalities, number of exercises, sets, frequency and total time per session; outcomes measured at pre- and post-intervention; group means and SDs for the following variables: quadriceps and hamstrings strength; hip and knee flexion and extension moments; hip initial flexion and abduction angles; hip peak flexion and abduction angles; hip maximum external rotation angle; knee peak valgus moment; knee external rotation moment; knee Peak internal-rotation moment; knee initial flexion angle; knee peak flexion angle; knee valgus angle; optimal knee flexion peak torque localization; optimal knee extension peak torque localization and conventional and functional H:Q. In order to analyse the observed results using comparable assessment methods, the information was organized into four categories: i) landing, ii) side cutting, iii) stop-jump, and iv) muscle strength.

Methods of the analysis and inclusion criteria were specified in advance, and documented in a protocol registered at the International prospective register of systematic reviews, PROSPERO (CRD42015028041).

3.3.1. Methodological assessment and risk of bias

Two reviewers (AM and FN) ascertained individual study information independently as part of the quality control process. The methodological quality of the included studies was assessed based on criteria adapted from Downs and Black (1998), Kennelly (2011) and Physiotherapy Evidence Database (PEDro) scale: 1) clearly described the aim/hypothesis/objective; 2) participants free of previous knee/hamstring injury; 3) groups at baseline similar (sex, age and activity/sport); 4) clearly described characteristic of the participants; 5) clearly described Inclusion/exclusion criteria; 6) main outcome clearly described; 7) replicable (clearly described intervention protocol); 8) clearly presented results; 9) reported actual probability value for the main outcomes (e.g. 0.035 rather than <0.05); 10) staff, places and facilities where the participants were treated, representative of the treatment of the majority of the population; 11) availability of control group; 12) blinded researcher measuring the outcomes of the intervention; 13) patients from different intervention groups recruited over the same period of time; 14) randomized study; 15) incompliance reported; 16) reliability of outcomes. For each item, each study could be scored either 1 or 0 points. If the item was not applicable or not reported in the study, 0 points were recorded. For each study, the total quality assessment scored ranged from 0 to 16. Higher quality assessment number indicated a better methodological approach.

3.3.2. Statistical analysis

From the collected data, we used the pre and post values of mean, standard deviation (SD), and sample size. The effect size was calculated using the Hedges' g.

3.4. Result

After removing the duplicates, 4801 records were found through three electronic databases. Title and abstract selection excluded 4370 and 354 records, respectively. The remaining 77 records were reviewed based on exclusion/inclusion criteria and 56 studies were rejected for different reasons (figure 9 and Appendix III). One of the reviewed studies (Myer et al., 2007) was excluded because of using selective participants (high-risk vs. low-risk athletes). Another study (Croisier et al., 2008) was also excluded because of unclear intervention protocol. Thus, a total of 19 studies were included (figure 9).

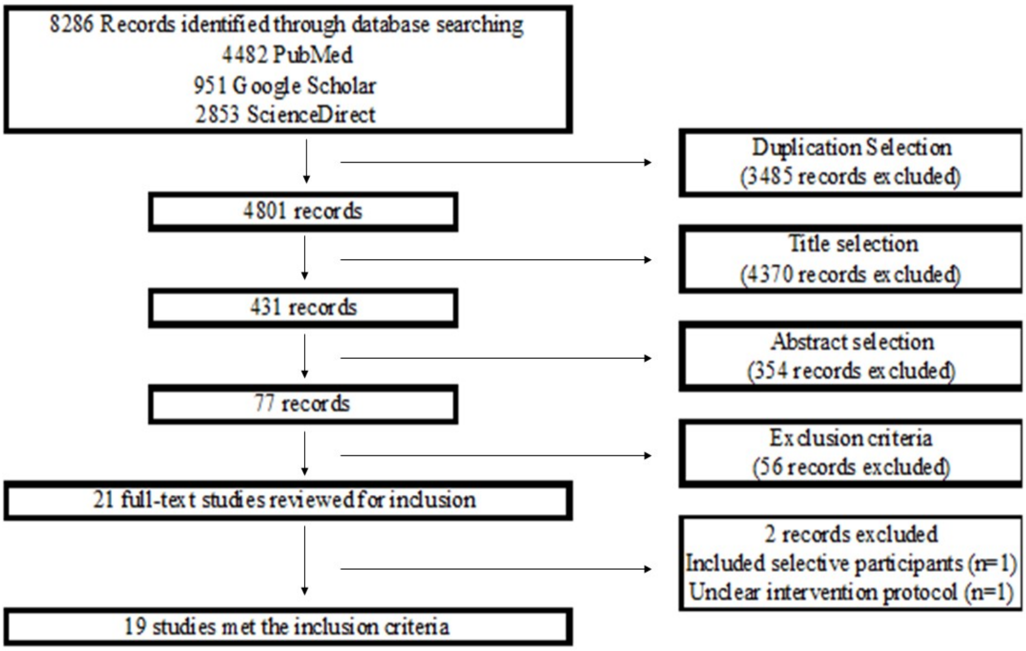

Figure 9, *Flow diagram of article selection according to PRISMA*

The scores for the methodological quality assessment ranged from 9 to 15 and the mean was 12.2 (table 3).

***Table 3**, Quality Assessment of the Included Studies*

Study	Quality score	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Brughelli *et al*. 2010	13	1	0	1	1	0	1	1	1	0	1	1	1	1	1	1	1
Chappel and Limpisvasti, 2008	9	1	0	0	1	1	1	1	1	1	1	0	0	0	NA	1	0
Clark *et al*., 2005	10	1	1	1	0	1	1	1	1	1	1	0	0	1	NA	0	0
Daneshjoo *et al*., 2012	13	1	1	1	1	0	1	1	1	0	1	1	1	1	1	0	1
Donnelly *et al*., 2012	13	1	1	1	1	1	0	1	1	0	1	1	1	1	0	1	1
Herman *et al*., 2008	14	1	1	1	1	1	1	1	1	0	1	1	0	1	1	1	1
Herrington, 2010	12	1	1	1	1	1	1	1	1	1	1	0	0	1	NA	0	1
Holcomb *et al*., 2007	12	1	1	1	1	1	1	1	1	1	1	0	0	1	NA	0	1
Kato *et al*., 2008	13	1	1	1	1	1	1	1	1	1	1	1	0	1	1	0	0
Lephart *et al*., 2005	12	1	1	1	1	1	1	1	1	0	1	0	0	1	1	0	1
Lim *et al*., 2009	13	1	1	1	1	1	1	1	1	0	1	1	0	1	1	0	1
Mendiguchia *et al*., 2014	15	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1
Mjølsnes *et al*., 2004	14	1	1	1	0	1	1	1	1	1	1	0	1	1	1	1	1
Naclerio *et al*., 2013	14	1	1	1	1	1	1	1	1	1	1	1	0	1	1	0	1
Nagano *et al*., 2011	11	1	1	1	1	1	1	1	1	0	1	0	0	1	NA	0	1
Ortiz *et al*., 2010	10	1	0	1	0	0	1	1	0	0	1	0	1	1	1	1	1
Pollard *et al*., 2006	12	1	1	1	1	1	1	1	1	1	1	0	0	1	NA	1	0
Wilderman *et al*., 2009	13	1	1	1	1	1	1	1	1	1	1	1	0	1	1	0	0
Zebis *et al*., 2008	9	1	0	1	1	0	1	0	1	1	1	0	0	1	NA	0	1

Note: NA: not applicable; Quality score criteria are explained in the methodological assessment and risk of bias section.

The total number of participants in all included studies was 485, comprising 285 females and 200 males. The included articles used different protocols involving resistance (Herman et al., 2008), eccentric (Mjolsnes et al., 2004, Clark et al., 2005), or plyometric exercises (Herrington, 2010) alone or combined with other exercise modalities (Brughelli et al., 2010, Chappell and Limpisvasti, 2008, Daneshjoo et al., 2012, Holcomb et al., 2007, Lephart et al., 2005, Naclerio et al., 2013, Ortiz et al., 2010, Pollard et al., 2006, Wilderman et al., 2009, Mendiguchia et al., 2014) supported by video feedback (Kato et al., 2008) and/or technical corrections (Lim et al., 2009, Nagano et al., 2011, Donnelly et al., 2012, Zebis et al., 2008).

Two studies analysed the effects of the applied interventions to modify some of the aforementioned risk factors during landing and stop-jump (Chappell and Limpisvasti, 2008, Herrington, 2010); three studies considered landing and muscle strength outcomes (Lephart et al., 2005, Lim et al., 2009, Ortiz et al., 2010); one study evaluated stop-jump and muscle strength outcomes (Herman et al., 2008); the rest of studies focused on a single test-task: landing (Nagano et al., 2011, Pollard et al., 2006); stop-jump (Kato et al., 2008); side cutting (Donnelly et al., 2012, Wilderman et al., 2009, Zebis et al., 2008); and muscle strength outcomes. (Brughelli et al., 2010, Clark et al., 2005, Daneshjoo et al., 2012, Holcomb et al., 2007, Mjolsnes et al., 2004, Naclerio et al., 2013, Mendiguchia et al., 2014)

Table 4 summarizes the type of intervention, main characteristics, and effects of the all-19 included studies.

Table 4, *Summary of the Main Characteristics and Relevant Finding of the 19 Included Studies.*

Study	Assessment	Participants	Design and type of intervention	Length	Relevant findings
(Chappell and Limpisvasti, 2008)	Landing (DJ) and stop jump	Female (n=30; 19±1.2 y) basketball (n=18) and football (n=12) players	Controlled within participants pre-post comparison. Ten exercises involving core, strengthening, dynamic joint stability and balance training, jump training, and plyometric exercises. With proper technical feedback, daily 10 to 15 minutes workout.	6 wk	From DJ: ↓HIAbdA (g=-0.44); ↑KIFA (g=0.54); ↑KPFA (g=0.54); ↓KFM (g=-0.46) From stop jump: ↓HIFA (g= 0.68); ↓HMxERA (g= -0.52); ↓ KERM (g=-0.26); ↓KPVM (g= -0.38) ↓KFM (g=-0.21)
(Herrington, 2010)	Landing (DJ) and stop jump	Female basketball players (n=15; 19.1±6.1 y)	Controlled within participants pre-post comparison. Progressive jump training from bilateral to unilateral activities with proper feedback and technical corrections, 3-day per week 15 min session.	4 wk	↓ KVA at both limbs: DJ (left g=1.54; right g=1.74) and Stop-Jump (left g=0.73; right g= 0.54)
(Lephart et al., 2005)	Landing (VJ) and muscle strength (isokinetic)	Female basketball or football players (n=27; 14.3±1.3 y)	Two PG, randomized pre-post comparison. Weeks 1st to 4th: Resistance flexibility and balance exercises for both groups. Weeks 5th to 8, different interventions 1) Plyometric + agility (P, n=14) 2) Basic resistance + flexibility + balance exercises (B, n=13), 3-day per week 30 min session programme supported with verbal and video feedback.	8 wk	Both groups (P and B): ↑QS at 60˚/s-1 and 180˚/s-1 ↑HIFA (P g=1.08; B g=0.24) ↑KPFA (P g=0.92; B g= 0.42); ↓HFM (P g=-0.26; B; g=0.17) ↓KFM (P g=0.61; B g= -0.69) P group only: ↑HPFA (g=0.77)

(Lim et al., 2009)	Landing (RVJ) and muscle strength (isokinetic)	Female basketball players (n=22; 15 to 17 y)	Two PG, randomized pre-post comparison. 1) Experimental (E, n=11) Modified version of Mandelbaum's Prevent Injury and Enhance Performance (PEP) Programme involving stretching, strengthening, plyometric and agility exercises supported by technical corrections. Daily 20 min session. 2) Control (C, n=11) only regular training	8 wk	E group to pre and to C: ↑KPFA (g=0.41; ↑KFM (g=0.41); ↓KPEM (g=-0.95); ↓KVM (g=-0.69) ↓QS and ↑H %EMG (g=0.84)
(Ortiz et al., 2010)	Landing (SLDJ) and muscle strength (isometric)	Female football players (n=30, 14 to 15 y)	Two PG, randomized pre-post comparison 1) Experimental (E, n=14): Flexibility, strengthening and plyometric exercises 2) Control (C, n=14) continue its regular practice and games. Two days/week, 20 to 25 min workout.	6 wk	From SLDJ: ↑KPEM; ↑ KPVM NS= between groups ** ↑QS E group to pre and to C
(Nagano et al., 2011)	Landing (SLDJ)	Female basketball players (n=8, 19.4±0.7 y)	Controlled within participants pre-post comparison Plyometric, balance exercises and specific basketball skills (first 3-weeks focused to improve landing technique). Three days/week, 20 min workout.	5 wk	↑ KIFA (g=2.21)
(Pollard et al., 2006)	Landing (DJ)	Female football players (n=18, 14 and 17 y)	Controlled within participants pre-post comparison. Prevent injury and enhance performance protocol involving flexibility, strengthening, plyometric and agility exercises supported by video feedback. Three days/week, 20 min session.	16 wk	↓HIRA (g=-0.71); ↑HPAbdA (g=-0.64)

(Naclerio et al., 2013)	Muscle strength (isometric)	Male professional football players (n=20, 23.8±3.1 y)	Two PG randomize pre-post comparison. 1) E experimental (E, n=10), strengthening eccentric and balance exercises. Performed 3 day/week 15 min session 2) control (C, n=10) no intervention.	4 wk	E group to pre and to C ↑H isometric PT at 800 (g=0.78) and 35°(g= 0.50) knee angles
(Brughelli et al., 2010)	Muscle strength (isometric)	Male football players (n=28, 21.1±1.4)	Two PG randomized pre-post comparison. 1) Experimental (E, n=13) Strengthening eccentric exercise program. Three days/week, 15min session. 2) Control (C, n=11) only regular football training.	4 wk	Both groups: ↑ KFPTL (E g= 1.10 C g= 0.74) E:↑ OKEPTL (g=0.87)
(Clark et al., 2005)	Muscle strength (isokinetic)	Male Australian Rules football players (n=9, >18 y)	Controlled within participants pre-post comparison. Progressive eccentric training involving only the Nordic Curl exercise (2 to 3 sets of 5 to 8 repetitions), 2-3 days/week	4 wk	↓QS at 60˚/s^{-1} (dominant g=-1.1; non-dominant g=-1)**;** ↑OKFPTL (dominant g=0.63; non-dominant g=0.95)
(Holcomb et al., 2007)	Muscle strength (isokinetic)	Female football players (n=12; 20± 0.8 y)	Controlled within participants pre-post comparison. Upper-body resistance exercises combined with speed and agility (2 days) and lower body (hamstring emphasized) resistance exercises combined with endurance conditioning training (2 days). Four days/week.	6 wk	↑H:Q functional ratio (average from concentric 240, 180, and 60˚/s^{-1} and eccentric 60, 180, and 240 ˚/s^{-1}; g=1.19)

(Daneshjoo et al., 2012)	Muscle strength (isokinetic)	Male, football players (n=36, 17 to 20 y)	Three PG randomized pre-post comparison. 1) FIFA+11 (F, n=12), involving strengthening, balance, plyometric and agility exercises 2) Harmoknee (H, n=12) involving strengthening and balance exercises 3) control (C, n=12) regular training and warm up. Both F and H consisted in 3 days/week (24 sessions), 20 to 25min workout.	8 wk	F: ↑H:Q conventional ratio (g= 0.99); and ↓H:Q (g=-1.17) functional ratio, from pre to post NS in H and C
(Mjolsnes et al., 2004)	Muscle strength (isometric and isokinetic)	Male football players (n=22, >18 y)	Two PG randomized pre-post comparison. 1) Nordic eccentric hamstring (NEH, n=11), 2) Concentric hamstring (CH, n=10). Progressive training from 2 sets of 6 reps to 3 sets of 8 to 12 reps over 4 weeks, and then increasing load for the final 6 weeks	10 wk	NEH: ↑HS eccentric at 60˚/s^{-1} (g=2.16) ↑isometric at 30^0 (g=1.86) 60^0 (g=1.32) and 90^0 (g=1.84) ↑H:Q functional ratio (g=1.99) NS in CH

Notes: ↑ increase; ↓ decrease; PG: parallel groups; NS: no significant differences, Sig= significant differences.

%EMG= percentage of electromyography activity; H= hamstring, MH=medial hamstring; Q= quadriceps; VM= vastus medialis; ST= semitendinosus; H:Q= hamstring to quadriceps ratio; QS= quadriceps strength, HS= hamstrings strength; PT= peak torque; DJ=Drop Jump; SLDJ= single legged drop jump; RVJ= Rebound vertical jump; VJ=Vertical Jump; HIFA= hip initial flexion angle; HPFA= hip peak flexion angle; HIAbdA= hip initial abduction angle; HPAbdA = hip peak abduction angle; HMxERA=hip maximum external rotation angle; HIerRA; HFM= hip flexion moment. KIFA= knee initial flexion angle; KPFA knee peak flexion angle; KVA; knee valgus angle KFM=knee flexion moment; KERM= knee external rotation moment; KPIRM= knee Peak internal-rotation moment; KPEM= knee peak extension moment; KPVM= knee peak valgus moment; OKFPTL= optimal knee flexion peak torque localisation OKEPTL= optimal knee extension peak torque localization.

** test 1 was performed between weeks 1 (pre) to 7 and test 2 (post) between week 18 to 25 during the 28-week intervention period. ** Missing information impeded the calculation of g values*

3.4.1. Landing

Seven studies including only female participants, n=143 (77 basketball and 66 soccer players) used plyometric combined with other exercise modalities (balance, strengthening and flexibility) to analyse the effects of injury prevention programmes on kinematic and kinetic variables during landing (Chappell and Limpisvasti, 2008, Herrington, 2010, Lephart et al., 2005, Lim et al., 2009, Nagano et al., 2011, Ortiz et al., 2010, Pollard et al., 2006). Three studies analysed a 30 cm drop vertical jump (DVJ) (Chappell and Limpisvasti, 2008, Herrington, 2010, Pollard et al., 2006), two a vertical jump (VJ) (Lephart et al., 2005, Lim et al., 2009), and the other two a 30 to 33 cm singled leg drop jump (SLD) (Nagano et al., 2011, Ortiz et al., 2010). The averaged quality of these studies was 11.5, ranging from 9 to 14, with 1 study scoring 14 (out of 16). Interventions lasted from 5 to 16 weeks.

Knee flexion angle increased after performing mixed interventions combining strength-balance and plyometric exercises (Chappell and Limpisvasti, 2008, Lephart et al., 2005, Nagano et al., 2011) or following a programme aiming to improve technique (Lim et al., 2009). Conversely, no significant changes on knee flexion angle have been reported after performing both a 6-week (Ortiz et al., 2010) or a 16-week (Pollard et al., 2006) mixed protocol in female soccer players.

Knee flexion moment was decreased in two studies where the intervention protocols involved active feedback aiming to improve the correct execution of selected balance exercises (Chappell and Limpisvasti, 2008, Lephart et al., 2005). Only one study involving a 4-week progressive jump training reported significantly decreased and large effect sizes in valgus angle during landing (Herrington, 2010), while no changes were observed by other 4 studies in which multifaceted interventions including plyometric, strengthening and balance exercises were implemented (Chappell and Limpisvasti, 2008, Nagano et al., 2011, Ortiz et al., 2010, Pollard et al., 2006).

3.4.2. Side-Cutting

Three studies involving 84 athletes (34 males and 50 females) analysed the effectiveness of different injury prevention protocols to modify knee biomechanics during side-cutting manoeuvres (Donnelly et al., 2012, Wilderman et al., 2009, Zebis et al., 2008). The mean quality score was 11.5, ranging from 9 to 13 (out of 16). Interventions lasted from 6 weeks to 12 months.

Two studies investigated 45º pivoting (Donnelly et al., 2012, Wilderman et al., 2009) and the other study did not report the pivoting angle (Zebis et al., 2008). All three studies focused on knee flexion angles and moments. The prevention programmes varied between studies from a progressive agility exercise protocol (Wilderman et al., 2009) toward a combination based on feedback protocols including balance, plyometric and agility exercise,(Donnelly et al., 2012) and a proprioceptive-balance programme (Zebis et al., 2008). The applied interventions did not increase knee flexion angles and moments measured during cutting manoeuver. Two studies examined the effect on vertical ground reaction forces, but again interventions did not alter this variable when performing either pre-planned (Donnelly et al., 2012, Wilderman et al., 2009) and unplanned sidestepping actions (Donnelly et al., 2012).

3.4.3. Stop-jump

Four studies involving a total of 131 female athletes, investigated the effect of exercise programmes on kinematic and kinetic variables during double leg stop-jump (DLSJ) (Chappell and Limpisvasti, 2008, Herman et al., 2009, Herrington, 2010, Kato et al., 2008). The average quality score was 12, ranged from 9 to 14 (out of 16). The interventions lasted 4 to 9 weeks.

Two studies performed the DLSJ after basketball drills (Herrington, 2010, Kato et al., 2008). Participants dribbled a basketball to free throw line and then performed a jump shot. For the other two studies participants take a three or four steps approach to run as fast as they felt comfortable followed by two-footed landing and a maximum height two-footed takeoff (Chappell and Limpisvasti, 2008, Herman et al., 2008).

