The effect of a six-week functional movement intervention on dynamic knee stability and physical performance in female netball players

by

Dimitrije Kovac

UNIVERSITEIT
iYUNIVESITHI
STELLENBOSCH
UNIVERSITY

Thesis presented in the fulfilment of the requirements for the degree of Master in Sport Science in the Faculty of Education at Stellenbosch University

Supervisor: Prof Ranel Venter

Co-supervisor: Dr Zarko Krkeljas

March 2018

DECLARATION

By submitting this thesis electronically, I declare that the entirety of the work contained therein is my own, original work, that I am the sole author thereof (save to the extent explicitly otherwise stated), that reproduction and publication thereof by Stellenbosch University will not infringe any third party rights and that I have not previously in its entirety or in part submitted it for obtaining any qualification.

March 2018

SUMMARY

Netball is a physically demanding game with high incidence of non-contact ACL injuries, especially among female players. Non-contact ACL injuries in female netball have a multifactorial etiology that requires adequate screening. Fortunately, certain ACL injury risk factors, related to altered biomechanics, can be modified by neuromuscular training.

To reduce the incidence of ACL injuries in female netball players, it is crucial to recognize biomechanical risk factors as early as possible. Knee valgus during landing was found to be one of the most common risk factors for the injury of the ACL among female athletes. FMS® is a testing battery designed to assess quality of movement within fundamental movement patterns and to identify possible injury risk factors related to movement deficiencies. FMS® is also designed to improve dysfunctional movement patterns and potentially reduce the risk of sport related injuries. The current study was conducted with the aim to investigate the effect of a six-week functional movement intervention on dynamic knee stability and physical performance in female netball players. The relationship between FMS® and dynamic knee stability tests, as well as performance tests, was also investigated in a group of university female netballers.

A total of 31 university female netball players volunteered for participation in the study. The study followed a convenience sampling design. A six-week intervention programme based on the FMS® results was implemented .

The primary finding in the current study was improvement in total FMS® score after the six-week standardized intervention programme ($p<0.001$). Significant differences in active straight leg raise (ASLR) ($p=0.01$) and trunk stability push up (TSPU) ($p=0.02$) score were found between pre- and post-intervention, while all other FMS® tests did not significantly improve.

The results demonstrated a moderate significant correlation of FMS® total score with the single leg hop, as well as the 5-0-5 agility test when performed with the dominant leg. The results also showed a positive correlation between the hurdle step total

score and single leg hop and hold test performed with the dominant leg before (p=0.35, p=0.05) and after the intervention (p=0.39, p=0.04). There were no other significant correlations between total and individual FMS® scores and dynamic knee stability and performance tests.

According to the results from in this study, FMS® performance can be improved by a standardized corrective exercise programme. Furthermore, a six week FMS® intervention does have positive effects on certain performance abilities, but does not have a significant effect on dynamic knee stability in female netball players.

Key words: FMS®, ACL, dynamic knee stability, performance, injury risk, netball.

OPSOMMING

Netbal is 'n fisiek uitdagende spel met 'n hoë voorkoms van nie-kontak ACL beserings, veral by vroulike spelers. Nie-kontak ACL beserings in vroulike netbalspelers het 'n multi-faktoriale etiologie wat voldoende sifting en vooraf-evaluering vereis. Gelukkig kan sekere risikofaktore vir ACL beserings wat met biomeganika verband hou, aangepas word deur neuromuskulêre oefening.

Om die voorkoms van ACL beserings in netbalspelers te verminder, is dit kritieis belangrik om die biomeganiese risikofaktore so vroeg as moontlik te identifiseer. Knie valgus met landings is aangedui as een van die mees algemene risikofaktore vir ACL beserings by vroulike atlete. FMS® is 'n toetsbattery wat ontwerp is om bewegingskwaliteit deur middel van fundamentele beweginspatrone vas te stel en moontlike risikofaktore te identifiseer wat verband hou met bewegingsbeperkings of – tekortkomings. FMS® is ook ontwerp om wanfunksionele bewegingspatrone te verbeter en moontlik die risiko van sportverwante beserings te verminder. Die doel van die huidige studie was om 'n ondersoek te doen na die effek van 'n ses-weke funksionele oefenintervensie op dinamiese kniestabiliteit en prestasietoetse in vroulike netbalspelers. Die verwantskap tussen tussen die FMS®, dinamiese kniestabiliteitstoetse en prestasietoetse is ook in die vroulike universiteitsvlak netbalspelers gedoen.