Knee valgus angle was reduced as a result of a four-week progressive jump training programme (Herrington, 2010) or a mixed intervention involving strength and balance exercises assisted by a video feedback protocol (Kato et al., 2008). Furthermore, Chappell and Limpisvasti (Chappell and Limpisvasti, 2008) reported significant reduction of both knee valgus moment and hip flexion angle as consequence of a 6-week strength, balance, plyometric and agility programme involving a constant monitoring of the proper technique execution. Only one of the aforementioned four studies did not report any significant modification in knee and hip biomechanics during a stop-jump after a 9-week strength training intervention using bands and balls in female athletes (Herman et al., 2008).

3.4.4. Muscle strength

Eleven trials involving 316 athletes (150 females and 166 males) reported the effects of exercise interventions on lower limb strength. Three studies considered only maximal isometric peak torques (Herman et al., 2008, Naclerio et al., 2013, Ortiz et al., 2010), seven studies measured isokinetic strength (Brughelli et al., 2010, Clark et al., 2005, Daneshjoo et al., 2012, Holcomb et al., 2007, Lephart et al., 2005, Lim et al., 2009, Mendiguchia et al., 2014) and only one study measured both isometric peak torques and isokinetic force (Mjolsnes et al., 2004). In addition, four of the aforementioned studies analysed the effect of intervention on H:Q (Brughelli et al., 2010, Clark et al., 2005, Daneshjoo et al., 2012, Mjolsnes et al., 2004, Mendiguchia et al., 2014) and only two monitored changes on the optimal knee flexor peak torque localization (Brughelli et al., 2010, Clark et al., 2005). The average quality score was 12.7, ranging from 10 to 15 (out of 16). The interventions lasted 4 to 10 weeks.

Both conventional and functional H:Q ratios increased after a 7-weeek neuromuscular multifaceted (plyometric, eccentric and acceleration exercises) programme (Mendiguchia et al., 2014). Additionally, functional H:Q ratio was also increased after a 4-week Nordic eccentric hamstring protocol in male soccer players (Mjolsnes et al., 2004), and also following a 6-week strength programme including at least two different hamstring concentric exercises in females football players (Holcomb et al., 2007). However, the latest study did not result in significant modification of the conventional H:Q ratio. One study involving only male athletes examined the FIFA11+ and the HarmoKnee protocols. The FIFA11+ increased the conventional H:Q ratio only in the dominant leg but both protocols decreased the functional H:Q ratio (Daneshjoo et al., 2012). Furthermore, no changes in the conventional H:Q ratio were observed after performing a 4-week eccentric exercise protocol involving different open or closed kinetic chain and antagonistic exercises (Brughelli et al., 2010). Two studies reported a shift to the optimal knee flexor peak torque toward to a more open angle position following a 4-week eccentric exercise intervention (Brughelli et al., 2010, Clark et al., 2005).

3.5. Discussion

The main finding of the current review is that multifaceted programmes including plyometric, balance, strength and/or agility exercises supported by appropriate feedback and technical indications seem to be more effective to positively modify biomechanical risk factors than protocols with no technical feedback, or involving only one mode of exercise. Furthermore, interventions using mainly strengthening exercises would improve muscle strength, H:Q ratios and/or promote a shift of optimal knee flexion peak torque toward a more open angle position, without further biomechanical modifications.

3.5.1. Landing

Kinetics and kinematics of the lower extremity during landing from vertical or rebound jumps, and from drop jump seem to be more modifiable compared to other testing manoeuvres such as side-cutting or stop-jump. Multifaceted interventions involving strengthening, balance, flexibility, plyometric or agility exercises, supported by appropriate feedback and technical corrections showed to be effective to improve hip (Chappell and Limpisvasti, 2008, Lephart et al., 2005, Pollard et al., 2006) and knee (Chappell and Limpisvasti, 2008, Herrington, 2010, Lephart et al., 2005, Lim et al., 2009) biomechanics. Conversely, when no feedback was used, less clear effects on knee kinetics during landing from single leg drop jump were observed (Ortiz et al., 2010). Indeed, a non-desirable increase of knee initial flexion angle during landing from single legged drop jump was observed after performing a protocol including plyometric and balance exercises with no technical feedback (Nagano et al., 2011). The lack of feedback and/or proper technical support during an unstable 1-leg landing task could have been the reason of the observed results. Furthermore, the improvements on landing technique after performing a 4-week protocol involving resistance, flexibility and balance exercises supported by verbal and video feedback did not ameliorate when a subsequent 4-week plyometric and agility protocol was implemented (Lephart et al., 2005). Nonetheless, Herrington (2010) observed a significant decrease of the knee valgus angle during landing from drop and stop-jump in female athletes after performing a 4-week progressive jump training programme supported with proper verbal and technique feedback.

Results from the previous investigations support the importance of proper feedback and technical correction to successfully improve landing biomechanics when performing protocols including different exercise modalities.

3.5.2. Side-cutting

All of the included studies reported no effects of the injury prevention protocols to modify lower limb biomechanics during side-cutting manoeuvres**.** Donnelly et al. (2012) used a two parallel group design to compare the effectiveness of an intervention including balance, plyometric, agility exercises supported by feedback and technical corrections to a contrast shadow-training group. Although positive changes on the knee biomechanics during planned and unplanned side cutting manoeuvres were observed, both protocols were equally effective, and therefore no advantage of implementing the preventive intervention was determined. Possibly, the low supervisor-to-participants ratio (1:40) together with the lack of specific side-cutting exercises including in the preventive protocol would explain the achieved results. Additionally, Wilderman et al. (2009) reported no effect of a 6-week progressive agility training to modify knee kinematics during a 45° side-step pivot manoeuvre. Perhaps the absence of specific exercises to address knee and hip flexion angles and the lack of feedback in regard to the knee and hip alignments would be the cause of the unsuccessful results. Moreover Zebis et al. (2008) were also unable to observe positive modification on a side-cutting manoeuvre after performing an 18-week neuromuscular protocol in elite handball and football female players. Maybe the high level of performance of the participants would have impeded further biomechanical improvements on the selected side cutting exercises.

In summary, an effective protocol to improve lower limb biomechanics during side cutting manoeuvres remains to be elucidated.

3.5.3. Stop-jump

Three studies using a 4-week (Kato et al., 2008, Herrington, 2010) or a 6-week (Chappell and Limpisvasti, 2008) multifaceted protocol including jumps and plyometric exercises combined with proper technical feedback improved knee valgus angle (Kato et al., 2008, Herrington, 2010) and moment (Chappell and Limpisvasti, 2008) during stop-jump. Conversely, a 9-week resistance-training programme with no technical feedback, although effective to increase quadriceps and hamstring strength, did not produce any biomechanical modification during stop-jump (Herman et al., 2009). The ineffectiveness of strength training alone to improve lower limb biomechanics during jump-related exercises was also observed in other studies (Trowbridge et al., 2005, McGinn et al., 2006). Nevertheless, meaningful biomechanical improvements have been observed when strength protocols are combined with proper technical instructions and feedback (Herman et al., 2009).

The above-mentioned studies support the notion of combining sport-specific exercises with proper technical feedback to promote correct execution and biomechanical improvements during stop-jump. In addition, the positive effect of strength training maybe amplified by proper technical support to the sports-specific actions.

3.5.4. Muscle strength

Eleven studies investigated the effect of resistance exercises alone (Brughelli et al., 2010, Clark et al., 2005, Herman et al., 2008), combined with balance (Naclerio et al., 2013), agility, speed (Holcomb et al., 2007), flexibility, jump (Lephart et al., 2005, Ortiz et al., 2010), plyometric and sprint training (Mendiguchia et al., 2014) or integrated within an standardized injury prevention protocol such as FIFA11+, Harmoknee (Daneshjoo et al., 2012) or Mandelbaum's Prevent Injury and Enhance Performance (Lim et al., 2009), Two interventions (Clark et al., 2005, Mjolsnes et al., 2004) using only the eccentric Nordic curl, improved hamstring strength along with a shift of the knee flexors maximal peak torque toward a more open angle position (Clark et al., 2005) and increase the functional H:Q ratio (Mjolsnes et al., 2004). Further increases on the hamstring torque relationship were reported when this particular exercise was combined with an eccentric (single-leg dead lifts) and an unstable closed chain exercise (forward lunges on a Bosu® balance trainer) (Naclerio et al., 2013). Additionally, substantial improvements in the functional H:Q ratio were observed after a 7-week neuromuscular protocol involving two eccentric exercises (Nordic hamstring and dead lift), plyometric and sprints (Mendiguchia et al., 2014). This multifaceted intervention induced twofold to threefold lower increases in quadriceps peak torque than in hamstring peak torque and consequently eliciting a meaningful increase of the functional H:Q ratio from 0.89 to 1.0.

A shift in maximal peak torque occurring at a more open knee angle position during both isokinetic flexion (+4º) and extension (+6.5º) was also observed as a results of a 4-week strengthening programme where the Nordic curl was combined with three predominantly quadriceps eccentric closed kinetic chain exercises (Brughelli et al., 2010). Conversely, (Holcomb et al., 2007) reported meaningful increases of the H:Q ratios, especially at greater velocities, in a group of female football players after performing a 6-week of a multifaceted programme including concentric but no eccentric hamstring exercises. As females have weaker hamstrings than men (Hewett et al., 2008), it could be possible that in this particular group of female football players, no regular resistance training exercisers, a strengthening protocol with no particular eccentric hamstring components would be enough to initially improve hamstring activation and diminish disproportionate quadriceps force imbalance. Indeed similar results were observed by Herman et al. (2008) in female team sport athletes, with no regular resistance training, who increased hamstring and quadriceps isometric strength after a 9-week resistance bands and exercise balls protocol including no hamstring eccentric exercises.

Only Daneshjoo et al. (2012) reported a non-desirable decrease of the H:Q functional ratio in both dominant and non-dominant limbs in male football players. This study analysed the impact of two specific injury prevention programmes (Harmoknee and FIFA11+) on conventional and functional H:Q ratio. Although no significant alterations were observed in the control and Harmoknee groups, participants allocated to the FIFA11+ showed a significant drop of the functional H:Q ratio from 0.83 to 0.49. The latest figures fall well below the recommended minimum threshold values of 0.89 on Biodex isokinetic dynamometer for preventing ACL injury in athletes (Holcomb et al., 2007). Although both Harmoknee and FIFA11+ protocols include different types of strengthening, balance, running, plyometric and agility exercises, FIFA11+ involves greater knee extension components along with a relative lower emphasis on hamstring eccentric movements (only 1 set of 3 to 15 repetitions of Nordic curl) and therefore would be emphasizing quadriceps concentric over hamstring eccentric actions. Additionally, the interventions used in this particular study have taken place during the competition period with no preseason component. This sequence has shown to be detrimental to attenuate the incidence of ACL injury in female athletes (Stevenson et al., 2015). Similarly, Lephart et al. (2005) reported a selective increase of quadriceps but not hamstring maximal peak torque in female team sport athletes after performing a multifaceted intervention excluding hamstring eccentric exercises. Conversely, Lim et al. (2009) using another mixed protocol involving flexibility, plyometric, agility and strength exercises including 3 sets of 10 repetitions of Nordic curl, reported a reduction of quadriceps peak torque along with a positive increase of the hamstring activation during jumping in female basketball players. Although the influence of H:Q ratio as a risk factor for hamstring injury has been questioned (Freckleton and Pizzari, 2013) lower values of both conventional and functional H:Q are still considered relevant risk factors for ACL injury (Myer et al., 2011). Additionally, given the multifaceted aetiology of both injuries the influence of H:Q ratios for increasing the risk of hamstring and ACL injuries should not be ignored.

In summary, hamstring eccentric exercises such of Nordic curl, alone or integrated with other exercise modalities (unbalance, strengthening, plyometric, agility, sprint or flexibility) would improve hamstring strength and increase H:Q functional ratio along with or a shift of optimal knee flexion peak torque toward a more open angle position. Nevertheless, less strength-conditioned athletes initially benefit from using multifaceted protocols including concentric hamstring, balance and other resistance exercises. Furthermore, in team sport involving a predominance of knee extension actions such as football or basketball it would be recommended to add hamstring eccentric exercises in order to balance the predominance of knee extension component resulted from the specific sport activities (i.e., jump-landing, stop-jump or side cutting manoeuvres).

The current systematic review revealed that the most common tasks used to evaluate the effectiveness of injury prevention protocols were single or double-leg drop jump, side-cut and vertical jumps. The single or double-leg drop jumps are limited to the assessment of the landing phase of a jump. Edwards et al. (2010) demonstrated that 60% of the variables were different when the landing phase of a jump was compared to the whole jump-landing. In addition, side-cut and vertical jump limit assessment of high intensity repeated movement that occur in sport specific tasks (Fort-Vanmeerhaeghe et al., 2017). Therefore, an alternative tool that monitor the whole jump-landing during repeated high intensity actions (such as tuck jump assessment) would be more reliable to evaluate the effectiveness of injury prevention programmes (Read et al., 2016, Fort-Vanmeerhaeghe et al., 2017).

Most of the included studies in this review utilised only the athletes’ body weight in order to guarantee higher participant compliance. Although exercising with no external resistance makes the programme easier to follow, a higher stimulus and possible greater adaptation could be obtained through a progressive protocol that increase the level of resistance using dumbbells, weight vest or flywheel devices.

3.5.5. Limitations and future studies

Seven studies were non-randomized single trials interventions (Chappell and Limpisvasti, 2008, Clark et al., 2005, Herrington, 2010, Holcomb et al., 2007, Nagano et al., 2011, Pollard et al., 2006, Zebis et al., 2008), while one study (Donnelly et al., 2012) used a two parallel group non-randomized comparison. The lack of a parallel control group and randomization creates potential discordance among groups and introduces inherent selection bias that is difficult to ignore.

All the included studies focused on very specific and relatively homogeneous populations, e.g. male Australian Rules football players (Clark et al., 2005) male professional (Brughelli et al., 2010) or amateur (Naclerio et al., 2013) football players; female national league division I basketball players (Herrington, 2010), etc. Maybe the specific training methods, including volume and intensity of different conditioning training, sport drills and competitive actions, body type, genetic variability, and other confounders would make it difficult to generalize results worldwide.

The uncertain effects of the analysed risk factors to attenuate the incidence of both HAM and ACL injuries impede to make real assertions about the benefits of the used protocols to reduce the injury rate, rather than to elicit supposed beneficial alterations in some of the analysed biomechanical and neuromuscular variables. In addition, from the analysed studies, it was not possible to evaluate the duration of effects and what would be optimal training dosage to maintain the obtained benefit over the complete season and between seasons. Futures studies using longer intervention periods lasting from more than 1 season should be designed in order to clarify proper dosage for maintaining and/or recover benefits on the analysed modifiable injury risk factors in team sports athletes.

3.6. Conclusions

Multifaceted programmes including eccentric hamstring exercises combined with other training modalities such as plyometric, balance, resistance, agility and/or flexibility exercises would promote positive modifications on the previously identified hamstring and ACL injury risk factors. The addition of appropriate technical feedback appears to be an essential component of the injury prevention protocols in team sport athletes.

Although the current systematic review demonstrated the effectiveness of multifaceted protocols to prevent hamstring and ACL injuries in team sports athletes, there is still no consensus on what is the ideal exercise combination and protocol design to achieve an optimal protective effect. Therefore, chapter 4 and 5 analyse the muscle activation patterns of the most common injury prevention exercises utilised in the reviewed papers to clarify how each component may affect the risk factors.

Chapter 4

Study 3- Analysis of the Hamstring Muscle Activation during Two Injury Prevention Exercises

4.1. Abstract

The aim of this study was to perform an electromyographic and kinetic comparison of two commonly used hamstring eccentric strengthening exercises: Nordic Curl and Ball Leg Curl. After determining the maximum isometric voluntary contraction of the knee flexors, ten female athletes performed 3 repetitions of both the Nordic Curl and Ball Leg Curl, while knee angular displacement and electromyografic activity of the biceps femoris and semitendinosus were monitored. No significant differences were found between biceps femoris and semitendinosus activation in both the Nordic Curl and Ball Leg Curl. However, comparisons between exercises revealed higher activation of both the biceps femoris (74.8 ± 20 vs 50.3 ± 25.7%, $p = 0.03$ d = 0.53) and semitendinosus (78.3 ± 27.5 vs 44.3 ± 26.6%, $p = 0.012$, d = 0.63) at the closest knee angles in the Nordic Curl vs Ball Leg Curl. Hamstring muscles activation during the Nordic Curl increased, remained high (>70%) between 60 to 40° of the knee angle and then decreased to 27% of the maximal isometric voluntary contraction at the end of movement. Overall, the biceps femoris and semitendinosus showed similar patterns of activation. In conclusion, even though the hamstring muscle activation at open knee positions was similar between exercises, the Nordic Curl elicited a higher hamstring activity compared to the Ball Leg Curl.

4.2. Introduction

The hamstrings, comprising biceps femoris (BF), semitendinosus (ST) and semimembranosus (SM), compose a bi-articular muscle group crossing the hip and knee joint that acts synergistically in extending the hip and flexing the knee during sprints related activities (Opar et al., 2012). Hamstrings are highly activated in sports involving deceleration, acceleration and jumping (Arnason et al., 2008) and represent one of the most frequently injured muscle groups in football (Woods et al., 2004, Monajati et al., 2016). Despite the complex aetiology, the occurrence of hamstring injury is associated with rapid actions involving hip flexion and knee extension, when the muscles are subject to high forces in combination with rapid muscle lengthening (Opar et al., 2012). In sprinting, hamstring injury occurs when hamstrings are actively lengthened and contract to decelerate the thigh and the lower leg to an angle of approximately 30° before extending the knee during the last half of the swing phase (Ditroilo et al., 2013, Heiderscheit et al., 2005). It is widely suggested that the repetition of fast eccentric muscle actions toward open knee angles results into accumulated microscopic muscle damage that may develop into an injury (Timmins et al., 2015).

Over the last decade, a large number of studies have investigated the effectiveness of injury prevention exercises in eliciting specific physiological adaptations aimed to attenuate sarcomere damage during repeated active lengthening actions (Brockett et al., 2001) along with an increase of hamstring strength at different knee angular positions (Opar et al., 2012). In addition to free weight and machine resistance exercises like dead lift (Heiderscheit et al., 2010, Timmins et al., 2015), trunk hyperextension or leg curl (Pollard et al., 2006, Holcomb et al., 2007), hamstring eccentric exercises (HEEs) using no external load such as Nordic Curl (NC) (Clark et al., 2005, Lim et al., 2009, Mjolsnes et al., 2004) and Ball Leg Curl (BLC) (Holcomb et al., 2007, Ortiz et al., 2010) have been proposed to be effective for increasing eccentric hamstring strength. Advantages of weight bearing exercises are as follows: 1) no additional equipment or facilities are required thus making the programme easy to follow, 2) they simulate the activity of daily living and 3) simulate the same tension on muscles that may occur during a sport activity. These advantages have prompted coaches to use weight-bearing exercises as a part of injury prevention protocols (Farrokhi et al., 2008). Conversely, the use of weight bearing exercises would not allow for individualised control of the overload, nor the application of a more intense stimulus that could be obtained through a progressive protocol using external resistances, such as dumbbells or weight vests.

Despite the aforementioned proposed effectiveness of NC and BLC for preventing hamstring injury, there is still a paucity of research that compares the differential level of activation of the individual hamstring muscles throughout the open knee angles during these injury prevention exercises.

Ditroilo et al. (2013) reported a higher level of BF activation during NC compared to a traditional maximal eccentric exercise performed on an isokinetic machine. However, in this study no other hamstring muscles were analysed. Iga et al. (2012) reported significant eccentric peak torque improvements and an increased capability to resist lengthening actions at more extended joint positions of the hamstrings of both limbs during NC after a 4-week progressive exercise programme involving only NC. More recently, Marshall et al. (2015) observed a statistically significant decrease in BF activation, but not of ST, during a 6-set of 5 repetitions NC-only exercise bout in 10 football players.

To the best of the authors' knowledge, no study so far has analysed and compared the patterns of hamstring activation over the knee open angles, where the majority of hamstring injuries occur, in two different exercises. Such an investigation would allow researchers, clinicians and coaches to quantify and monitor the training-related adaptations based on kinematic and electromyographic analysis. Therefore, the aim of the present study was twofold: (a) to analyse the pattern of eccentric hamstring activation of two commonly used hamstring strengthening exercises, NC and BLC, by measuring the activity of the BF and ST with respect to knee angles, (b) to determine differences in the level of BF and ST muscle activation between NC and BLC exercises. The achievement of the aforementioned objectives will allow coaches to determine whether the two analysed exercises are appropriate for strengthening the hamstrings at more open length and consequently protecting athletes from hamstring injuries.

4.3. Material and Method

4.3.1. Procedures

This study utilised a single-group repeated measures design, where 2 within-participant conditions, i.e. NC and BLC, were examined. Once considered eligible for the study, participants were required to attend the laboratory on two different occasions. On the first visit participants were assessed for body mass and height. In addition they were familiarised with both NC and BLC exercises. The second visit required participants' determination of the maximum voluntary isometric contraction (MVIC) before performing the NC and BLC exercise. The muscle activity of the BF and ST was monitored through the root mean square (RMS) surface electromyography signal amplitude (sEMG). To maintain a suitable balance between different possible order of treatments and minimise any confounding effects, the order of exercises was randomised in a controlled manner. Thus, half of the participants started with the NC and half with the BLC. The study was carried out in accordance with the guidelines contained in the Declaration of Helsinki and was approved by the University of Greenwich Research Ethics Committee.

4.3.2. Participants

Ten female football players from the English Women's Super League, second division (mean ± SD age 22 ± 4.7 yrs, body mass 56 ± 4.8 kg and body height 163 ± 5.4 cm) participated in this study. All participants were engaged in regular football training (3 sessions per week) for a minimum of 6 years and used resistance exercises as an essential component of their conditioning preparation during the last 12 months before the beginning of the study. Participants were excluded if they had: 1) hamstring injuries 6 months prior to the study; 2) history of knee injury; or 3) participated in any hamstring injury prevention programme during the last 12 months prior to the study. Before participating in this study, all players read and signed an informed consent form. They were also asked to refrain from caffeine ingestion and any unaccustomed or hard exercise during the 72 h before the assessment sessions.

4.3.3. Exercises description

Three trials of the NC and BLC were completed in randomised order. On the first visit participants were familiarised and shown the correct technique for each exercise. During the next visit the participants performed both exercises and received individual feedback. The remaining visit comprised the testing session that consisted of a 10 min warm up involving dynamic stretching, jogging, running and jumping exercises. Participants had 30 s rest between trials and 2 min rest between exercises to allow full recovery.

Nordic Curl - Participants began by kneeling on the floor with the upper body vertical and straight with the knee flexed to 90° and hip fully extended. A partner applied pressure on the heels in order to make sure that the feet kept contact with the floor throughout the movement. The participants began moving their upper body forward while keeping their hip extended (avoiding hyperextension) and slowly lowered their upper body and extended their knee trying to resist the fall by contracting their hamstring muscles. Arms were kept flexed with hands by the shoulders as long as possible and they would be pushed forward only if necessary to buffer the fall avoiding a violent landing of the body onto the ground at the final stages of the movement (Figure 10A).

Ball leg curl - Participants began by lying supine on the floor with their heels on the ball, knee extended and hands on the floor by their sides, palm facing down. They were asked to simultaneously flex their knee while rolling the ball toward themselves and lifting their pelvis from the ground to form a plank and maintain this position for about 1 s before slowly returning to the starting position by simultaneously extending the knee and lowering the pelvis (Figure 10B).

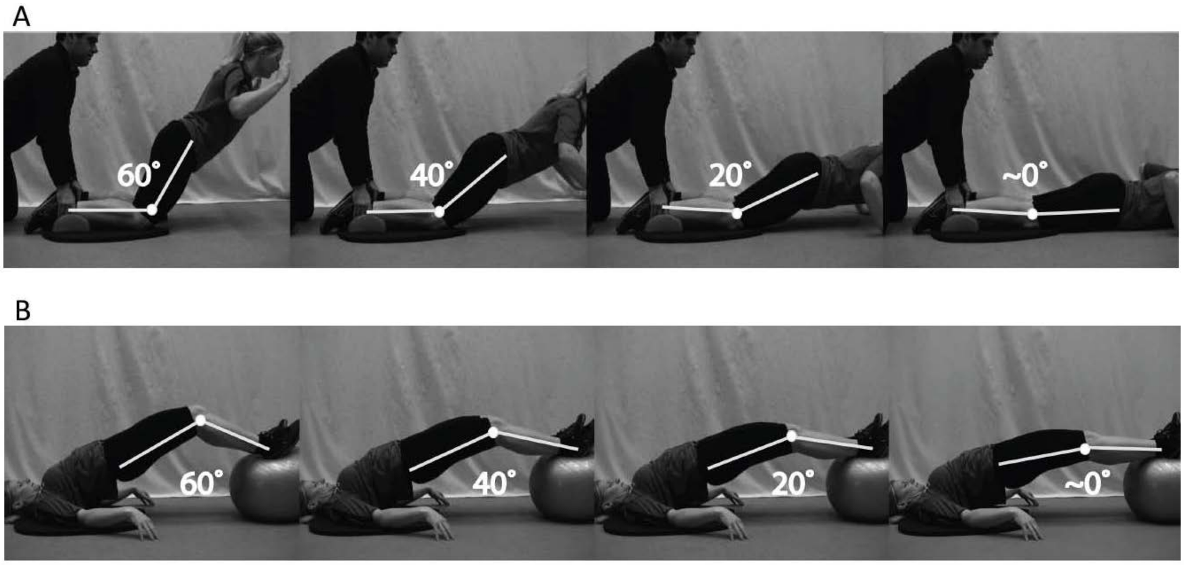

***Figure 10**, Nordic curl and Ball leg curl exercises*
A) Nordic Curl exercise, over the last 60° range of motion (60 to 0° of the anatomical angle) B) Ball leg Curl exercise, a descending phase performed over the last 60° of the range of motion (60 to 0° of the anatomical angle)

4.3.4. sEMG and Kinematic data collection

The dominant (preferred kicking) limb was selected for data collection. Prior to electrode placement, the skin was shaved abraded and cleaned with isopropyl alcohol. Parallel-bar EMG Sensors (DE-2.1, DELSYS, USA) were then placed over the BF and ST in accordance to SENIAM guidelines (Hermens et al. 2000). EMG signals were amplified (1 k gain) via a Delsys Bagnoli system (Delsys Inc. Boston, MA, USA) with a band-width of 20–450 Hz. The common mode rejection rate and input impedance were -92 dB and $>10^{15}\Omega$, respectively. Data was collected at 1000 Hz synchronously with the kinematic data.

Lower extremity planar kinematics was monitored using a 10-camera retroreflective system at 200 Hz (Oqus 3, Qualisys Gothenburg, Sweden). Four retroreflective soft markers (19 mm) were placed over the lateral malleolus, lateral knee joint, greater trochanter and acromion process of the dominant limb. Following tracking, kinematic and sEMG data were exported for analysis to Visual 3D (C-Motion Inc. USA).

4.3.5. Data processing

Sagittal plane knee angles were derived in Visual3D and all data processed in this trial was based on analysis within 20° movement epochs. For the purpose of this study, the exercises were analysed during the eccentric phase and over the knee open angles (> 60°). As a consequence each exercise was divided into 3 phases (phase 1, 60-40°; phase 2, 40-20°; phase 3, 20-0°) where 0 was defined as a fully extended knee joint. For each phase the RMS of the EMG amplitude data was calculated and then low pass filtered with the cut-off frequency of 6 Hz. The start of each phase for NC and BLC exercises was confirmed from the knee angle (Figure 10). Data were collected from 60° until the participants completed the eccentric phase for both the NC and BLC.

4.3.6. sEMG normalization procedure

In order to compare values of different muscle activation patterns, sEMG data were normalised as a percentage of the EMG signal recorded during a dominant leg maximum isometric voluntary contraction of the knee flexors (MVIC). The MVIC test was performed with participants in the prone position with knees flexed to 30° (anatomical angle)**.** The MVIC was held for 5 s and the peak 3 s of the EMG signal were used for normalization purposes. The muscle activity of the BF and ST was recorded and considered the reference value for normalizing EMGs measured during the NC and LBC tests.

4.3.7. Statistical analysis

A descriptive analysis was performed and subsequently the Kolmogorov-Smirnov and

Shapiro-Wilk test were applied to assess normality. Two independent 2 × 3 mixed analysis of variance (ANOVA) models, one per exercise (NC and BLC), were performed in order to determine differences in muscle activation between muscles (BF vs ST) over the three phases. Furthermore, two independent 2 × 3 mixed ANOVA models, one per muscle, were performed to determine differences in muscle activation between exercises and over the three phases.

Generalised eta squared (η_G^2) and Cohen´s *d* values were reported to provide an estimate of standardised effect size (small d = 0.2, η_G^2 = 0.01; moderate d = 0.5, η_G^2 = 0.06; and large d = 0.8, η_G^2 = 0.14). The level of significance was set at $p < 0.05$ for all tests.

4.4. Results

No main effects were observed between the activation of the BF and ST across the three analysed phases for both exercises, NC (F(1,18) = 0.046, p = 0.833) and BLC (F(1,18) = 0.387, p = 0.542).

4.4.1. Biceps Femoris Activation

No significant effect between exercises (F(1,18) = 2.20, p = 0.155, η_G^2 = 0.09) or interaction effects were determined for exercise and phases (F(1,18) = 3.42, p = 0.081, η_G^2 = 0.02). However, a significant main effect between phases (F(1,18) = 87.08, p < 0.001, η_G^2 = 0.36) was determined. Pairwise comparisons revealed significant differences (p < 0.001) and large effect sizes (phase 1 vs. 2, d = 1.38; phase 1 vs. 3, d = 1.78 and phase 2 vs. 3, d = 0.86) for the NC. A similar pattern was determined for the BLC, where the activation of the BF during both phase 1 (p < 0.001, d = 1.19) and 2 (p < 0.001, d = 1.11) was significantly higher than in phase 3, and a strong trend with a moderate effect size to produce a higher activation during the phase 1 compared to phase 2 was also determined (p = 0.058, d = 0.45). Furthermore, the activation of the BF during phase 1 was significantly higher in the NC compared to the BLC (74.8 ± 20 vs 50.3 ± 25.7%, p = 0.03, d = 0.53) (Figure 11A).

4.4.2. Semitendinosus Activation

Significant phase effects (F(1,18) = 50.79, p < 0.001, η_G^2 = 0.34) and interaction effects between phases and exercises (F(1,18) = 4.91, p = 0.040, η_G^2 = 0.05) were observed.

However, no main effects between exercises were determined (F(1,11) = 4.05, p = 0.060, η_G^2 = 0.14). Pairwise comparisons revealed significant differences and large to moderate effect sizes for both analysed exercises, i.e. NC (p < 0.001, phase 1 vs. 2, d = 1.58; phase 1 vs. 3, d = 1.48 and phase 2 vs. 3, d = 0.86) and BLC (phase 1 vs. 2 p = 0.036, d = 0.51; phase 1 vs. 3, p = 0.003, d = 0.78 and phase 2 vs. 3, p < 0.001, d = 0.96). Furthermore, the activation of the ST during phase 1 was significantly higher in the NC than in the BLC (78.3 ± 27.5 vs 44.3 ± 26.6%, p = 0.012, d = 0.63) (Figure 11B).

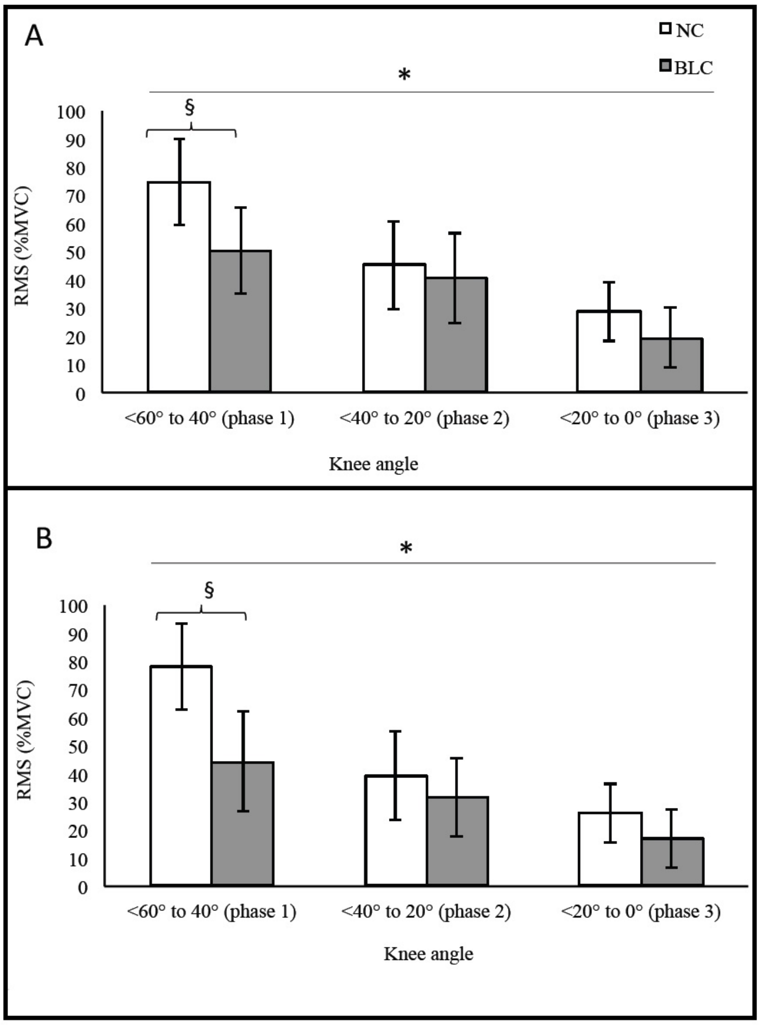

***Figure 11**, Biceps Femoris and Semitendinosus activation during Nordic Curl (NC) and Ball Leg Curl (BLC).*

*A) Biceps Femoris activation during Nordic Curl (NC) and Ball Leg Curl (BLC). (Mean ± 95% confidence intervals). * p < 0.001 between phases 1 vs 2; 1 vs 3 and 2 vs 3 for NC as well as 1 and 2 vs 3 for BLC. § p = 0.03 between NC and BLC at phase 1. B) Semitendinosus activation during NC and BLC. (Mean ± 95% confidence intervals). * p < 0.001 between phases 1 vs 2; 1 vs 3 and 2 vs 3 for NC and BLC. § p = 0.012 between NC and BLC at phase 1.*

4.5. Discussion

The main finding of the present study showed that for uninjured female football players the pattern of ST and BF activation during both the NC and BLC was similar throughout the knee open angles over the eccentric displacement. However, when comparing the level of muscular activation elicited by each exercise, the following differences were identified: 1) at the closest knee angle position (60-40°) the activation of both the BF (74.8 ± 20 vs 50.3 ± 25.7%) and ST (74.8 ± 20 vs 50.3 ± 25.7%) was greater in the NC compared to the BLC; 2) during the NC, the activation of hamstring remained high from 60 to 40° (~77% of the MVIC) and then significantly decreased from 40° to full extension (from 77% to 27% of the MVIC) and 3) the activation of hamstring was similar between the NC and BLC at the most extended angles (<40°).

Results from the present study provide an important insight into the understanding of the pattern of hamstring activation throughout the eccentric phase of the NC and BLC. The present investigation supports the finding of Zebis et al. (2013) who reported a very similar activation of the medial (ST) and lateral (BF) hamstrings during the NC and supine bridging exercises. The ST and BF have the ability to counteract the frontal plane applied force and help prevent an exaggerated knee varus and valgus mechanism during landing or changes of direction activities (Hubley-Kozey et al., 2006). Although the NC and BLC require a similar BF and ST activation, due to a shorter moment arm of the BF, the capacity of these muscles to generate torque is not equal (Lynn and Costigan, 2009). Therefore, in order to balance the force applied on the frontal plane, the BF must generate greater force compared to the ST. Due to this inherent imbalance, performing BF dominated exercises, such as hip extension and supine leg curl (Zebis et al., 2013), may help to achieve a balance between ST and BF torques in the frontal plane. Such enhancement in the balance between hamstrings torque on the frontal plane may help to prevent hamstring injury, improve knee stabilization and consequently reduce the risk of other knee-related injuries, such as anterior cruciate ligament laceration (Stevenson et al., 2015).

It is widely accepted that hamstring weakness and muscle imbalances increase the risk of HSI in athletes. Thus, hamstring-strengthening exercises should be considered as an essential component of the injury prevention programmes (Orchard et al., 1997, Thelen et al., 2005). The relative load applied to the musculoskeletal system positively influences strength. Heavy loads (3-5 RM) are associated with greater strength gains compared to lighter loads (9-11 RM) (Campos et al., 2002). The relative load recommended for novice and advanced individuals to improve muscle strength is about 60-70% and 80-100% of 1 RM, respectively (Guex and Millet, 2013). Our results indicated that during the NC, hamstring activity was significantly higher over the first phase (60-40°) of the range of motion and therefore, the NC would result in greater strength enhancement compared to the BLC. Even though hamstring activation of the two analysed exercises (NC and BLC) remained high from 60 to 40° knee angles, and then progressively declined toward the end of the movement, the observed decline was higher for the NC. These findings are in line with those reported by Ditroilo et al. (2013) who observed a control of the downward movement during the first half of the range of motion and peak velocity of the downward movement occurred at 44° of the knee angle. The above findings suggest that the NC exercise would be divided into the following two parts:

Part 1, from 60 to 40° knee angle (phase 1), where the movement is controlled, hamstring muscles resist knee extension and decelerate the downward movement of the trunk. Thus hamstrings are highly activated along with an eccentric controlled muscle action that peaked at the middle of the range of motion (60 to 40°).

Part 2, from the middle of the range of motion (knee angle 40°) until the end of the movement where the trunk approaches the ground (phases 2 and 3). As the trunk moves forward, the movement becomes progressively uncontrolled. The hamstring moment arm is shortening while the body mass moment arm is gradually lengthening (41% and 73% from 60° to 45° and 60° to 30°, respectively). Due to this biomechanical disadvantage, it is expected that hamstring activation will increase to overcome the greater load as the trunk leans forward. However, it is important to highlight that our results show a decreased hamstring activation during the last 40°. Therefore, the hamstrings fail to attenuate the increased torque and the downward moment is accelerated.

During the NC, the hamstring acts at the hip and knee simultaneously to resist knee extension as well as hip flexion. One possible explanation for the decreased hamstring activity during the late phase of the NC may be due to the high biomechanical disadvantage observed during the last 40° of the movement as hamstrings act mainly at the hip level to retain full hip extension and prevent uncontrolled falls. Furthermore, it is also possible that during the second part of the movement (phases 2 and 3), as the torque produced at the knee increases and overcomes the hamstring peak torque, the muscles cease resisting against the knee torque in order to avoid muscle strain and only act at the hip to prevent hip flexion. Therefore, the pattern of hamstring activation during the two aforementioned parts is distinctly different. During the first part the hamstring contracts to break knee extension, while during the second part the hamstring resists the hip flexion. Although speculative, it could be possible to hypothesize that as the capacity of the hamstring to apply force improves and its peak torque increases and shifts toward more flexed knee angles, the extension of the second part would progressively be reduced. Thus, before using the NC, coaches should consider the use of methodological exercise progression starting with relatively low demanding exercises as LBC or assisted Nordic Curl with a band attached to the participant's back in order to facilitate control of the overload during the last part of the range of motion (Naclerio et al., 2015).

Results of the present study also indicate a similar level of muscle activation (<45% of the MVIC) during the last 40° knee angles between the NC and BLC. It is widely accepted that the majority of hamstring injuries occur during the late swing phase of the sprint where the knee is at the more extended angle position (<40°) (Heiderscheit et al., 2005, Guex and Millet, 2013). Thus, in order to prevent athletes from hamstring injury, it is crucial to increase the overall hamstring strength, emphasising the capacity to apply force over the more extended knee angles. Nonetheless, the present results do not enable to evaluate the pattern of muscle activation when performing a typical injury prevention programme involving 3 to 5 exercises of 8 to 10 repetitions, or whether the level of muscle activation measured at the most extended angles by the two exercises is sufficient to reduce the incidence of hamstring injury in athletes.

During the eccentric phase of both analysed exercises, NC and BLC, hamstring muscles actively lengthen while the hip is fully extended (~ 0°) and the knees extend from 60° until the full extension position (~ 0°). However, during the late swing phase of a sprint cycle, the hip and knees are flexed to about 55-65° and 30-40°, respectively. Due to a greater hamstring moment arm determined at the hip compared to the knee, the effect of changing the hip angle on BF and ST length is much greater than that at the knee angle (Visser et al., 1990). Therefore, during the late swing phase, where the hip is flexed, the hamstring muscles achieve a higher overall stretch compared to the exercises analysed in the present study (NC and BLC). In addition, during the NC and BLC, knees extend progressively along with an extended hip, therefore hamstring muscles contract within their nominal upright length.

4.5.1. Limitations

The reference values for the muscle activity elicited during the analysed exercise were presented in terms of the percentage of the MVIC measured with knees flexed to 30° (open angle). Therefore it is not possible to evaluate whether the percentage of muscle activation produced by the tested exercises would be similar to that produced during the late swing phase of a sprint cycle, where the majority of hamstring injuries occur (Thelen et al., 2005).

Further investigations, using sprint as a reference exercise, would be needed in order to evaluate the relative degree of hamstring activation elicited by different proposed hamstring strengthening exercises.

4.6. Conclusions

The NC exercise elicited a higher level of hamstring activation compared to the BLC. The level of muscle activation during the NC (70-80% of the MVIC) suggests that performing the NC exercise would enhance hamstring muscle strength. In addition, the level of BF and ST activation was similar throughout the range of motion, which indicates that using any of the analysed exercises as may not result in muscle imbalances between the BF and ST.

During the NC and BLC, hamstring muscles activate within their resting length and therefore, it is not clear whether the analysed exercises would have the ability to simulate a similar pattern of muscle activation as occurred during hamstring strain related injuries, where muscles lengthen beyond their upright length.