'n Totaal van 31 universiteitvlak vroulike netbalspelers het vrywillig aan die studie deelgeneem. 'n Gerieflikheidstreekproef is geneem vir die die doel van die studie. Die verhouding tussen die FMS® en ACL siftingstoetse, asook prestasietoetse, is in die groep vroulike netbalspelers ondersoek.

Die primêre bevinding van die studie was 'n verbetering in die totale FMS® telling na die ses-weke gestandaardiseerde intervensieprogram ($p<0.001$). Betekenisvolle verskille is gevind vir die aktiewe reguitbeen opligtoets ($p=0.01$) en die rompstabiliteit opstootstoets ($p=0.02$) na die intervensieprogram, terwyl die ander FMS® toetse nie betekenisvol verbeter het nie.

Die resultate het 'n matige betekenisvolle korrelasie getoon tussen die totale FMS® telling en eenbeensprong, asook die 5-0-5 ratsheidstoets wanneer dit met die dominante been uitgevoer was. Resultate het 'n positiewe korrelasie getoon tussen die hekkie-tree en eenbeensprong, asook die hou-toets met die dominante been, voor (p=0.35, p=0.05) en na die intervensie (p=0.39, p=0.04). Daar was geen ander betekenisvolle korrelasies tussen die totale en individuele FMS® tellings en die dinamiese kniestabiliteits- en prestasietoetse nie.

Uit die resultate blyk dit dat FMS® prestasie kan verbeter deur die implementering van 'n gestandaardiseerde korrektiewe oefeningsprogram. Die ses-weke FMS® intervensie het 'n positiewe effek gehad op sekere prestasie-aspekte van die netbalspelers, maar nie 'n beduidende effek op die dinamiese kniestabiliteit van die vroulike netbalspelers gehad nie.

Sleutelwoorde: FMS®, ACL, dinamiese kniestabiliteit, prestasie, beseringsrisiko, netbal.

ACKNOWLEDGMENTS

I wish to thank the following persons who contributed time and effort to my study and for the institutions who assisted me in my work.

Prof. Ranel Venter, my supervisor, for her efforts and advice given on an academic as well as on a personal level.

Prof. Martin Kidd, for statistical support.

The Department of Sport Science at Stellenbosch University, for granting me the opportunity to do my MSc degree.

My family, friends, collegues, for all the support over the last two years.

Maties netball: all the players, as well as the management (Karen Swart and Charle Coetser) .

Language center of Stellenbosch University.
International office of Stellenbosch University.

Lastly, but not least, great gratitude goes to Dr Zarko Krkeljas who inspired me to start this wonderful journey. Thanks Z.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Chapter One

PROBLEM STATEMENT, AIMS AND HYPOTHESIS

A. INTRODUCTION

1. Netball

Netball is the most popular team sport in the Commonwealth and in South Africa, played predominantly by females. Around 9700 adult netball players have been registered in South Africa, while about half a million play at the level of high school (Venter, 2005). Netball is a fast, dynamic, team game, consisting of running, jumping, catching, pivoting, explosive power, and sudden changes in direction.

Steele and Milburn (1987) described netball as a game reliant on rapid acceleration to "break free" from an opponent, sudden and rapid changes in direction in combination with leaps to receive a pass, intercept a ball or rebound after attempting to goal. Consequently netball is also a very physically demanding game with a high incidence of traumatic and overuse injuries, especially of the lower extremities (Otago & Peake, 2007). Globally, ankle and knee injuries in netball account for 19.3% and 37.4% respectively (Flood & Harrison, 2009).

Despite the lack of statistical data on the number and nature of injuries among netball players in South Africa, the knee (28.6%) and the ankle (37.5%), were designated as the most frequently injured body regions (Pillay & Frantz, 2012). Langeveld et al. (2012) showed that ligament sprains and tears were the most common type of injuries of these structures.

Some netball players finish their career early due to injuries of the anterior cruciate ligament (ACL) (Hopper, 1995). According to Flood and Harrison (2009) representation of anterior cruciate ligament (ACL) alone was 17.2% of total injuries sustained. Therefore, the occurrence of ACL injuries can be of vital importance for netball players and preventative measures require special attention (Hopper, 1995).

2. ACL injury prevalence in netball

The highest number of ACL injuries happen without physical contact, that is, with non-contact mechanisms (Munro et al., 2012). According to Yu and Garrett (2007) ACL injuries occur when excessive shear forces are applied to the ACL. Certain risk factors that can be modified, in particular biomechanics of the lower extremities related to motor control, have to be recognized in order to reduce the risk of ACL injuries. Poor landing mechanics has been shown as one of the most common mechanism of injury (Steele & Lafortune, 1989).