This chapter demonstrated the benefits (ability to increase muscle strength) and shortcomings (activating within resting length) of NC exercise. In order to overcome the shortcomings of the current injury prevention exercises, a protocol involving new or modified exercises were designed and compared with a traditional injury prevention programme in chapter 6.

Chapter 5

Study 4- Surface electromyography analysis of three squat exercises

5.1. Abstract

Anterior Cruciate Ligament injury is the most commonly and frequently injured knee ligament in team sports. Several squat exercise modalities have been proposed to enhance knee stabilization and potentially prevent the injury. The aim of study was to perform an electromyography comparison of three commonly used lower limb injury prevention exercises: single-leg squat on a bench (SLSB), double-leg squat (DLS) and double-leg squat on a BOSU® balance trainer (DLSB). After determining the maximum isometric voluntary contraction of the hamstring and quadriceps, eight female athletes performed 3 repetitions of each exercise, while electromyography activity of the biceps femoris (BF), semitendinosus (ST), vastus lateralis (VL) and vastus medialis (VM) were monitored. Comparisons between exercises revealed higher activation in BF (descending; p=0.016, d=1.36, ascending; p=0.046, d=1.11), ST (descending; p=0.04, d=1.87, ascending; p=0.04, d=1.87), VL (ascending; p=0.04, d=1.17) and VM (descending; p=0.05, d=1.11, ascending; p=0.021, d=1.133) muscles for the SLSB compared to the DLS. Furthermore, higher muscular activation of ST, (ascending; p=0.01, d=1.51, descending p=0.09, d=0.96) and VM, (ascending p=0.065, d=1.03, descending p=0.062, d=1.05)] during the SLSB respect to the DLSB were observed.

In conclusion, single-leg squat on bench elicits higher neuromuscular activation in both hamstring and quadriceps muscles compared to the other two exercises. Additionally, the higher muscle activation of both medial muscles (ST and VM) during the SLSB suggests that single leg squatting exercises may enhance lower limb medial to lateral balance, and improve knee stability in frontal plane.

5.2. Introduction

The anterior cruciate ligament (ACL) plays an important role in stabilizing the knee (Guelich et al., 2016). The ACL injury is the most commonly and frequently injured knee ligament in team sports (Stevenson et al., 2015, Monajati et al., 2016). Although ACL injuries can be produced as a consequence of contact situations (e.g., an external load from other players), two thirds of ACL injuries are non-contact in nature (Alentorn-Geli et al., 2009a) and, thus, are potentially preventable (Chappell et al., 2002, Silvers and Mandelbaum, 2007). Unilateral landing involving exaggerated knee abduction (valgus) has been identified as one of the most frequent actions associated with the incidence of ACL injuries (Ireland, 1999, Boden et al., 2000). Indeed, similar body position with the knee close to full extension along with an external rotation of the tibia and foot planted have been identified as a common knee valgus mechanism (Olsen et al., 2004, Boden et al., 2000, Krosshaug et al., 2007). It has been suggested that neuromuscular deficits, muscle activation strategy and poor muscle coordination during high risk manoeuvres (unilateral landing, cutting, deceleration, etc.) can cause exaggerated valgus and consequently increase the risk of ACL injury (Hewett et al., 2005, Myer et al., 2005a, Ford et al., 2003). Dedinsky et al. (2017) stated that disproportionate quadriceps to hamstring activation might increase the load on the ACL and augment the risk of injury. Subsequently, a hamstring to quadriceps (H:Q) activation ratio of > 0.6 has been recommended as appropriate to decrease the risk of ACL injuries, whilst a ratio closer to 1 indicates higher activation of the hamstring in supporting the ACL to resist anterior tibia translation and to stabilise the knee. Furthermore, unbalanced medial to lateral muscle activation has been associated with increased knee valgus in the frontal plane (Myer et al., 2005a).

Due to the synergistic muscle actions involving a coordinated contraction of hamstring and quadriceps, several squat exercise modalities using different levels of stability (double or single leg squat on stable or unstable surfaces) have been proposed to enhance knee stabilization and potentially avoid excessive valgus and varus in athletes (Escamilla, 2001). For instance, unilateral and bilateral squatting exercises such as single (Ortiz et al., 2010, Daneshjoo et al., 2012) or double leg squat (DiStefano et al., 2009) and lunge (Lim et al., 2009) performed on stable and unstable (Donnelly et al., 2012, Naclerio et al., 2013) surfaces, or a combination of different squatting movements (Myer et al., 2006a) have been suggested as effective exercises to improve neuromuscular control and prevent ACL injuries in team athletes.

McBride et al. (2006) reported decreased muscle activation of both knee extensor and flexors muscles during isometric unstable squat compared to isometric normal squat. McCurdy et al. (2010) showed higher activation of hamstrings respect to the quadriceps during a single leg squat with respect to a double leg squat. Furthermore, De et al. (2014) compared the muscle activity of lower extremity muscle between double leg and single leg squat reporting similar muscle activation for the quadriceps muscle along with a higher activation of biceps femoris during double leg squat. The aforementioned studies utilised either absolute or relative load to monitor muscle activation. There is evidence that using external load would elicit higher muscle activation, strength and neural enhancement (Fisher et al., 2017, Schoenfeld et al., 2016). However, in an attempt to provide a time efficient and easy to follow protocol, team sports coaches have extensively used body weight exercises with no external additional load. In fact, most of the proposed prevention protocols such as FIFA11^{+}and Harmoknee (Lim et al., 2009, Daneshjoo et al., 2012) utilised the resistance provided by the athletes' body weight. Consequently, in order to have a full understanding of muscle activation profile during the most recommended preventive exercises an investigation focused on squatting exercise performing with no external load is required.

To the best of authors' knowledge no studies have investigated activation of both medial and lateral hamstring and quadriceps muscles during single leg squat on bench (SLSB), double leg squat (DLS), and double leg squat on a BOSU® balance trainer (DLSB). Such a study will provide useful information for properly selecting different squatting exercises in the design of injury prevention programmes. The aim of the present study, therefore, was to analyse the electromyography activation of biceps femoris (BF), semitendinosus (ST), vastus lateralis (VL) and vastus medialis (VM) during ascending and descending movement-phases in three different squatting exercise modalities: DLS, DLSB and SLSB.

5.3. Material and Method

5.3.1. Procedures

The present study utilised a single-group repeated measures design, with 3 within-participant conditions: DLS, DLSB and SLSB. Once considered eligible for the study and consented to participate, participants were required to attend the laboratory on two different occasions.

On the first visit, participants were assessed for body mass and height. In addition, they were familiarised with all the exercises. The second visit intended to determine participants' maximum voluntary isometric contraction (MVIC) before performing the DLS, SLSB and DLSB exercises. The muscle activities of BF, ST, VL and VM were monitored through surface electromyography (EMGs). To maintain a suitable balance between all the possible orders of treatments and minimise any confounding effects, the order of exercises was randomised in a controlled manner. The study was carried out in accordance with the guidelines contained in the Declaration of Helsinki and was approved by the University Research Ethics Committee.

5.3.2. Participants

Eight female football players from the English Women's Super League, second division (mean±SD age 21±4 yrs, weight 55±4.4 kg and height 163±4.1 cm) participated in this study. All participants were engaged in regular football training (3 sessions per week) for a minimum of 6 years, and were using resistance exercises as an essential component of their conditioning preparation during the last 12 months before the beginning of the study. Participants were excluded if they had: 1) hamstring injuries 6 months prior to the study; 2) history of a knee injury; or 3) participated in any hamstring injury prevention programme during the last 12 months prior to the study. Before participating in this study, all participants read and signed an informed consent. Participants were asked to refrain from caffeine ingestion and any unaccustomed or hard exercise during the 72-h before the assessment sessions.

5.3.3. Measures

Three trials of each exercise (DLS, SLSB and DLSB) were completed in a randomised order. On the first visit participants were familiarised and instructed the correct technique for each exercise. During the next visit, participants performed as many repetitions as needed to achieve a correct technique. Participants were shown and instructed to maintain a good upper body posture by retaining the natural lower back curve and avoiding excessive trunk flexion throughout the movement. The pace was also practiced and controlled using verbal pacing cue. The remaining visit comprised the testing session that consisted of a 10-minute warm up protocol involving dynamic stretching, jogging, running and jumping exercises.

Participants had a 30 s rest between trials of the same exercise and 2 minutes between exercises to allow full recovery.

5.3.4. Exercises description

DLS: participants standing on the floor with feet shoulder-width and arms crossed over the chest. They were asked to squat down to approximately 90° knee flexion. Participants were guided by a counter to perform the movement in five seconds; the first count indicated the start of the descending phase, and the third count indicated the lowest point of the squat (end of descending and start of ascending phase). They were asked to maintain the appropriate technique throughout the movement as they were instructed during familiarisation sessions (Figure 12A).

DLSB: participants were asked to stand on BOSU® balance trainer with feet shoulder-width and arms crossed over the chest. The same procedure as DLS was followed. The trial was accepted if participants maintain their balance keeping both feet on the BOSU® balance trainer device (Figure 12B).

SLSB: participants standing on a 30 cm high platform on their dominant limb were asked to squat down to approximately 60° knee flexion. An adjustable plinth was used during the DLS to determine the 60° knee flexion for SLSB. The same procedure as in the DLS test was followed to control the pace of movement. Trials were accepted if the participants succeeded to maintain their balance while keeping their non-stance foot off the floor and retain the proper technique as they were instructed during the familiarisation sessions (Figure 12C).

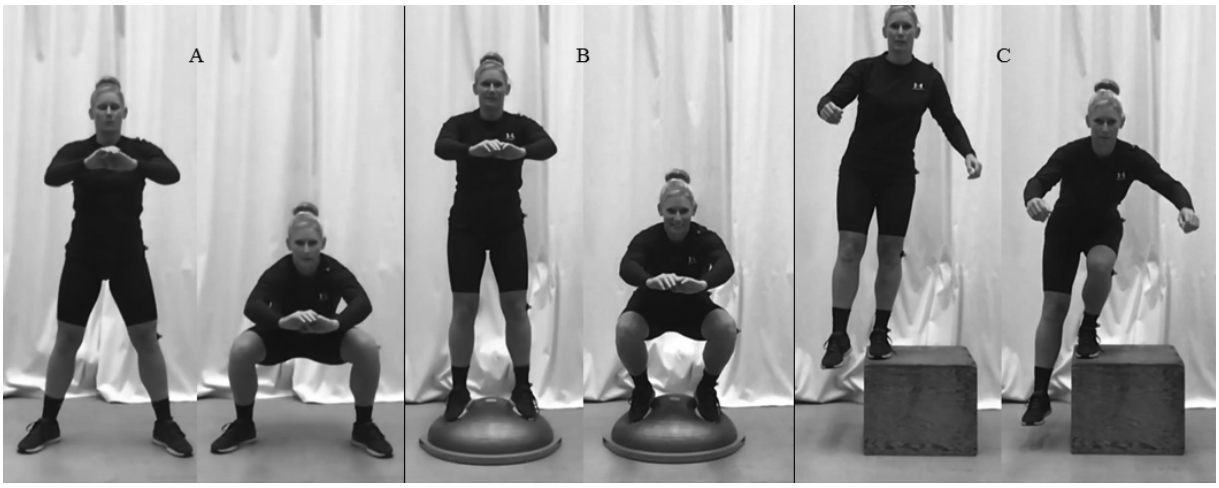

Figure 12*, Double-Leg Squat (A), Double-Leg Squat on BOSU 397 (B) and Single-Leg Squat on Bench (C).*

5.3.5. sEMG and Kinematic data collection

The dominant (preferred kicking) limb was selected for data collection. Prior to electrode placement, the skin was shaved, abraded and cleaned with isopropyl alcohol. Parallel-bar EMG Sensors (DE-2.1, DELSYS, USA) were then placed over the BF, ST, VL and VM in accordance to SENIAM guidelines (Hermens et al., 2000). EMG signals were amplified (1k gain) via a Delsys Bagnoli system (Delsys Inc. Boston, MA, USA) with a band-width of 20–450 Hz. Common mode rejection rate and input impedance were -92 dB and $>10^{15}\Omega$, respectively. Data was collected at 1000 Hz synchronously with the kinematic data.

Lower extremity planar kinematics was monitored using a 10-camera retroreflective system at 200Hz (Oqus 3, Qualisys Gothenburg, Sweden). Four retroreflective soft markers (19mm) were placed over the lateral malleolus, lateral knee joint, greater trochanter and acromion process of the dominant limb. Following tracking, kinematic and sEMG data were exported for analysis in Visual 3D (C-Motion Inc. USA).

5.3.6. Data processing

For the purpose of this study the exercises were analysed during both descending and ascending phases. The start and finish of the phases for all exercises were determined using vertical displacement of the greater trochanter marker. For each phase, RMS of the EMG amplitude data was calculated.

5.3.7. sEMG normalization procedure

In order to compare values of different muscle activation patterns, sEMG data were normalised as a percentage of EMG signal recorded during a dominant leg maximum isometric voluntary contraction of the knee flexors and extensors (MVIC). The MVIC test for knee flexors was performed with participants in the prone position with knees flexed to 30° (anatomical angle)**.** The Knee extensors' MVIC was performed with participants sat upright on a high bench with the knees flexed to 90° and hands grasping the edges of the bench for stabilization. MVIC were held for 5 seconds and the peak 3 seconds of EMG signal were used for normalization purpose. The muscle activity of the BF, ST, VL and VM was recorded and considered the reference value for normalizing EMG signals measured during the DLS, SLSB and DLSB tests.

5.3.8. Statistical analysis

A descriptive analysis was performed and subsequently the Kolmogorov-Smirnov and Shapiro-Wilk test were applied to assess normality. Four independent 3 (exercises) x 2 (phase) mixed ANOVA models, one per muscle, were performed to determine differences in muscle activation between exercises and over the two phases.

Generalised eta squared (η_G^2) and Cohen´s *d* values were reported to provide an estimate of standardised effect size (small d = 0.2, η_G^2 = 0.01; moderate d = 0.5, η_G^2 = 0.06; and large d = 0.8, η_G^2 = 0.14). The level of significance was set at $p < 0.05$ for all tests. The statistical analyses were performed using IBM SPSS v.22, and the generalised eta squared was calculated by hand as proposed elsewhere (Bakeman, 2005).

5.4. Results:

5.4.1. Biceps Femoris Activation

Significant main effects of exercises [F(2,14)=8.13, p=0.005, η_G^2=0.29] and phases [F(1,7)=17.33, p=0.004, η_G^2=0.14], and a significant interaction between exercises and phases [F(2,14)=3.97, p=0.043, η_G^2=0.04] were observed. Subsequent pairwise comparisons revealed significant higher activation and large effect size in SLSB compared to DLS during both descending (p=0.016, d=1.36) and ascending (p=0.046, d=1.11) phases. In addition, a strong trend (p= 0.078) and a high effect size (d=0.98), to produce a higher BF activation during the descendent phase in SLSB compared to DLSB was determined. Furthermore, a trend and large effect size to produce higher activation in DLSB compared to DLS during the ascending phase ($p=0.096$, $d=0.94$) was observed, Figure 13A. No other differences were determined.

5.4.2. Semitendinosus Activation

Significant main effect for exercises [$F(2,14)=13.39$, $p=0.001$, $\eta_G^2=0.31$] but not between phases [$F(1,7)=0.13$, $p=0.733$, $\eta_G^2 \approx 0$] or interaction of exercise and phases [$F(2,14)=0.08$, $p=0.792$, $\eta_G^2 \approx 0$] were determined. Pairwise comparisons showed higher significant activation and large effect size during the SLSB compared to DLS for both, the descending ($p=0.042$, $d=1.16$) and ascending ($p=0.04$, $d=1.87$) phases. In addition, significant or strong trend along with large effect sizes to produce higher ST activation in SLSB compared to DLSB during ascending ($p=0.01$, $d=1.51$) and descending phase ($p=0.09$, $d=0.96$), were also determined. Figure 13B.

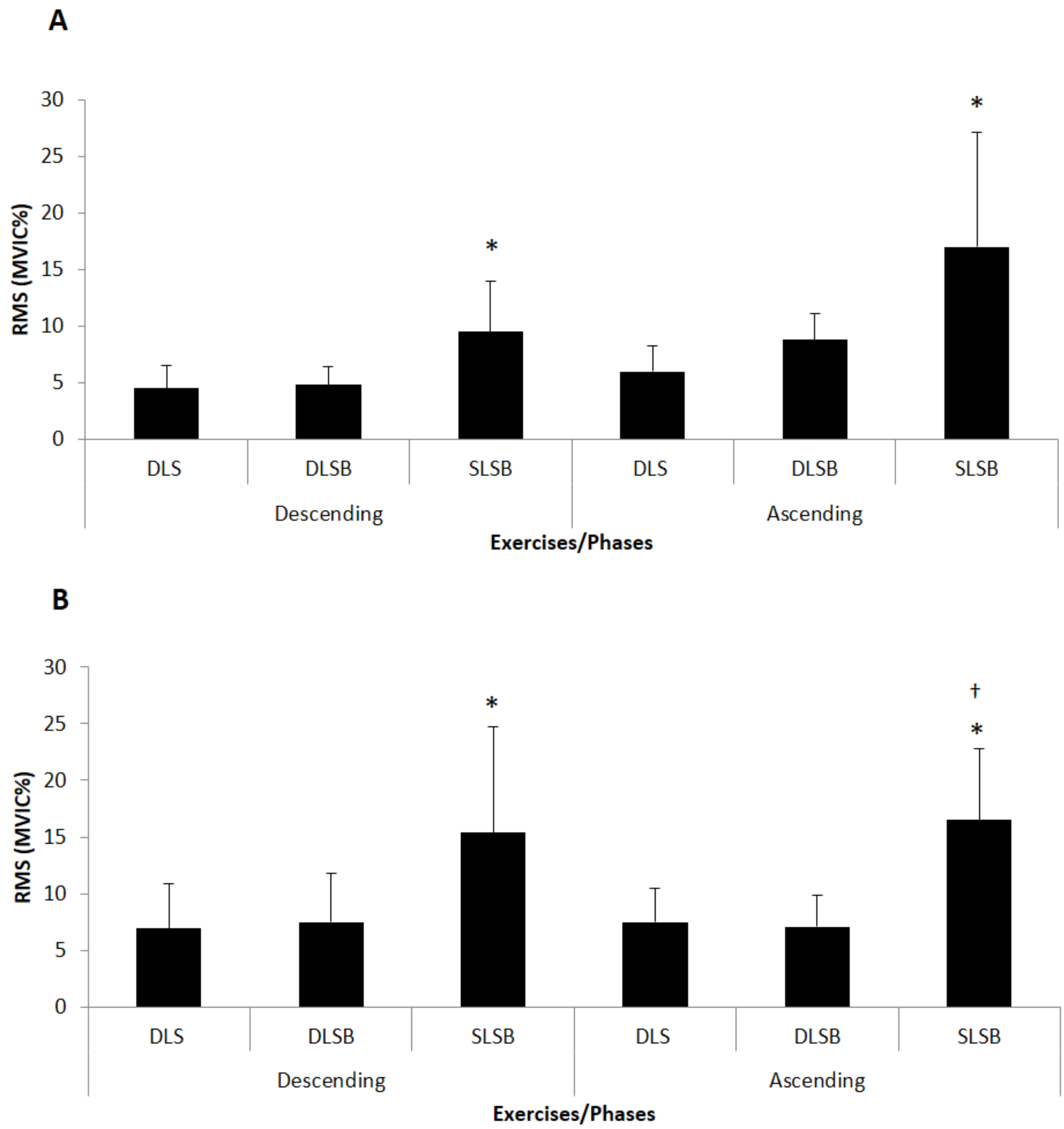

Figure 13*, Normalised EMG activity for the Biceps femoris (A) and Semitendinosus (B). (Mean ± 95% confidence intervals)*
** p<0.05 from SLSB to DLS during both phases for both biceps femoris and Semitendinosus*
† p=0.01 from SLSB to DLSB during the ascending phase for the Semitendinosus.
DLS: Double-Leg Squat, DLSB: Double-Leg Squat on BOSUR and SLSB: Single-Leg Squat on Bench

5.4.3. Vastus Lateralis Activation

Significant main effects of exercises [F(2,7)=5.78, p=0.015, η_G^2=0.12] and phases [F(1,7)=10.62, p=0.014, η_G^2=0.05] were observed. However, no significant interaction effects [F(2,14)=0.77, p=0.480, η_G^2≈0] was determined. Pairwise comparison demonstrated significant higher activation and large effect size in SLSB respect to DLS for the ascending phase (p=0.04, d=1.17), Figure 14A. No other differences were determined.

5.4.4. Vastus Medialis Activation

Significant main effect for exercises [F(2,14)=9.05, p=0.003, η_G^2=18] and phases [F(1,7)=23.97, p=0.002, η_G^2=0.07] but no interaction effects [F(2,14)=0.823, p=0.459, $\eta_G^2 \approx 0$] were determined. Pairwise comparison revealed higher activation and large effect size in SLSB compared to DLS during both descending, (p=0.05, d=1.11) and ascending (p=0.021, d=1.13) phases. Furthermore, strong trends and large effects sizes favouring a higher VM activation during the SLSB respect to DLSB during both, the descending (p=0.062, d=1.05) and ascending (p=0.065, d=1.03) phases were determined. Figure 14B

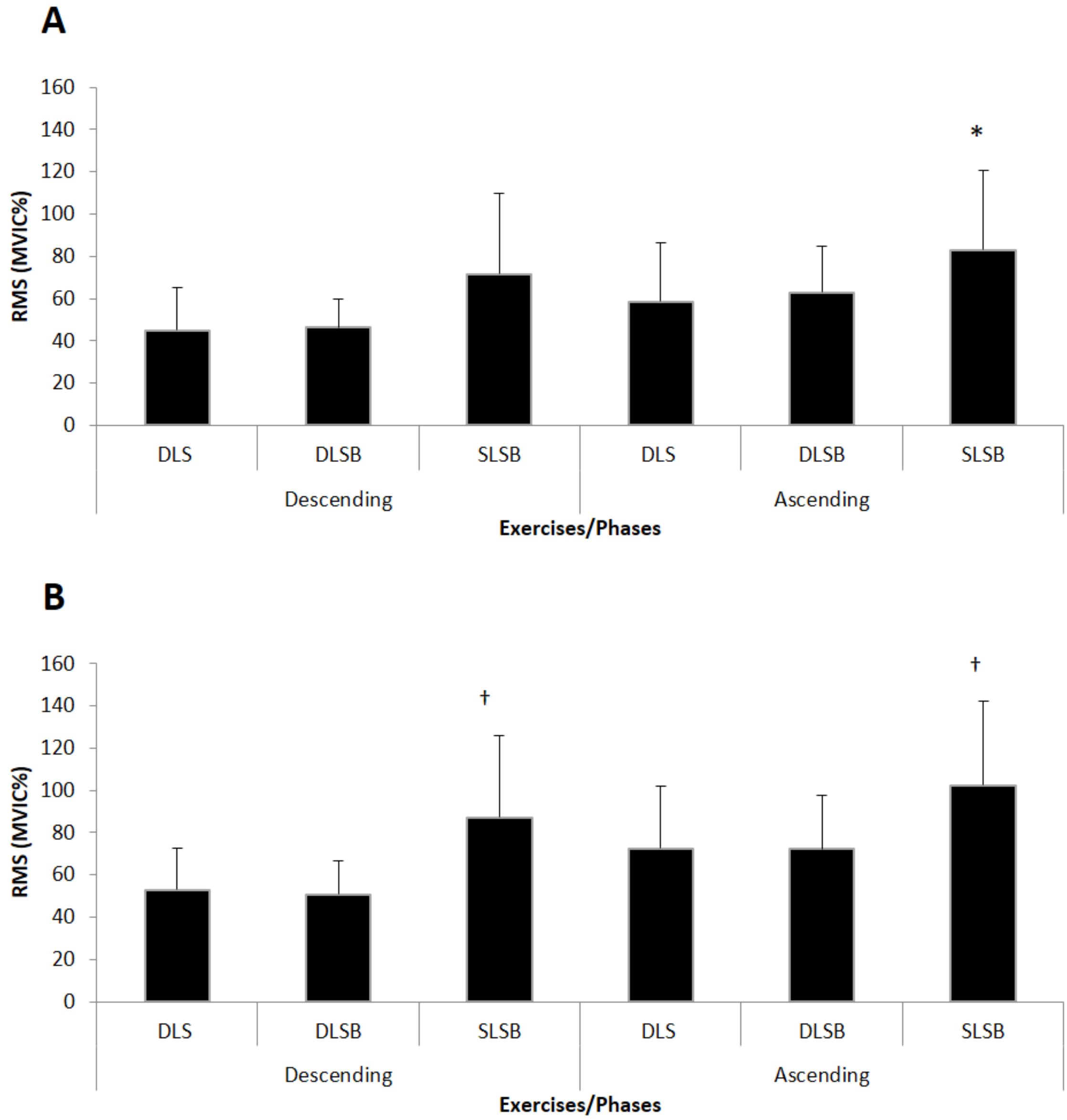

Figure 14, *Normalised EMG activity for the Vastus Lateralis (A) and Vastus Medialis (B).*
(Mean± 95% confidence intervals).
**p= 0.04 from SLSB to DLS during the ascending phase for Vastus Lateralis*
†p<0.05 from SLSB to DLS during both phases for the Vastus Medialis
DLS: Double-Leg Squat, DLSB: Double-Leg Squat on BOSUR and SLSB: Single-Leg Squat on Bench

5.5. Discussion

The present study compared the lower extremity muscle activation of three different squat exercises DLS, SLSB and DLSB. The main finding of the investigation was that SLSB elicits higher hamstring (BF and ST) and quadriceps (VM and VL) muscle activation compared to both DLS and DLSB. Additionally DLS and DLSB produced similar levels of hamstring and quadriceps activation during both the descending and ascending phases.

The observed results can be explained by the higher relative overload applied by the single-leg stance position during the SLSB. The increased overload would potentially augment the demand for activation of the lower limb muscles. In addition, associated postural changes may also be determining the higher muscle activity observed during SLSB. There is evidence that large relative mass of the trunk can potentially displace the centre of the body mass and influence the hip and knee loading during the unilateral squat (Horan et al., 2014, Hewett and Myer, 2011), and consequently result in the increased lower limb muscle activation. Considering that the body acts as an inverted pendulum, in which the centre of gravity is constantly displaced with the trunk muscles acting to maintain the balance (Gage et al., 2004), when reducing the weight-bearing support during SLSB, the trunk displacement would potentially increase. The degree of trunk displacement is associated with core stability and will be accentuated when the hip muscles are not strong enough to support the increased overload (Hewett and Myer, 2011). Therefore, the reduced support and concomitant increase of the trunk motion might be in part the reason for the increased muscle activation during SLSB.

Contrasting with the present study, De et al. (2014) demonstrated no differences in activation of hamstring and quadriceps between unilateral and bilateral squats. Furthermore, McCurdy et al. (2010) reported higher quadriceps and lower hamstring activation during unilateral respect to bilateral squat. In contrast to this study where participants squatted with no external overload (only the resistance provided by the body mass), both aforementioned studies used different levels of external resistance that was substantially higher for the bilateral compared to unilateral squat. Thus, the greater absolute overload using during the bilateral squat could have been caused the similar muscle activation elicited by the single-leg and double-leg squatting techniques used by two mentioned investigations. Other possible causes of discrepancies would be the variety of techniques used to perform the unilateral squat. There is evidence that position of the non-stance leg could significantly change the biomechanics of trunk, pelvic and lower extremity (Khuu et al., 2016). In the present study, participants were standing on a 30 cm high platform and the non-stance leg was extended throughout the movement. Conversely, the participants assessed by De et al. (2014) and McCurdy et al. (2010) were standing on their squatting limb, keeping the other limb elevated behind them (knee flexed) with their toes placed on a stable platform. The contribution of the non-stance foot, specifically during lower positions, may result in upright trunk position with less flexion of the hip that in turn reduce hamstring activation (Escamilla, 2001).

The present findings suggested no differences in the level of muscle activation when performing double-leg squat on stable compared to unstable surface. These results are in line with previous studies (Andersen et al., 2014, Anderson and Behm, 2005, McBride et al., 2006, Saeterbakken and Fimland, 2013, Wahl and Behm, 2008). Wahl and Behm (2008) reported no significant differences in the lower limb muscles activation when squatting on different unstable surfaces (ie, BOSU, Swiss ball, wobble board etc.). Andersen et al. (2014), showed no differences in muscle activation during double-leg squat on stable and unstable surface (cushion foam). On the other hand, Anderson and Behm (2005) found increased truck muscles activation (i.e. lumbosacral erector spinae and lower abdominal) when squatting on unstable compared to stable surfaces. Therefore, it is possible that the trunk, instead of the lower limb muscles, works as the primary stabilizer to maintain balance while squatting on unstable surfaces such as BOSU, foam cushion etc.

In the present study, both medial hamstring (ST) and quadriceps (VM) produced higher activation (with a large effect size, $d>1$) during the SLSB than DLSB in both, descending and ascending phases. Literature suggests that co-contraction of hamstring and quadriceps would decrease the load on ACL and potentially prevent ACL excessive overload (Hewett et al., 2010). Disproportional increase in activation of VL also may result in low quadriceps medial to lateral ratio, increase the anterior shear force and load the ACL (Myer et al., 2005a). In addition, high activation of the BF may combine with unbalanced quadriceps medial to lateral ratio and compress the lateral knee joint, resulting in dynamic valgus (Myer et al., 2005a). Serpell et al. (2015) showed that medial hamstring and quadriceps co-activation reduces knee rotation, abduction and translation. Despite the wide utilization of unstable exercises to prevent ACL injury, results from the present investigation indicate that SLSB elicits higher medial hamstring and quadriceps compared to both DLS and DLSB.

Therefore, using SLSB would be recommended for improving stability in the frontal plane and potentially prevent ACL injury.

Even though calculated medial to lateral activation ratio for both hamstring and quadriceps during the SLSB was adequate (>1), the produced Hamstring to Quadriceps H:Q activation ratio was very low (0.20) compared with the recommended ratio (0.60) to reduce ACL injury risk. The H:Q ratio observed in the present study for SLSB was in line with others. Dedinsky et al. (2017) reported H:Q activation ratio during unilateral squat between 0.17 and 0.39 in females. The low observed ratio would be due to the fact that females are often quadriceps dominant in functional movements and preferably activate their quadriceps over hamstring (Myer et al., 2005a). There is evidence that co-activation of quadriceps and hamstring can decrease the elongation stress on ACL and enhance knee stabilization (Cheung et al., 2012, Parulytė et al., 2011, Dedinsky et al., 2017). Therefore, SLSB might be beneficial in improving medial to lateral knee balance in the frontal plane, but the level of hamstring relative to quadriceps activation is not sufficient to decrease the quadriceps load on ACL.

In conclusion, SLSB elicited a high level of hamstring (BF and ST) and quadriceps (VL and VM) compared to other analysed exercises. The higher activation of both medial hamstring and quadriceps during SLSB suggested that performing this exercise might be more beneficial compared to DLSB to reduce the knee rotation, abduction and translation, and potentially decrease the risk of injury. However, results of the present study do not invalidate the benefit of unstable exercises, as they may increase activation of the trunk stabilizers and improve balance.

5.6. Conclusions

Despite the popularity of performing exercises on unstable surfaces to prevent injury, results from the present study suggest that performing SLSB may be more beneficial to improve the knee medial to lateral balance in the frontal plane. Nonetheless, as the observed H:Q activation ratio was below the recommended values, optimal injury prevention protocols should consider, a combination of single leg squatting exercises with other active lengthening hamstring movements, such as eccentric dead lift and Nordic Curl (Monajati et al., 2016).

The current chapter highlighted that single leg squat would be more beneficial than the other tested squatting exercises. Additionally, the benefits (adequate medial to lateral ratio) and shortcomings (low H:Q ratio) of unstable squatting to prevent ACL injuries were discussed. Chapter 6 presents a newly designed injury prevention programme to overcome the weaknesses of the current preventative exercises and compare that with a traditional injury prevention programme.

Chapter 6

Study 5- Comparison of Two Different Injury Prevention Programmes Based on Flywheel vs. Body Weight Resistance on Modifiable Risk Factors and Performance in Recreational Athletes

6.1. Abstract

The aim of the present study was to compare the effect of an injury prevention programme using flywheel (FY) or gravity-dependent (GT) exercises with no external overload on modifiable risk factors and repeated sprint ability. Eighteen recreationally trained volleyball players (FY, n=10; GT, n=8) completed 6 weeks of intervention. Both training programmes consisted of 2 sessions/week involving 2 sets of 8 repetitions for 6 exercises. The measured outcomes included a 10 s Tuck Jumps assessment (TJA) score, landing knee valgus score, hamstring and quadriceps concentric and eccentric isokinetic peak torque at $60°\cdot s^{-1}$, optimal peak torque localization, conventional and functional eccentric to quadriceps ratio and repeated shuttle sprint ability. Results of the study demonstrated that only FY group showed significant improvement in TJA (-2, IQR = -3 to -1) and valgus (-1, IQR = -1 to 0) scores, hamstring eccentric (20.37 N·m, 95% CI = 9.27, 31.47 N·m) and concentric (17.87 N·m, 95% CI = 0.40, 35.34 N·m) peak torque, as well as in mean repeated shuttle sprint time (0.28, 95% CI = -0.45, -0.10), while GT improved only the hamstring eccentric peak torque (21.41 N, 95% CI = 9.00, 33.82 N). In conclusion, a 6-week protocol using flywheel technology seems to provide better positive adaptations on some modifiable injury risk factors and repeated sprint ability performance respect to exercising with no external resistance other than athletes' body weight.

6.2. Introduction

Hamstring and anterior cruciate ligament (ACL) injuries are, respectively, the most prevalent (Opar et al., 2012) and serious (Stevenson et al., 2015) non-contact occurring injuries in team sports. Several preventive programmes involving jumps, strength, unstable or a combination of different exercise modes have been proposed to prevent both ACL and HAM injuries (Monajati et al., 2016).

Understanding mechanisms underlying these injuries is crucial for choosing suitable approach to develop effective preventive protocols. Researchers suggest that prior to a non-contact ACL injury, knee is extended along with an external rotation of the tibia, foot planted and knee abducted (valgus) and lateral compression occurs (Myer et al., 2005a). This compressive load combines with anterior force vector produced by quadriceps contraction, resulting in ACL rupture (Koga et al., 2017). Furthermore, most of the hamstring injuries occur when hamstrings are actively lengthening beyond their upright length (i.e., hip and knee at 0° flexion) to decelerate the forward movement of the tibia during the terminal swing phase of the sprint cycle (Yu et al., 2017). Based on the above described mechanisms Monajati et al. (2016) identified eight modifiable risk factors associated with the incidence of ACL and HAM injuries: i) knee valgus/varus angle and moment; ii) hip adduction/abduction angle and moment; iii) knee and hip rotation angle; iv) knee and hip flexion angle; v) hamstring and quadriceps muscle strength; vi) hamstring to quadriceps (H:Q) conventional and functional strength ratios; and vii) the angle at which the optimal knee flexor peak torque occurred. Current literature suggests that the most effective preventive protocols involve a combination of different exercise modalities (balance, plyometric, strength, flexibility), emphasizing active lengthening movement and a correct technique of execution (Monajati et al., 2016).

In order to increase implementation and compliance by coaches and athletes, a time-efficient and easy-to-follow comprehensive protocol is needed to successfully prevent injuries in team-sport athletes. Currently, most of the proposed prevention protocols, such as FIFA11^{+}and Harmoknee (Lim et al., 2009, Daneshjoo et al., 2012) utilize no external resistances apart from the athletes' body weight. However, there is evidence that utilizing external loads produce further neural adaptation, lead to larger muscle strength gains, and therefore it would be more effective in injury prevention (Guex and Millet, 2013). Consequently, several alternative methods including the use of non gravity-dependent technology have been recently proposed (Prieto-Mondragón et al., 2016). The isoinertial technology uses the inertia of a rotatory wheel and consequent stored kinetic energy to offer higher eccentric load compared to traditional weight training (Prieto-Mondragón et al., 2016). Norrbrand et al. (2010) demonstrated greater hamstring muscle activity and mechanical stress when performing hamstring exercises using an isoinertial flywheel-device compared to the typical weight stack machine. Askling et al. (2003b) reported a substantial decrease in a number of hamstring injuries along with improvement in 30 m sprint and muscle strength after a 10-week resistance-training using isoinertial technology. Finally, de Hoyo et al. (2015) reported substantial and possible decreases in incidence and severity of hamstring injuries, together with an increase in sprint performance in football players after a 10-week training with an isoinertial device. The aforementioned studies support the notion that, in addition to its preventive effect, the isoinertial technology may also enhance performance in athletes.

To the best of the authors' knowledge, no studies have analysed the effect of an injury prevention protocol including a range of exercises performed with isoinertial technology (flywheel devices), on modifiable risk factors and performance. The aim of the present study, therefore, was to compare the effect of an isoinertial technology vs. a traditional gravity-dependent exercise protocol on modifiable factors associated with the incidence of ACL and hamstring injuries in athletes. In addition, the potential effect on sprint performance was also considered.

6.3. Study Design

This study used a two parallel group randomized controlled pre-post design. Once considered eligible for the study, participants were randomly allocated into two intervention groups: 1) flywheel (FY) and 2) gravity dependent (GT) injury prevention protocols. After completing two sessions of familiarization and the pre-intervention assessment, the participants were matched for age, sex, hamstring and quadriceps isokinetic peak forces, and then randomly assigned to one of the groups by block randomization, using a block size of two.

6.4. Methods

6.4.1. Participants

Twenty college volleyball players (10 males and 10 females) met the requirements to participate in this study. Participants were excluded if they had 1) hamstring injuries 6 months prior to the study; 2) history of knee injury; or 3) participated in any injury prevention programme during the last 12 months.

Both groups participated in their normal volleyball training sessions twice a week in addition to the intervention protocols. The University Research Ethics Committee approved the study. All procedures were in accordance with the Helsinki declaration. Prior to providing written informed consent, participants were fully informed of the nature and risks of the study. Presented as mean (SD), the initial groups characteristics were as follows: FY: age 22.6±2.33 years, height 175.3±7.38 cm, body mass 69.9±8.26 Kg, hamstring and quadriceps peak torque 96.6±18.54 N·m and 154±32.12 N·m, respectively; GT: age 21±1.41years, height 176.9±6.44 cm, body mass 70.6±7.34 kg, hamstring and quadriceps peak torque 101.4±29.46 N·m and 157.7±38.47 N·m.

6.4.2. Familiarisation

Participants attended the laboratory on two different occasions. On the first visit, participants were assessed for body mass and height, and familiarized with all the testing procedures and exercises. In addition, they were instructed on how to use the flywheel devices (YoYo Squat and Versa-Pulley).

During the second visit, participants performed as many repetitions as needed to achieve a correct technique for each exercise and were instructed about the assessment procedures.

6.4.3. Training protocol

Participants in both groups completed 12 training sessions over 6 weeks (two sessions per week on alternate days). After a warm-up, all the participants performed 2 sets of 8 repetitions with two minutes of active rest (walking or slight movements) of each of the six exercises included in both (FY and GT) protocols. Workouts were completed in less than 25 min. All training sessions occurred during the afternoon with close monitoring by experienced strength and conditioning coaches.

6.4.3.1. *Isoinertial programme*

Two flywheel devices, YoYo Squat (Inertial Power SRL, Argentina) and Versa-Pulley (Versa-Pulley portable; VersaClimber, UK), were used to perform the following six exercises; 1) Double leg Squat, 2) Single leg Squat 3) Straight leg deadlift 4) Leg curl 5), Lunges 6) Hip extension. The isoinertial technology is a gravity independent system that uses the moment of inertia of a rotatory wheel over the concentric phase whilst braking to resist against the accumulated kinetic energy until stopping the wheel at the end of eccentric phase (Prieto-Mondragón et al., 2016).

Participants were instructed to apply maximum force during the concentric phase and resist the braking during the eccentric phase (Askling et al., 2003b, de Hoyo et al., 2015, Norrbrand et al., 2010). The YoYo Squat device was equipped with a 6.5 kg flywheel with a moment inertia of 0.13 kg/m^2, and the Versa-Pulley's moment inertia was 0.22 kg/m^2.

Double leg squat: Participants wore a vest equipped with a pulley guiding the strap onto the shaft holding the flywheel. At the starting position, participant stand on the YoYo Squat platform with feet shoulder-width apart and arms crossed over the chest. The rotation of the flywheel was initiated by squatting up from half squat position (knee ~90°). Once the concentric phase was completed the subsequent eccentric muscle action was executed by gently resisting in the first third of the action, and then, by resisting the pull of the strap, aimed at bringing the flywheel to a stop at about 90° knee angle then again performed concentric phase as fast as possible (de Hoyo et al., 2015), figure 15A.

Single leg squat: The same procedure as for double leg squat was followed to perform the exercise, figure 15B.

Straight leg deadlift: The starting position involved the barbell (attached to the flywheel through a strap) making light contact with the anterior portion of both legs, with the tibias aligned in a vertical position. During the exercise, the knees remained extended while the participants were instructed to maintain their spine in a neutral position throughout the range of motion. The arms were held just outside of the thighs. The concentric phase started by extending the hip to ~0° flexion (anatomical angle) and then resisting the flywheel rotation during the eccentric phase until returning to the starting position, figure 15C.

Leg curl: From an initial prone position (hip ~140° anatomical angle), the participants performed a unilateral leg curl, ranged from 0° to ~130° knee flexion, by accelerating and decelerating the flywheel through a concentric, and subsequently eccentric action of hamstrings. For this particular exercise, during the eccentric phase the participants were instructed to start resisting the descendent movement when the knee reached about 90° (de Hoyo et al., 2015), figure 15D.

Lunges: Participants stood straight facing the Versa-Pulley while holding the attachment. They were then asked to perform alternating lunges while keeping their elbows fully extended and stand erect through the movement (Tous-Fajardo et al., 2016), figure 15E.

Hip extension: Lying supine, hip ~ 80° and knee lightly flexed, participants extended their hip until the heel touched the floor, and resisted the hip flexion movement during the eccentric phase until returning the initial position. Core muscle activation was emphasized during the exercise, and the free leg was blocked to prevent lifting (Mendez-Villanueva et al., 2016), figure 15F.

Figure 15*, Six exercises performed by the isoinertial group*
Double leg squat (A), Single leg squat (B) Straight leg deadlift (C) Leg curl (D), Lunges (E), and Hip extension (F)

6.4.3.2. Gravity-dependent programme

Participants performed the following exercises: 1) Single leg jump, 2) Single leg land, 3) Jump lunge, 4) Single leg deadlift, 5) Ball leg curl and 6) Nordic curl. All the exercises were performed with no external resistance.

6.4.4. Measurements and control of the intervention compliance

Assessments were performed in one individual session and following the subsequent order: 1) Body mass and height, 2) Isokinetic dynamometry, 3) tuck jump and 4) repeated shuttle sprint ability. Prior to the testing session, participants were instructed to refrain from any vigorous activity and avoid caffeine ingestion for at least 48 hr. All tests were performed at the same time of the day for each participant. Identical testing procedures were repeated at the end of the intervention. The post assessment session was performed no later than a week after completing the last workout. Only participants who completed the 12 workouts with a training frequency of 2 sessions per week were included in the analysis.

7.4.4.1. Isokinetic dynamometry

An isokinetic dynamometer (Humac Norm, CSMI, Stoughton,USA) was used to measure peak torque and angle of peak torque during knee flexion and extension. The isokinetic test was carried out only for the dominant leg, which was determined as the participants preferred leg to kick a ball for distance. The right leg was the dominant leg for 9 of 10 subjects in the FY and all for the subjects in the GT group.

The isokinetic protocol consisted of quadriceps concentric, hamstring concentric and hamstring eccentric tests performed at a movement velocity of $60^{0}·s^{-1}$. This velocity was chosen to enable reliable and safe measurement for the selected sample (Coombs and Garbutt, 2002, Mjolsnes et al., 2004). Participants completed a standardized warm-up including jogging, dynamic stretch, and two sets of 50% and 80% of their perceived maximum effort. They then performed 3 maximum repetitions for each test with 2 minutes of rest between them. Participants were instructed to sit on the dynamometer with their hips at approximately 80^{0} (Guex et al., 2012) and with the upper body secured with dual crossover strap. The knee range of motion was set from 0^{0} to 105^{0} (0^{0} full extension position). Thigh and ankle straps were used to restrict thigh lateral movement and stabilize the lower leg, respectively. In addition, to ensure an accurate assessment of peak torque angle, a hand-held goniometer was used to standardize the knee full extension between testing sessions. The data obtained from the isokinetic tests were used to calculate conventional and functional H:Q ratios. The functional and conventional ratios were respectively determined by dividing either the maximal eccentric or concentric hamstring peak torque by the maximal concentric quadriceps peak torque.

7.4.4.2. Tuck jump assessment (TJA)

Five minutes after completing the Isokinetic test, participants underwent the TJA test consisting in 10 s of continuous maximal height tuck jumps (Fort-Vanmeerhaeghe et al., 2017). All tests were recorded from frontal and sagittal planes. The assessment involves the analysis of ten quantitative and dichotomous items from both frontal and sagittal view (table 5). Participants scored zero, one or two (magnitude of score) for each criterion described in table 5. These criteria are used to assess the risk factors related to the incidence of ACL injury (Myer et al., 2008). The modified style of the test as described by (Fort-Vanmeerhaeghe et al., 2017) that showed high Intra- and Inter-Rater Reliability, was carried out. A researcher, blinded to training status and groups, analysed the video recorded for each of the participants and scored them according to the modified TJA criteria.

Table 5*, Scoring criteria for each item of the Tuck Jump Assessment.*

Criterion	Scores		
	0	1	2
1. Lower Extremity valgus at landing	No valgus	Slight Valgus	Obvious valgus: Both knees touch
2. Thighs do not reach parallel (peak of jump)	The knees are higher or at the same level as the hips	The middle of the knees are at a lower level than the middle of the hips	The whole knees are under the entire hips
3. Thighs not equal side-to-side during flight	**Thighs equal side-to-side**	**Thighs slightly unequal side-to-side**	**Thighs completely unequal side-to-side (one knee is over the other)**
4. Foot placement not shoulder width apart	Foot placement exactly shoulder width apart	Foot placement mostly shoulder width apart	Both feet fully together and touch at landing
5. Foot placement not parallel (front to back)	Foot (the end of the feet) placement parallel	Foot placement mostly parallel	Foot placement obviously unparalleled (one foot is over half the distance of the other foot/leg)
6. Foot contact timing not equal (Asymmetrical landing)	Foot contact timing equal side-to-side	Foot contact timing slightly unequal	Foot contact timing completely unequal
7. Excessive landing contact noise	Subtle noise at landing (landing on the balls of their feet)	Audible noise at landing (heels almost touch the ground at landing)	Loud and pronounced noise at landing (contact of the entire foot and heel on the ground between jumps)
8. Pause between jumps	Reactive and reflex jumps	Small pause between jumps	Large pause between jumps (or double contact between jumps)
9. Technique declines prior 10 seconds	No decline in technique.	Technique declines after five seconds	Technique declines before five seconds
10. Does not land in same foot print (Consistent point of landing)	Lands in same footprint	Does not land in same footprint, but inside the shape	Lands outside the shape

7.4.4.3. Repeated shuttle sprint ability test (RSSA)

Fifteen minutes after the TJA, participants performed the modified repeat shuttle sprint ability assessment. The test involved 6 repetitions of 30 m (4 x 7.5 m with 180º turn) shuttle sprint separated by 20 s of passive recovery. Timing was recorded via photocell timing gates (Brower Timing Systems, HaB International Ltd, UK). Two seconds prior to each sprint, participants were asked to assume the starting position while the front foot was placed 0.5 m before the timing gate. This test was modified from previous protocols (Buchheit et al., 2010, Impellizzeri et al., 2008), and was chosen because it requires rapid acceleration, deceleration and change of direction with a short recovery to simulate the high intensity actions during athletic tasks. Strong verbal encouragement was provided through the sprint. Two scores were calculated: 1) best sprint time, and 2) mean sprint time (determined by the average of the six shuttle sprints).

7.4.5. Statistical Analysis

A power analysis for the sensitivity of the final sample size was calculated assuming a model with 2 groups and 2 repeated measures, 0.05 type I error probability (α), and 0.80 power (1-β), to ensure adequacy of the study. A descriptive analysis was performed and subsequently the Kolmogorov-Smirnov and Shapiro-Wilk test were applied to assess normality. Sample characteristics at baseline were compared between conditions (FY vs. GT) using an independent means Student`s t-test. Pre, post, and change continuous data were summarized as mean (SD), whilst ordinal data for the TJA and valgus scores, as median (interquartile range). Differences in change from pre- to post-treatment were assessed using one-way Analysis of Covariance (ANCOVA) between groups and adjusted for baseline values and sexes, and Wilcoxon's rank-sum test, respectively. Confidence intervals (CI) of the adjusted differences were calculated and presented. Additionally, one-sample Student's t tests were used to test for null effect hypotheses. Eta squared (η^2) values were reported to provide an estimate of standardized effect size (small η^2=0.01; moderate, η^2=0.06; and large η^2=0.14 values were used as reference). Significance level was set to $p<0.05$. Results are reported as mean (SD) unless stated otherwise. Data analyses were performed with the IBM SPSS software package v.20.0 for Windows.

6.5. Results

Due to reasons not related with the investigation, 2 participants (1 male and 1 female) allocated in GT group did not complete the study. All the remaining athletes in the FY (n=10, 5 males and 5 females) and GT (n=8, 4 males and 4 female) completed all the training sessions and were included in the final analysis. Consequently, the final composition of the two groups was balanced (50% women and men) and equivalent at baseline.
Table 6 summarizes the pre and post absolute values, the calculated adjusted differences from baseline and between treatment conditions.

***Table 6**, Mean (M) and standard deviation (SD) of pre, post values and corresponding differences adjusted by the pre values and sexes in the analysed variables for the two intervention groups*

Variables	Isoinertial Group			Traditional bodyweight group			Between-Groups ANCOVA or Rank-sum test
	Pre	Post	Adjusted changes [95% CI]	Pre	Post	Adjusted changes [95% CI]	
Hamstring eccentric peak torque (N·m)	127.20 (38.62)	147.40 (46.25)	20.37 [9.27, 31.47] **	131.13 (36.13)	152.75 (50.90)	21.41 [9.00, 33.82] *	F(1,14)=0.018, p=0.895, η^2=0.001
Hamstring concentric peak torque (N·m)	96.6 (18.54)	113.8 (44.25)	17.87 [0.40, 35.34] *	104.5 (29.46)	113 (33)	7.66 [-11.93, 27.25]	F(1,14)=0.677, p=0.425, η^2=0.046
Quadriceps concentric peak torque (N·m)	154 (32.12)	163 (32.31)	7.16 [-11.38, 25.71]	165.25 (3847)	173 (42.55)	10.04 [-10.74, 30.83]	F(1,14)=0.048, p=0.829, η^2=0.003
Hamstring optimum peak torque (N·m)	28 (14.15)	21.7 (8.27)	-5.30 [-11.81, 1.20]	24.63 (10.22)	27.63 (11.75)	1.75 [-5.53, 9.03]	F(1,14)=2.380 p=0.145, η^2=0.145
H:Q conventional ratio	0.63 (0.08)	0.71 (0.28)	0.07 [-0.08, 0.22]	0.63 (0.07)	0.65 (0.07)	0.02 [-.15, 0.19]	F(1,14)=0.261, p=0.617, η^2=0.018
H:Q functional ratio	0.82 (0.19)	0.90 (0.19)	0.08 [-0.02, 0.19]	0.79 (0.12)	0.87 (0.16)	0.07 [-0.05, 0.19]	F(1,14)=0.02 p=0.886, η^2=0.002
Best RSSA	8.49 (0.67)	8.24 (0.63)	-0.23 [-.40, -0.53] *	8.24 (0.46)	8.25 (0.5)	-0.02 [-0.21, 0.18]	F(1,14)=2.77, p=0.118, η^2=0.16
Mean RSSA	8.72 (0.68)	8.43 (0.60)	-0.28 [-0.45, -0.10] *	8.41 (0.50)	8.41 (0.56)	-0.02 [-0.22, 0.18]	F(1,14)=3.94, p=0.067, η^2=0.22
TJA Score, median (IQR)	9 (7, 11)	6.5 (5, 9)	-2 (-3, -1) **	7 (6, 9)	6.5 (5.5, 7.5)	-1 (-1, -0.5)	Z=2.056, p=0.039
Knee Valgus, median (IQR)	2 (1, 2)	0.5 (0, 1)	-1 (-1, 0) **	1.5 (1, 2)	1.5 (1, 2)	0 (0, 0)	Z=2.899, p=0.004

Notes: data are presented as pre and post values, and individual change from baseline to follow up adjusted for baseline assessment and sex. P-values for individual changes were adjusted by Bonferroni's method and tested the null hypothesis that adjusted differences equal 0. Descriptive values of TJA and V are median (interquartile range), and the comparison between groups was performed using Wilcoxon rank-sum test.

**p<0.05 **p<0.01 compared to zero difference*

Only FY produced positive changes in TJA, valgus and RSSA scores. Although both groups increased hamstring eccentric peak toque, only FY produced a significant rise of the hamstring concentric peak torque. At post-intervention, the FY group showed a significant lower valgus (p=0.004) and TJA (p=0.039) along with improved RSSA performance (p=0.067, η^2=0.22) compared with GT.

6.6. Discussion

The main finding of the present study indicates that the FY protocol enhanced TJA score, improved landing technique by reducing valgus and enhancing RSSA performance. Even though both protocols showed no significant changes in the optimal hamstring peak torque angle or both the conventional and functional H:Q ratios, the FY group increases hamstring concentric and eccentric peak torque meanwhile the GT improved only the hamstring eccentric peak torque.

The TJA is an assessment tool monitoring 10 criteria to identify high-risk mechanisms (i.e. valgus) and screen neuromuscular control during repeated landing. One of the important scoring criteria of the TJA is lower extremity valgus at landing. In fact, valgus is considered one of the most common risk factors for ACL injury (Myer et al., 2006b) . The present results showed significant post-intervention improvement in valgus score during TJA for the FY group. Despite the popularity of including mainly bodyweight exercises in the preventive protocols (Lim et al., 2009) our findings suggest that 6 weeks of GT were not enough to significantly modify the biomechanical factors associated with changes of the valgus and TJA scores. On the same lines, Pollard et al. (2006) reported no differences in knee valgus after implementation of a preventive bodyweight exercises programme throughout a football season. Furthermore, Nagano et al. (2011) observed no change in knee valgus after 5 weeks of a similar bodyweight based preventive intervention. Lephart et al. (2005) demonstrated that knee valgus at landing remained unchanged after 8 weeks of a preventive programme using no external resistance. Finally, Klugman et al. (2011) reported that a 10-week of an in-season only bodyweight preventive protocol did not change the TJA score above and beyond the control group. The positive effect of the FY training to reduce the valgus score, might be due to the higher eccentric overload offered by isoinertial technology compared to exercising with no additional resistance rather than the body weight. During the concentric phase, athletes produce and store kinetic energy in the system by rotating the flywheel through concentric action. The kinetic energy stored at the end of the concentric phase rotates the flywheel back forcing the trainee to resist decelerating and stopping the wheel through an eccentric action. Unlike the gravity dependent method, isoinertial technology ensures the accommodated resistance and optimal muscle loading at any particular joint angle through the entire concentric phase. Therefore, the kinetic energy accumulated at the end of the concentric phase is higher than the energy achieved when performing the typical gravity dependent exercises (i.e., lifting and jumps) (Tesch et al., 2017). Consequently, the higher overload created during eccentric phase by the both isoinertial-flywheel systems impose a superior workload on the muscles increasing the level of muscle activity during the eccentric portion of the movement. The enhanced TJA score and the reduced valgus showed by the FY group suggests that using isoinertial technology would be an alternative to improve neuromuscular control and protect athletes from injuries.

The increased hamstring eccentric and concentric strength measured in both groups could be explained by the inclusion of hamstring specific exercises such as Nordic curl or leg curl for the GT and FY protocols respectively. Mjølsnes et al. (2004) observed increased hamstring eccentric and isometric strength following 10 weeks Nordic curl exercises. Furthermore, 10 weeks leg curl exercise on a YoYo Squat device significantly increased hamstring concentric and eccentric muscle strength. The present results indicated that a 6-week GT or FY protocol would be enough to improve hamstring eccentric strength. However, despite the increased hamstring strength, H:Q functional and conventional ratio remained unchanged for both training conditions. The observed results can be explained by the inclusion of a variety of exercises requiring the synergistic activation of hamstring and quadriceps in the two intervention programmes. Therefore, improvement in quadriceps strength, even though non-significant, may have attenuated any expected increase of the H:Q ratios.

The effectiveness of training using isoinertial technology on sprint performance has been reported by previous investigations. de Hoyo et al. (2015) demonstrated significant improvement in 20 m sprint and counter movement jump following a 10-week programme involving squat and hamstring leg curl using a YoYo Squat device. Furthermore, Askling et al. (2003b) reported improvement in 30 m sprint performance following a hamstring specific training using an leg curl isoinertial device. However, to the bets of authors' knowledge, the present study is the first investigation to report improvement in RSSA following 6 weeks of training using isoinertial technology. Athletic actions such as sprinting and change of direction require acceleration and deceleration in horizontal plane (de Hoyo et al., 2015). The importance of specificity to transform power training to sport specific related task has been addressed previously (Young, 2006). Performing exercises such as lunge using a Versa-Pulley machine, which requires high intensity acceleration and deceleration in horizontal plane might be the reason for the observed improvement in the shuttle sprint test.

In conclusion, compared to exercising with gravity-dependent exercise using the resistance offered by bodyweight, a 6-week injury prevention programme exercising with isoinertial technology seems to elicit better positive adaptations on some modifiable hamstring and ACL injury risk factors as well as to enhance RSSA performance in female and male volleyball players.

6.7. Practical Applications

The present findings may have implications for future injury prevention protocols aiming to reduce the risk of hamstring and ACL injuries in athletes. It seems that a 20-minute program, involving 6 multifaceted exercises performed with isoinertial technology, implemented twice a week during a period of 6 weeks is effective to enhance lower body strength and repeated sprint ability. This programme would also be effective to improve landing technique reducing the degree of valgus in team sports athletes.

Chapter 7

GENERAL DISCUSSION

The studies conducted for the present thesis have focused on the analysis of the effectiveness of injury prevention protocols to modify the ACL and hamstring biomechanical and neuromuscular risk factors. Several programmes used different exercise modalities such as strength, balance, plyometric or agility integrated within protocols using athletes' body weight rather than external resistance (i.e., FIFA 11^+), or specific devices (i.e., resistance band, weight, flywheel machine) have been suggested as effective methods to reduce the incidence of injuries (Askling et al., 2003a, Herman et al., 2008, Daneshjoo et al., 2012).

The preliminary study compared the effect of eccentric (ECC) versus unstable (UNS) exercises on hamstring strength and torque-angle relationship. The results revealed that although both ECC and UNS increased hamstring strength, the effect of interventions on knee flexors torque-angle relationship was significantly different. The ECC group increased the peak torque at more open knee angles (<45°) while UNS enhanced the strength at more closed angles (>60°). These findings are in a line with previous investigations. For example, Kilgalon et al (2007) demonstrated improvement in hamstring muscle strength at more open knee angles (< 50°) but not at close angles (>50°) after completing 3 weeks hamstring eccentric exercises. Furthermore, Naclerio et al. (2013) demonstrated that hamstring eccentric training combined with unstable exercises increase hamstring strength throughout the knee range of motion, from 35° to 80° knee angle, and potentially prevent both ACL and hamstring injuries. In addition, Myer et al. (2005b) and Opar et al. (2012) reported exercises that requires synergistic contraction of hamstring and quadriceps, such as exercise in the UNS group, would help to increase the knee stability and protect athletes from ligament injuries.

Therefore, the combination of active lengthening hamstring exercises (ECC) with unstable training (UNS) does not eliminate the positive effect of eccentric exercises on hamstring injury risk factors, and might also have a preventive effect on other injuries too. Hamstring muscles are ACL-agonist providing knee stabilisation in dynamic movements and resistance to anterior translation of the tibia. However, medial and lateral hamstring muscles' function in frontal plane are different (Lynn and Costigan, 2009). Due to their difference in insertion sites, medial hamstring (ST) contributes to knee internal rotation whereas lateral hamstring

(BF) rotates the knee externally (Hubley-Kozey et al., 2006). There is evidence that adequate balance between medial and lateral hamstring muscles in frontal plane helps knee stabilization and potentially prevent knee injuries (Myer et al., 2005a). Since different hamstring exercises, even with a similar kinematics, activate the muscles differently (McAllister et al., 2014), it is not clear whether the exercises in the ECC would affect the hamstring medial to lateral ratio. Findings from the preliminary study suggested opposing adaptation in response to injury prevention programmes involving different exercises: emphasising hamstring active lengthening vs. unstable squatting. The observed contrasting results led us to conduct a systematic review of the literature (study 2) aimed to clarify the effect of different preventive strategies to modify ACL and hamstring risk factors.

Study 2 identified seven modifiable risk factors; i) knee valgus/varus angle and moment; ii) hip adduction/abduction angle and moment; iii) knee and hip rotation angle; iv) knee and hip flexion angle; v) hamstring and quadriceps muscle strength; vi) hamstring to quadriceps (H:Q) conventional and functional strength ratios; and vii) knee angle at peak torque, that have been monitored by researchers to evaluate the effectiveness of an injury prevention programmes. Additionally, the study revealed that multifaceted programmes are the most successful to positively modify the ACL associated risk factors, and strength training is an effective component of injury prevention programmes to create protective adaptation for preventing hamstring injury in athletes. More specifically, emphasised hamstring eccentric exercises, showed promising effect on hamstring injury risk factors such as muscle strength, H:Q ratio and shift in maximal peak torque toward more open knee angles. However, when exercises that emphasise hamstring activation are combined with other exercise modalities such as jump, balance etc., the obtained results were contradictory. For instance, the Harmoknee and FIFA11+ (Daneshjoo et al., 2012), two popular injury prevention programmes, combined hamstring eccentric exercises, Nordic curl, with balance, running and jump training, and revealed significant reduction in H:Q functional ratio. Furthermore, when Nordic curl was combined with unstable exercises (lunge on Bosu and single leg deadlift), additional increases in hamstring peak torque along with change in torque-angle relation were observed (Naclerio et al., 2013). The above results demonstrated that the particular effects of some type of exercises might be attenuated or expanded when combined with other movement patterns.

Although the association of the aforementioned risk factors with the incidence of injury have been previously reported (Hewett et al., 1996, Alentorn-Geli et al., 2009a, Hewett et al., 2005), the degree of contribution of each singular risk factor within a multifactorial approach on the injury rate is still not clearly determined. In fact, some of the reviewed manuscripts in the systematic review showed conflicting results on risk factors after completing a similar preventive protocol. Pollard et al. (2006) demonstrated favourable change in hip kinematics (i.e., hip abduction and internal rotation) but not in knee kinematics (i.e., knee flexion angle and valgus) after completing a multifaceted preventive exercise on female athletes, whilst, Chappell and Limpisvasti (2008) reported desirable effects of a multifaceted programme on knee kinematic (knee flexion angle) but not on hip kinematic (hip abduction) in female athletes.

Epidemiological and video analysis studies revealed that unilateral landing (unequal side-to-side contact time) involving exaggerated knee abduction (valgus) is the most frequent actions associated with the incidence of ACL injuries (Ireland, 1999, Boden et al., 2000). Indeed, similar body position with the knee close to full extension along with an external rotation of the tibia and foot planted have been identified as a common knee valgus mechanism, figure 16. Myer et al. (2005a) stated that dynamic valgus during repeated high intensity manoeuvres may lead to the valgus collapse and ACL rupture. Therefore, based on the evidence it would be rational that injury prevention exercises aim to avoid dynamic valgus during the task that simulates high intensity, sport-specific actions. The most common tools used in the review papers were single or double-leg drop jump, side-cut and vertical jumps. The single or double-leg drop jumps are limited to the assessment of the landing phase of a jump. Edwards et al. (2010) demonstrated that 60% of the variables were different when the landing phase of a jump was compared to the whole jump-landing. In addition, side-cut and vertical jump limit assessment of high intensity repeated movement that occur in sport specific tasks (Fort-Vanmeerhaeghe et al., 2017). Therefore, an alternative tool that monitor the whole jump-landing during repeated high intensity actions (such as tuck jump assessment) would be more reliable to evaluate the effectiveness of injury prevention programmes (Read et al., 2016, Fort-Vanmeerhaeghe et al., 2017).

***Figure 16**, lower extremity kinematic prior to ACL injury (Hewett et al., 2005, Koga et al., 2010)*

Understanding the effect of each component of an injury prevention protocol solely or in combination with other exercises will provide useful information to design an effective prevention programme. The inconsistent results of the effectiveness of exercises alone (i.e., Nordic curl) or a combination of different exercises modalities (multifaceted programme such as FIFA 11^{+}) highlights that, to optimize the effect of preventive protocols, it is important to understand how each component affect the neuromuscular adaptation. Several investigations monitored the hamstring and quadriceps muscle activations when performing different movements (McCurdy et al., 2010, McBride et al., 2010, Andersen et al., 2014). However, the effects of injury prevention exercises performed with no external load (bodyweight only) on hamstring and quadriceps activation patterns have not been reported previously. Therefore, from the injury prevention prospective it is important to evaluate lower extremity muscle activation when performing bodyweight training. Consequently, two observational studies aimed to evaluate the lower extremity muscle activation during five common preventive exercises were conducted.

Study 3, analysed the muscle activity of the biceps femoris (BF) and semitendinosus (ST) during Nordic curl (NC) and Ball leg curl (BLC). Findings indicate that the level of hamstring (BF and ST) activation during the NC was higher than that in Ball leg curl and would be adequate to enhance muscle strength, however, during both exercises hamstrings are activating within their upright length (knee and hip angle ~ 0°). There is evidence that hamstring injury occur when muscles are actively lengthening (~12%) beyond their upright length. Therefore, an alternative movement that has the ability to activate hamstring muscles beyond their upright length, and simulate similar muscle activation that occurs during hamstring injury, may optimise the effect of a preventive protocol. In addition, BF and ST showed very similar activation patterns during both NC and BLC. Due to the shorter moment arm of the BF compared to ST, the capacity of these two muscles to generate force is not equal (Lynn and Costigan, 2009) , and consequently, BF must generate more force to balance the torque production in frontal plane and stabilize the knee. This biomechanical disadvantage of the BF, shorter moment arm, might be the reason for the higher rate of injury compared to other hamstring muscles.

Results from study 3 suggested that to optimise the effect of an injury prevention protocol 1) exercises that actively lengthening hamstring beyond their upright length and 2) BF dominant movements, to overcome the biomechanical disadvantage of BF compared to ST, need to be included in preventive protocols.

Study 4, analysed the muscle activity of BF, ST, vastus lateralis (VL) and vastus medialis (VM) during three commonly used squatting exercises; single-leg squat on bench (SLSB), double-leg squat (DLS) and double-leg squat on a BOSU® balance trainer (DLSB).

The main finding of the study was that both hamstring and quadriceps muscle activity was higher in SLSB compared to other two exercises. Additionally, the activity of both medial muscles (ST and VM) was higher during SLSB compared to the other two exercises. Previous investigations highlighted the role of hamstring and quadriceps medial muscles (ST and VM) to reduce knee rotation, abduction and translation (Serpell et al., 2015). Low medial to lateral quadriceps ratio combined with disproportional activity of lateral hamstring may result in compression of the lateral knee and open the medial joint. The compression load combined with anterior force vector produced by quadriceps muscle will result in ACL torn, figure 17 (Koga et al., 2010, Myer et al., 2005a). Therefore, it is crucial that injury prevention programmes integrate exercises involving a high level of hamstring and quadriceps medial to lateral balance. These activities will increase knee stability and prevent lateral knee compression.

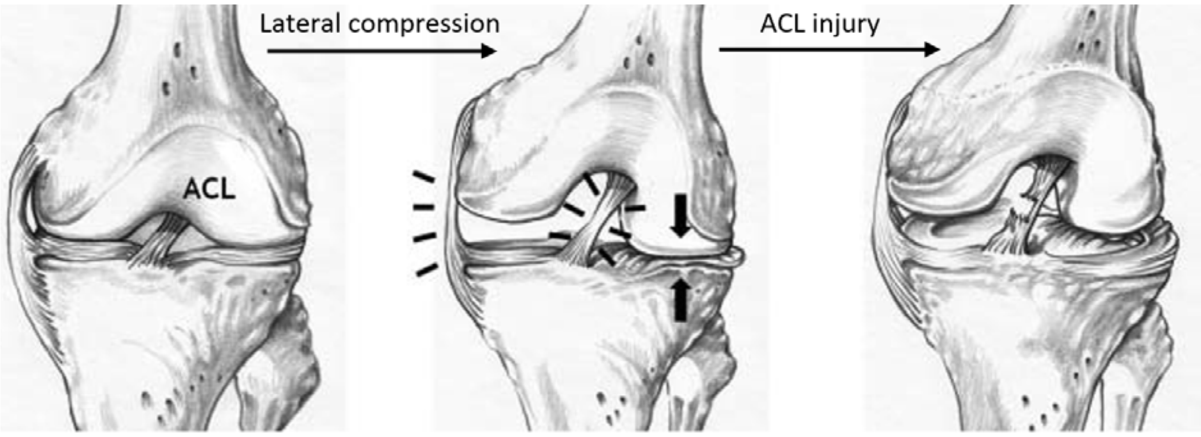

Figure 17 *knee lateral compression, due to imbalanced medial to lateral hamstring and quadriceps, combined with quadriceps anterior vector results in ACL tor (Koga et al., 2010).*

Results from the study 4 demonstrated that despite the popularity of performing exercises on unstable surfaces (i.e., squat on unstable surface), unilateral squat exercises (i.e., single leg squat on bench) are the important component of an effective injury prevention protocol and can potentially enhance knee balance in the frontal plane.

Another important consideration from the injury prevention prospective is to provide knee dynamic stability by co-activation of the hamstring and quadriceps muscles, and consequently, reduce the load on ACL. During dynamic stabilization of the knee if the load applied by quadriceps is higher than the load exerted by hamstring muscles the tibia will be translated anteriorly causing an excessive overload on the ACL (Hughes and Dally, 2015).

Current literature suggests that hamstring to quadriceps activation ratio greater that 0.6 is adequate to prevent ACL injury (Dedinsky et al., 2017). However, the results of the 4th study demonstrated that when performing unilateral squat H:Q ratio (~0.2) is lower than the recommended ratio. Although this exercise may enhance the knee balance in frontal plane and potentially prevent knee lateral compression, the observed H:Q ratio will not be adequate to decrease the quadriceps load and prevent ACL injury. Therefore, combining unilateral squat with hamstring active lengthening exercises, such as Nordic curl or deadlift, will help to improve the H:Q ratio.

To increase the chance of implementation and compliance of injury prevention programmes, most of the proposed preventive interventions utilised no external resistance and only athletes' bodyweight. Although exercising with no additional weight makes programmes easier to follow and may increase the chance of implementation by players and coaches, higher stimulation could be achieved if additional load is applied during training. There is evidence that utilizing external load produces further neural adaptation, increases muscle strength and is more effective to prevent injuries (Guex and Millet, 2013). The isonertial technology is one of the latest trends in resistance training and offers higher eccentric load compared to other training methods such as free weights or machines. This technology generates resistance by opposing to the trainee's effort with the inertial force generated by a lightweight rotating flywheel such that the same inertia must be overcome during each repetition by means of accommodated loading (Norrbrand et al., 2008). This inertia is determined by mass, configuration and diameter of the rotatory wheel (Tesch et al., 2017). This technology ensures accommodated resistance, and provided effort is maximal, optimal muscle loading at any particular joint angle through the entire concentric action. The kinetic energy, produced during the concentric phase, is decelerated in a restricted portion of eccentric action, force exceeding that generated during the corresponding concentric phase must produce eccentric overload (Norrbrand et al., 2008, Núñez and Sáez de Villarreal, 2017). Current literature (de Hoyo et al., 2015, Askling et al., 2003b) demonstrates the effectiveness of training with isoinertial technology to reduce hamstring severity and incidence of injury as well as performance enhancement.

Based on the proposals from previous studies (de Hoyo et al., 2015, Mendez-Villanueva et al., 2016, Maroto-Izquierdo et al., 2017, Núñez and Sáez de Villarreal, 2017) and findings of the two observational studies (study 2 and 3), an isoinertial technology-based protocol was designed and compared with a traditional bodyweight programme.

Tuck jump assessment, hamstring and quadriceps peak torque, hamstring to quadriceps ratio, localization of hamstring eccentric peak torque and repeated shuttle sprint ability were assessed to evaluate the effectiveness of the programmes on ACL and hamstring injury risk factors as well as performance. Based on the previously defined biomechanical risk factors and video analysis of ACL injuries, four theories referring to neuromuscular imbalances, have been proposed for ACL injuries during jump landing in athletes (Lopes et al., 2017, Hewett et al., 2010) 1) Ligament dominant: where knees are in valgus position along with hip internal rotation, therefore ligaments are loaded excessively; 2) quadriceps dominant: imbalanced activation between quadriceps and hamstring and knee in extended position, thus increased anterior shear force on the tibia; 3) trunk dominant: lack of controlling the trunk; 4) leg dominant theory: side to side asymmetry. The TJA is a repeated high intensity plyometric jump that mimics the sport specific action (Read et al., 2016, Fort-Vanmeerhaeghe et al., 2017). The ten criteria for the tuck jump assessment monitor the four abovementioned neuromuscular imbalances, in addition to fatigue and feedforward, figure 18. This approach allows coaching staff to identify individual's neuromuscular imbalance and target the specific risk factor (Lopes et al., 2017).

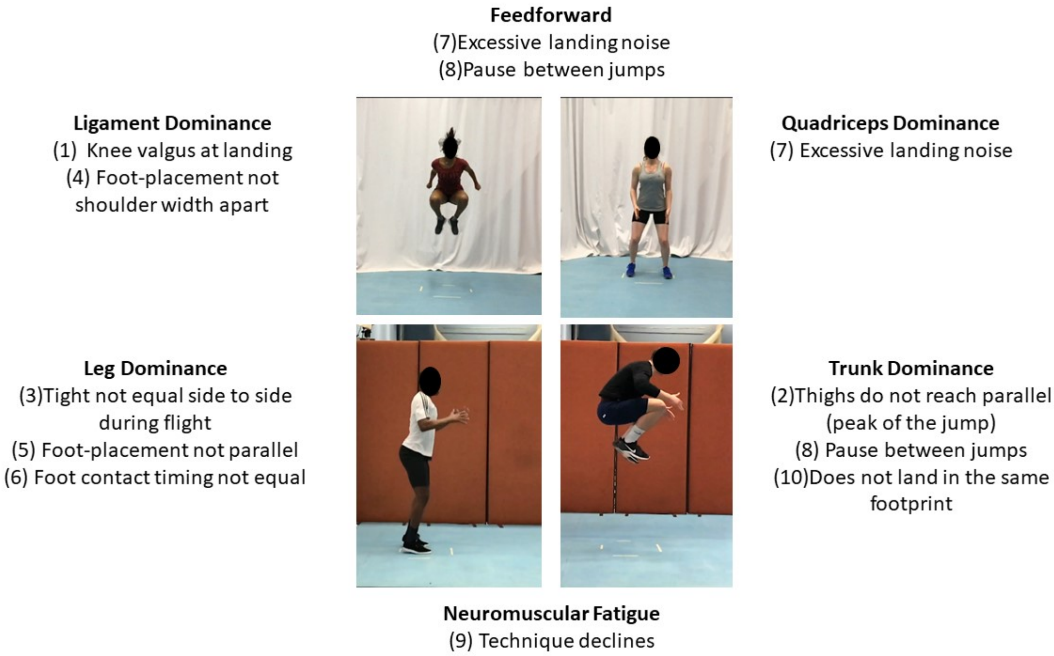

Figure 18*, Items related to neuromuscular imbalances associated to ACL injury.*

Training with flywheel devices was effective to positively modify injury risk factors and support performance after only 6 weeks of intervention. These results suggest that using isoinertial-technology would induce rapid and positive protective adaptation in team sports athletes. The traditional programme still could have been effective but perhaps needs more time, volume, frequency or use additional external overload to hasten adaptations. The effectiveness of resistance training performed with isoinertial technology on functional and structural muscle adaptation has been well documented (Maroto-Izquierdo et al., 2017). A recent meta-analysis demonstrated higher positive effect on vertical jump performance in groups using isoinertial technology compared to gravity dependent training (i.e., weight training) (Maroto-Izquierdo et al., 2017). In addition, there is evidence that the ground reaction force, knee loading and work done by the knee and hip muscles elevate with increasing landing height (McNitt-Gray, 1993, Yeadon et al., 2010). Therefore, it may be speculated that, for the participants of our study who trained with isoinertial technology, despite increased jump height in the post-test and the subsequent potential increased load applied at knee during landing, biomechanical parameters (i.e TJA score) improved, and consequently the risk of injury decreased.

An important advantage of isoinertial technology-based training for team sports athletes could be the time efficiency of training. Team sports usually have a short period of preparation during pre-season to optimize their performance. In fact, as mentioned earlier, the majority of proposed injury prevention programmes use bodyweight exercises to reduce the amount of time needed to complete the programme. Therefore, a time-efficient programme can be beneficial for preventing injuries and improving performance in athletes. Another advantage of this training method is the possibility to perform sport specific movements in all three dimensions of space, with similar kinematics as in sport events, which does not occur in conventional training (Prieto-Mondragón et al., 2016). Current literature suggests that eccentric actions optimize the effect of resistance training (Meylan et al., 2008). Although performing traditional training (weight training) is popular, even at maximum intensity the eccentric phase is still under loaded. However, isoinertial technology differs by offering eccentric overload, and consequently optimizes the efficiency of training and potentially results in earlier adaptation (Maroto-Izquierdo et al., 2017).

As highlighted in the introduction and the rational of the current thesis, the effectiveness of hamstring and ACL injury preventions are unclear. In addition, epidemiological studies demonstrate increased rate of ACL and hamstring injuries during the last decades. The current thesis has systematically reviewed and analysed proposed injury prevention programmes and highlighted the advantages and disadvantages of the current preventative exercises to modify hamstring and ACL risk factors (Chapter 2, 3, 4 and 5). Furthermore, in order to overcome the shortcomings of the current preventative exercises, a new protocol involving 6 exercises performing on flywheel devices has been designed and implemented (Chapter 6).

The main challenge in the use of larger groups of recreationally trained athletes in long experimental studies lasting several weeks or months, is participant adherence. During the last experimental study, participants were required to attend to the laboratory, where exercises were performed at least 16 times to successfully complete the intervention.

7.1. Practical Application

When taken together, in the context of analysis of hamstring and ACL injury prevention programmes in team sport athletes, the following practical applications are recommended for team sport athletes:

Although performing bodyweight exercises, does not require additional equipment and consequently guarantee higher population compliance, increasing the level of resistance, using dumbbells weight vest or flywheel devices, will augment the level of muscular stimulation and hence promote a better training outcome. Findings of the current thesis suggest that performing a 20-minute flywheel based program, involving 6 exercises, twice a week during a period of 6 weeks significantly improve both males and females hamstring and ACL injury risk factors. However, future works need to investigate longer interventions and also determine what would be the best dose-response strategy for maintaining the achieved protective adaptations over a whole competitive season (>6 to 10 months) in team sports.

This thesis does not nullify the effect of bodyweight training on injury risk factors. Many team sport athletes may not have access to equipment such as flywheel devices. Therefore, to optimise the effectiveness of an injury prevention programmes when using bodyweight exercises only the following recommendations need to be considered:

Multifaceted programmes including eccentric hamstring exercises combined with other training modalities performing two to three sessions a week would promote positive modifications on hamstring and ACL injury risk factors. In addition, appropriate technical feedback appears to be an essential component of the protocols. Some exercises modalities such as unilateral squats or unstable exercises performing on specific devices (Bosu balance trainer) are popular within team sport athletes to prevent ACL injury. The current thesis demonstrates that unilateral squatting would be more beneficial to enhance the knee medial to lateral balance in the frontal plane compared to squatting on unstable surfaces. However, when performing unilateral squat exercises the H:Q activation ratio is below the recommended values. Therefore, to optimise injury prevention protocols, a combination of unilateral exercises with other active lengthening hamstring movements, such as eccentric deadlift and Nordic Curl is recommended. The Nordic Curl exercise is also a popular exercise performing by team sport athletes to prevent hamstring injuries. The high level of hamstring muscle activation (70-80% of the MVIC) during Nordic Curl suggests that performing this exercise would enhance hamstring muscle strength. However, during the Nordic Curl hamstring muscles activate within their resting length and, thus, the exercise does not simulate a similar pattern of muscle activation as occurred during hamstring strain related injuries, where muscles lengthen beyond their upright length. Therefore, combining Nordic Curl with other hamstring strengthening exercises, such as deadlift where hamstring muscles are lengthening beyond their upright length is recommended.

7.2. Conclusions

Injury prevention protocols using a combination of different exercises modalities including the use of isoinertial-technology and technical feedback seems to be effective to positively modify the associated hamstring and ACL risk factors in uninjured team sport athletes.

Hamstring eccentric and unstable exercises affect hamstring torque-angle relationship differently, therefore performing only eccentric or unstable exercises would produce positive adaption on hamstring or ACL, respectively.

The multifaceted programmes including plyometric, balance and strength seems to be more effective to positively modify the biomechanical risk factors. Furthermore, hamstring eccentric emphasized training are essential components of injury programmes aimed to modify the hamstring risk factors.

Hamstring muscles are highly activated during Nordic curl exercise, and the level of activation seems to be enough to increase the muscle strength. However, hamstrings are activated within their upright length, therefore, the elongation stress would be lower than that occur during the late swing phase of sprint, where majority of hamstring injuries occur.

The activation of knee flexors and extensors is higher during unilateral squat compared to double leg squat on stable or unusable surface and has the ability to stabilize the knee in frontal plane. However, due to the low hamstring to quadriceps ratio, combination of this exercise with a hamstring eccentric movement is recommended.

A 6-week flywheel-based exercise programme is a time efficient injury prevention strategy that positively changes modifiable ACL and hamstring risk factors and also improves repeated sprint ability.

7.3. Future Work

The studies included in this thesis included recreational team sport athletes, however, the hamstring and ACL injuries are also common across other populations, such as various age groups and athletes, future investigation should focus on these cohorts.

The effect of different moment inertia, volume and frequency of isoinertial technology-based exercises on injury risk factors is not well clarified. Further investigation in this area is needed to optimize the effect of training using isoinertial devices.

In addition, there are several commercially available technologies that offer eccentric overload training, such as Exerbotics Squat Machine or Exentrix Squat, etc. (Tinwala et al., 2017). Future investigation should focus on comparing the effect of different eccentric overload training technologies from the injury preventive prospective.

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APPENDICES

9.1. Appendix I- Example Participant information sheet

PARTICIPANT INFORMATION SHEET

FACULTY OF ENGINEERING AND SCIENCES
DEPARTMENT OF LIFE AND SPORT SCIENCE

Title: Analysis of the hamstring and quadriceps muscle activation during fly-wheel machine based injury prevention exercises; pilot study

Researchers: **Alireza Monajati**

Supervisor: **Dr Fernando Naclerio**

Tel: **020 8331 8441** A.monajati@gre.ac.uk

PARTICIPANT INFORMATION

Alireza Monajati is currently a PhD student specialising in injury prevention at the University of Greenwich. He obtained an MSc in Strength and Conditioning from the University of Greenwich in 2013.This study is part of his PhD research. You are invited to take part in a research study to examine muscle activation of the lower extremity during proposed Hamstring and Anterior Cruciate Ligament (ACL) injury preventive exercises.

The research questions are:

1) What is the effect of the selected exercise on muscle activation?
2) What is the most activated muscle during the selected exercise?
3) What is the relationship between the angular position and the amount of muscle activation achieved while performing the exercise

Important

You are free to take part or not in this study. You can withdraw from your participation at any time without any reason given to consequences.

What will be expected of you?

You are expected to attend three exercise sessions (2 familiarisation and 1 trial session). To ensure that you are at the laboratory in an appropriate condition of fitness, you are expected do not performing any kind of lower body resistance training during a week before the trial. Please abstain from caffeine, alcohol and performing any intense exercise the day before the test.

During the familiarizations and the trial sessions, 5 electrodes will be placed on your thigh to monitor the hamstring and quadriceps muscles activation. You will be asked to perform the exercise under supervision of a member of the research team. The exercises will first be demonstrated by the researcher and then you will be asked to perform with a correct technique. Your technique will be corrected by the researcher, if needed.

Are there any risk?

The risk is very low; depends on your fitness level, you may experience muscle soreness (DOMS) the day after of the trial.

What are the benefits to you?

you will be informed about the most appropriate exercise to prevent hamstring and ACL injury. In addition, you will be given some advice about how to perform the selected exercises with a correct technique.

How the result of the study will be used?

Your data will be mathematically analysed together with all the other participants' data, and the findings from this analysis will be communicated to other researchers and scientists. Communication of the findings will be in the form of reports in scientific journals, articles in newsletters, and presentation at conferences. The participant's names will be deleted from the sheets and replaced by a code. Only the investigators will have access to these codes.

Confidentiality

All data and personal information will be stored securely within University of Greenwich premises in accordance with the terms of the Data Protection Act 1998 and the University's own data protection requirements, and will be accessed only by researchers. After completion of the study, all data will be made anonymous (i.e. all personal information associated with your data will be removed). Your data will be anonymous in any written reports, articles, and presentations of the results of the study.

Deciding whether to participate

If you would like to participate, please return the consent form to a member of our research team me in the envelope provided. You may wish to inform your General Practitioner that you are taking part in this study in case there are any contraindications.
If you have any questions, please contact me on the telephone number or email address above.

Many thanks for your time

9.2. Appendix II - Example Consent form

UNIVERSITY *of* GREENWICH

Faculty of Engineering & Science

RESEARCH ETHICS COMMITTEE

CONSENT FORM

SCHOOL/DEPARTMENT Science / Life and Sport Science	
Title of Study: Analysis of the hamstring and quadriceps muscle activation during injury prevention exercises	
Researcher's name: Alireza Monajati	
To be completed by the participant:	
• I have read the information sheet about this study. • I have had an opportunity to ask questions and discuss this study. • I have received satisfactory answers to all my questions. • I have received enough information about this study. • I understand that I am free to withdraw from this study: o At any time. o Without giving a reason for withdrawing. o Without affecting my future with the University. • I understand that my research data may be used for a further project in anonymous form, but I am able to opt out of this if I so wish, by ticking here. • I agree to take part in this study.	
Signed (participant)	**Date**
Name in block letters	
Signature of researcher	**Date**
This project is supervised by: Dr Fernando Naclerio, Centre for Sports Science and Human Performance, Tel: 0208 331 8441 Email: f.j.naclerio@gre.ac.uk	
Researcher's contact details (including telephone number and e-mail address): Alireza Monajati o E-mail: A.monajati@gre.ac.uk o Tel: 020 8331 8441	

9.3. Appendix III – Summary of the 56 rejected studies and the corresponding reason for rejection

	Study	Reason for exclusion
1	Paterno MV, Myer GD, Ford KR, Hewett TE. Neuromuscular training improves single-limb stability in young female athletes. Journal of Orthopaedic & Sports Physical Therapy. 2004 Jun;34(6):305-16.	Intervention shorter than 4 weeks or sessions longer that 35 minutes
2	DiStefano LJ, Padua DA, Blackburn JT, Garrett WE, Guskiewicz KM, Marshall SW. Integrated injury prevention program improves balance and vertical jump height in children. The Journal of Strength & Conditioning Research. 2010 Feb 1;24(2):332-42.	Age of participant less than 14 years old
3	Wilkerson GB, Colston MA, Short NI, Neal KL, Hoewischer PE, Pixley JJ. Neuromuscular changes in female collegiate athletes resulting from a plyometric jump-training program. Journal of Athletic Training. 2004 Jan 1;39(1):17-23.	Intervention shorter than 4 weeks or sessions longer that 35 minutes
4	DiStefano LJ, Blackburn JT, Marshall SW, Guskiewicz KM, Garrett WE, Padua DA. Effects of an age-specific anterior cruciate ligament injury prevention program on lower extremity biomechanics in children. The American journal of sports medicine. 2011 May 1;39(5):949-57.	Age of participant less than 14 years old
5	Parsons JL, Alexander MJ. Modifying spike jump landing biomechanics in female adolescent volleyball athletes using video and verbal feedback. The Journal of Strength & Conditioning Research. 2012 Apr 1;26(4):1076-84.	Age of participant less than 14 years old
6	Myers CA, Hawkins D. Alterations to movement mechanics can greatly reduce anterior cruciate ligament loading without reducing performance. Journal of biomechanics. 2010 Oct 19;43(14):2657-64.	No intervention or intervention shorter than 8 sessions;
7	Louw Q, Grimmer K, Vaughan CL. Biomechanical outcomes of a knee neuromuscular exercise programme among adolescent basketball players: a pilot study. Physical Therapy in Sport. 2006 May 31;7(2):65-73.	Intervention shorter than 4 weeks or sessions longer that 35 minutes
8	Greska EK, Nelson Cortes D, Van Lunen BL, Oñate JA. A feedback inclusive neuromuscular training program alters frontal plane kinematics. Journal of Strength and Conditioning Research. 2012 Jun;26(6):1609.	Intervention shorter than 4 weeks or sessions longer that 35 minutes
9	Noyes FR, Barber-Westin SD, Smith ST, Campbell T. A training program to improve neuromuscular and performance indices in female high school soccer players. The Journal of Strength & Conditioning Research. 2013 Feb 1;27(2):340-51.	Intervention shorter than 4 weeks or sessions longer that 35 minutes

10	Noyes FR, Barber-Westin SD, Smith ST, Campbell T. A training program to improve neuromuscular indices in female high school volleyball players. The Journal of Strength & Conditioning Research. 2011 Aug 1;25(8):2151-60.	Intervention shorter than 4 weeks or sessions longer that 35 minutes
11	Noyes FR, Barber-Westin SD, Smith ST, Campbell T, Garrison TT. A training program to improve neuromuscular and performance indices in female high school basketball players. The Journal of Strength & Conditioning Research. 2012 Mar 1;26(3):709-19.	Intervention shorter than 4 weeks or sessions longer that 35 minutes
12	Grandstrand SL, Pfeiffer RP, Sabick MB, DeBeliso M, Shea KG. The effects of a commercially available warm-up program on landing mechanics in female youth soccer players. The Journal of Strength & Conditioning Research. 2006 May 1;20(2):331-5.	Age of participant less than 14 years old
13	DiStefano LJ, Padua DA, DiStefano MJ, Marshall SW. Influence of age, sex, technique, and exercise program on movement patterns after an anterior cruciate ligament injury prevention program in youth soccer players. The American Journal of Sports Medicine. 2009 Mar 1;37(3):495-505.	Age of participant less than 14 years old
14	Barber-Westin SD, Smith ST, Campbell T, Noyes FR. The drop-jump video screening test: retention of improvement in neuromuscular control in female volleyball players. The Journal of Strength & Conditioning Research. 2010 Nov 1;24(11):3055-62.	Intervention shorter than 4 weeks or sessions longer that 35 minutes
15	Vescovi JD, Canavan PK, Hasson S. Effects of a plyometric program on vertical landing force and jumping performance in college women. Physical Therapy in Sport. 2008 Nov 30;9(4):185-92.	Intervention shorter than 4 weeks or sessions longer than 35 minutes
16	Leporace G, Praxedes J, Pereira GR, Pinto SM, Chagas D, Metsavaht L, Chame F, Batista LA. Influence of a preventive training program on lower limb kinematics and vertical jump height of male volleyball athletes. Physical Therapy in Sport. 2013 Feb 28;14(1):35-43.	Age of participant less than 14 years old
17	McCurdy KW, Langford GA, Doscher MW, Wiley LP, Mallard KG. The effects of short-term unilateral and bilateral lower-body resistance training on measures of strength and power. The Journal of Strength & Conditioning Research. 2005 Feb 1;19(1):9-15.	Non-athletes participants

18	Herman DC, Oñate JA, Weinhold PS, Guskiewicz KM, Garrett WE, Yu B, Padua DA. The effects of feedback with and without strength training on lower extremity biomechanics. The American Journal of Sports Medicine. 2009 Jul 1;37(7):1301-8.	No intervention or intervention shorter than 8 sessions
19	Kraemer R, Knobloch K. A Soccer-Specific Balance Training Program for Hamstring Muscle and Patellar and Achilles Tendon Injuries An Intervention Study in Premier League Female Soccer. The American journal of sports medicine. 2009 Jul 1;37(7):1384-93.	No risk factors were controlled but the incidence of injury
20	Verrall GM, Slavotinek JP, Barnes PG. The effect of sports specific training on reducing the incidence of hamstring injuries in professional Australian Rules football players. British journal of sports medicine. 2005 Jun 1;39(6):363-8.	No risk factors were controlled but the incidence of injury
21	Ono T, Fujii H. Comparison of different hamstrings training effect on hamstrings. Japanese Journal of Physical Fitness and Sports Medicine. 2013;62(1):87-94.	Non English publication (only tittle and abstract were available in English)
22	Andersson N. The Effects of a New ACL-Injury Prevention Device on Knee Kinematics and Hamstring and Quadriceps Co-Contraction: A Pilot Study.2013	Risk factors non properly monitored
23	Sañudo B, Feria A, Carrasco L, de Hoyo M, Santos R, Gamboa H. Does whole body vibration training affect knee kinematics and neuromuscular control in healthy people?. Journal of sports sciences. 2012 Oct 1;30(14):1537-44.	Non-athletes participants
24	Shultz R, Silder A, Malone M, Braun HJ, Dragoo JL. Unstable Surface Improves Quadriceps: Hamstring Co-contraction for Anterior Cruciate Ligament Injury Prevention Strategies. Sports Health: A Multidisciplinary Approach. 2014 Dec 31:1941738114565088.	Risk factors non properly monitored
25	van der Horst N, Smits DW, Petersen J, Goedhart EA, Backx FJ. The Preventive Effect of the Nordic Hamstring Exercise on Hamstring Injuries in Amateur Soccer Players A Randomized Controlled Trial. The American journal of sports medicine. 2015 Mar 20:0363546515574057.	No risk factors were controlled but the incidence of injury
26	Petersen J, Thorborg K, Nielsen MB, Budtz-Jørgensen E, Hölmich P. Preventive effect of eccentric training on acute hamstring injuries in men’s soccer a cluster-randomized controlled trial. The American journal of sports medicine. 2011 Nov 1;39(11):2296-303.	No risk factors were controlled but the incidence of injury

27	Stearns KM, Powers CM. Improvements in hip muscle performance result in increased use of the hip extensors and abductors during a landing task. The American journal of sports medicine. 2014 Mar 1;42(3):602-9.	Non-athletes participants
28	Nyland J, Burden R, Krupp R, Caborn DN. Whole body, long-axis rotational training improves lower extremity neuromuscular control during single leg lateral drop landing and stabilization. Clinical Biomechanics. 2011 May 31;26(4):363-70.	Non-athletes participants
29	Small K, McNaughton L, Greig M, Lovell R. The effects of multidirectional soccer-specific fatigue on markers of hamstring injury risk. Journal of Science and Medicine in Sport. 2010 Jan 31;13(1):120-5.	No intervention or intervention shorter than 8 sessions;
30	Verrall GM, Slavotinek JP, Barnes PG. The effect of sports specific training on reducing the incidence of hamstring injuries in professional Australian Rules football players. British journal of sports medicine. 2005 Jun 1;39(6):363-8.	No risk factors were controlled but the incidence of injury
31	Silvers HJ, Mandelbaum BR. ACL injury prevention in the athlete. Sport-Orthopädie-Sport-Traumatologie-Sports Orthopaedics and Traumatology. 2011 Dec 31;27(1):18-26.	No intervention or intervention shorter than 8 sessions;
32	Myer GD, Chu DA, Brent JL, Hewett TE. Trunk and hip control neuromuscular training for the prevention of knee joint injury. Clinics in sports medicine. 2008 Jul 31;27(3):425-48.	No intervention or intervention shorter than 8 sessions;
33	Myklebust G, Engebretsen L, Brækken IH, Skjølberg A, Olsen OE, Bahr R. Prevention of anterior cruciate ligament injuries in female team handball players: a prospective intervention study over three seasons. Clinical Journal of Sport Medicine. 2003 Mar 1;13(2):71-8.	No risk factors were controlled but the incidence of injury
34	Petersen W, Braun C, Bock W, Schmidt K, Weimann A, Drescher W, Eiling E, Stange R, Fuchs T, Hedderich J, Zantop T. A controlled prospective case control study of a prevention training program in female team handball players: the German experience. Archives of orthopaedic and trauma surgery. 2005 Nov 1;125(9):614-21.	No risk factors were controlled but the incidence of injury
35	Hewett TE, Stroupe AL, Nance TA, Noyes FR. Plyometric training in female athletes decreased impact forces and increased hamstring torques. The American Journal of Sports Medicine. 1996 Dec 1;24(6):765-73.	Intervention shorter than 4 weeks or sessions longer that 35 minutes

36	Mandelbaum BR, Silvers HJ, Watanabe DS, Knarr JF, Thomas SD, Griffin LY, Kirkendall DT, Garrett W. Effectiveness of a neuromuscular and proprioceptive training program in preventing anterior cruciate ligament injuries in female athletes 2-year follow-up. The American Journal of Sports Medicine. 2005 Jul 1;33(7):1003-10.	No risk factors were controlled but the incidence of injury
37	Myer GD, Brent JL, Ford KR, Hewett TE. A pilot study to determine the effect of trunk and hip focused neuromuscular training on hip and knee isokinetic strength. British journal of sports medicine. 2008 Jul 1;42(7):614-9.	Intervention shorter than 4 weeks or sessions longer than 35 minutes
38	Myer GD, Ford KR, PALUMBO OP, Hewett TE. Neuromuscular training improves performance and lower-extremity biomechanics in female athletes. The Journal of Strength & Conditioning Research. 2005 Feb 1;19(1):51-60.	Intervention shorter than 4 weeks or sessions longer than 35 minutes
39	Myer GD, Ford KR, Brent JL, Hewett TE. Differential neuromuscular training effects on ACL injury risk factors in. BMC musculoskeletal disorders. 2007 May 8;8(1):39.	Intervention shorter than 4 weeks or sessions longer than 35 minutes
40	Myer GD, Ford KR, McLean SG, Hewett TE. The effects of plyometric versus dynamic stabilization and balance training on lower extremity biomechanics. The American journal of sports medicine. 2006 Mar 1;34(3):445-55.	Intervention shorter than 4 weeks or sessions longer than 35 minutes
41	Hewett TE, Lindenfeld TN, Riccobene JV, Noyes FR. The effect of neuromuscular training on the incidence of knee injury in female athletes a prospective study. The American journal of sports medicine. 1999 Nov 1;27(6):699-706.	No risk factors were controlled but the incidence of injury
42	Myer GD, Ford KR, Brent JL, Hewett TE. The effects of plyometric vs. dynamic stabilization and balance training on power, balance, and landing force in female athletes. The Journal of Strength & Conditioning Research. 2006 May 1;20(2):345-53.	Intervention shorter than 4 weeks or sessions longer that 35 minutes
43	Mendiguchia J, Martinez-Ruiz E, Morin JB, Samozino P, Edouard P, Alcaraz PE, Esparza-Ros F, Mendez-Villanueva A. Effects of hamstring-emphasized neuromuscular training on strength and sprinting mechanics in football players. Scandinavian journal of medicine & science in sports. 2015 Dec 1;25(6):e621-9.	Intervention shorter than 4 weeks or sessions longer that 35 minutes

44	Blackburn JT, Norcross MF, Cannon LN, Zinder SM. Hamstrings stiffness and landing biomechanics linked to anterior cruciate ligament loading. Journal of athletic training. 2013 Dec;48(6):764-72.	No intervention or intervention shorter than 8 sessions;
45	Chappell JD, Herman DC, Knight BS, Kirkendall DT, Garrett WE, Yu B. Effect of fatigue on knee kinetics and kinematics in stop-jump tasks. The American journal of sports medicine. 2005 Jul 1;33(7):1022-9.	No intervention or intervention shorter than 8 sessions;
46	McCurdy K, Walker J, Saxe J, Woods J. The effect of short-term resistance training on hip and knee kinematics during vertical drop jumps. The Journal of Strength & Conditioning Research. 2012 May 1;26(5):1257-64.	Non-athletes participants
47	Gabbe BJ, Branson R, Bennell KL. A pilot randomised controlled trial of eccentric exercise to prevent hamstring injuries in community-level Australian Football. Journal of science and medicine in sport. 2006 May 31;9(1):103-9.	No intervention or intervention shorter than 8 sessions;
48	Irmischer BS, Harris C, Pfeiffer RP, DeBeliso MA, Adams KJ, Shea KG. Effects of a knee ligament injury prevention exercise program on impact forces in women. The Journal of Strength & Conditioning Research. 2004 Nov 1;18(4):703-7.	Non-athletes participants
49	Söderman K, Werner S, Pietilä T, Engström B, Alfredson H. Balance board training: prevention of traumatic injuries of the lower extremities in female soccer players?. Knee surgery, sports traumatology, arthroscopy. 2000 Nov 1;8(6):356-63.	No risk factors were controlled but the incidence of injury
50	Croisier JL, Ganteaume S, Binet J, Genty M, Ferret JM. Strength imbalances and prevention of hamstring injury in professional soccer players a prospective study. The American journal of sports medicine. 2008 Aug 1;36(8):1469-75.	No risk factors were controlled but the incidence of injury
51	Karatrantou K, Gerodimos V, Dipla K, Zafeiridis A. Whole-body vibration training improves flexibility, strength profile of knee flexors, and hamstrings-to-quadriceps strength ratio in females. journal of Science and Medicine in Sport. 2013 Sep 30;16(5):477-81.	Non-athletes participants
52	Khodayari B, Dehghani Y. The investigation of mid-term effect of different intensity of PNF stretching on improve hamstring flexibility. Procedia-Social and Behavioral Sciences. 2012 Dec 31;46:5741-4.	No intervention or intervention shorter than 8 sessions;
53	Brockett CL, Morgan DL, Proske UW. Human hamstring muscles adapt to eccentric exercise by changing optimum length. Medicine and science in sports and exercise. 2001 May 1;33(5):783-90.	No intervention or intervention shorter than 8 sessions;

54	Oliveira AD, Caputo F, Gonçalves M, Denadai BS. Heavy-intensity aerobic exercise affects the isokinetic torque and functional but not conventional hamstrings: quadriceps ratios. Journal of Electromyography and Kinesiology. 2009 Dec 31;19(6):1079-84.	Intervention shorter than 4 weeks or sessions longer than 35 minutes
55	van Beijsterveldt AM, van de Port IG, Krist MR, Schmikli SL, Stubbe JH, Frederiks JE, Backx FJ. Effectiveness of an injury prevention programme for adult male amateur soccer players: a cluster-randomised controlled trial. British journal of sports medicine. 2012 Aug 9:bjsports-2012.	No risk factors were controlled but the incidence of injury
56	Kamani, N. and Nikseresht A. The Effect of 8 Weeks Plyometric Training and 3 Weeks Detraining on Sprint, Agility and Leg Explosive Power in Female Runners: International journal of Biology, Pharmacy and Allied science. 2015 Jan:4(1):147-159	Risk factors not properly monitored

Notes: A) Age of participant less than 14 years old; B) Non-athletes participants; C) Duration of Intervention session (30 min each session); D) No intervention or intervention shorter than 8 sessions; E) Identified risk factors non properly monitored; F) Monitoring the incident of injury not risk factors; G) Non English publication (only tittle and abstract were available in English)

9.4. Appendix – Publications and submitted papers

Peer Reviewed Publication

Monajati, A., Larumbe-Zabala, E., Goss-Sampson, M. and Naclerio, F., 2017. Analysis of the hamstring muscle activation during two injury prevention exercises. *Journal of Human Kinetics*.

Monajati, A., Larumbe-Zabala, E., Goss-Sampson, M. and Naclerio, F., 2016. The effectiveness of injury prevention programs to modify risk factors for non-contact anterior cruciate ligament and hamstring injuries in uninjured team sports athletes: a systematic review. *PloS one*, *11*(5), p.e0155272.

Naclerio, F., Larumbe-Zabala, E., **Monajati, A**. and Goss-Sampson, M., 2015. Effects of two different injury prevention resistance exercise protocols on the hamstring torque-angle relationship: a randomized controlled trial. *Research in Sports Medicine*, *23*(4), pp.379-393.

Submitted papers for publication

Monajati, A., Larumbe-Zabala, E., Goss-Sampson, M. and Naclerio, F., 2017. Surface Electromyography Analysis of Three Squat Exercises in Female Football Players.
Submitted to the Journal of Sport Rehabilitation

Monajati, A., Larumbe-Zabala, E., Goss-Sampson, M. and Naclerio, F., 2017. Injury prevention programs Based on Flywheel vs. Body Weight Resistance in Recreational Athletes.
Submitted to the Journal of Athletic Training