Great effort has been made to study and determine modifiable risk factors in an attempt to reduce the incidence of non-contact ACL injuries. Several studies have shown differences between female and male athletes in certain biomechanical parameters. Female athletes, on average, had greater knee valgus, smaller knee flexion angle, greater ground reaction forces, greater proximal anterior tibial shear force and greater extension moment during landing of selected athletics tasks (Malinzak et al., 2001; Ford et al., 2003; Chappell et al., 2002). Nagano et al. (2010) found a correlation between physical measurements and the knee motion during landing and they allocated knee valgus as a parameter that requires special evaluation. Femoral adduction and tibial abduction leads to knee valgus during landing usually because of weak hip abductors, especially gluteus medius (Claiborne et al., 2006). Restricted ankle dorsiflexion may also adversely affect the knee valgus and knee flexion angle (Howe & Cushion, 2017). Decreased ankle dorsiflexion range of motion has been associated with greater frontal plane knee excursion during landing (Sigward & Powers, 2007), and with a lower knee flexion angle during a jump landing task (Fong et al., 2011).

3. Screening tools

Hence, the ability to possibly predict and prevent injuries is as important as the methods of rehabilitation and treatment. Reducing the disability and costs from sport-related injuries, depends primarily on injury prevention programmes (Soomro et al., 2016). In order to create an intervention programme, it is necessary to identify dynamic movement limitations (Onate et al., 2012).

Over recent years, sports medicine physical examinations and rehabilitation strategies have changed from isolated assessment and treatment to an approach based on functional movement (Cook et al., 2014a).
Fundamental movement patterns of individual athletes are the focus of recent athletic screening methods. Limitations and asymmetries in basic movement patterns can reduce the effects of functional training and possibly lead to injury (Cook et al., 2006a). These movement limitations in an active population may cause compensations and substitutions that lead to poor efficiency and increased injury risk (Minick et al., 2010).

Screening tools in the form of a drop vertical jump (Huston et al., 2001), single-leg squat (Ugalde et al., 2015) and single-leg hop-and-hold test (Fitzgerald et al., 2001) are often used to detect and diagnose weaknesses and predispositions to ACL injury. Recently, functional movement screening (FMS®) has become a widely used tool for detecting movement deficiency and/or diagnosis of injury predisposition (Gribble et al., 2013).

4. Functional movement screen (FMS®)

The Functional movement screen (FMS®) is a screening test battery which is proposed to assess movement quality and to identify potential injury causing deficits in the human body. It is mainly based on the identification of poor motor control, mobility/stability problems, as well as right to left asymmetries. The FMS® consists of seven active movement tasks (deep squat, hurdle step, in-line lunge, shoulder mobility, active straight leg raise, trunk stability push up, and rotary stability), accompanied by three clearing examinations (spinal flexion, spinal extension, and shoulder internal rotation with flexion).

3

Scoring consists of a score from zero to three with a maximum total score of 21 being possible. If pain is reported on any of the clearing exams, a score of zero is awarded for the associated movement (Cook et al., 2014a). The FMS® is indicated as a test to find the weakest link in the kinetic chain that may be responsible for the development of deviations or compensations in movement patterns (Schneiders et al., 2011). Livingston et al. (2016) found a strong association between the deep squat and in-line lunge test with passive measures of medial/lateral knee stability.

Authors of this study also found a significant relationship between Lachman's test and dynamic performance during a hurdle-step movement pattern. Frost et al. (2017) reported greater frontal plane knee motion in a group of athletes who scored less than 14 on the FMS, which represents promising results in the field of identification of athletes who are more inclined towards the ACL injuries.

B. PROBLEM STATEMENT

Despite many preventative programmes, netball players still have a large number of ACL injuries. Kiesel et al. (2007) found that professional football players (NFL®) who have an FMS® score less than 14 have a higher risk for the occurrence of injuries that would restrict players from participating for at least three weeks. Chorba et al. (2010) concluded that a score of 14 or less had a high correlation with a fourfold increase in lower extremity injuries that required medical attention in female collegiate athletes (69% of the players with score of 14 or less). The study of Garrison et al. (2015) demonstrated a predictive relationship between FMS® and previous injury history because college athletes who scored 14 or less had a 15 times increased risk of injury. Contrary to this, Bardenett et al. (2015) demonstrated that the FMS® screening tool does have benefits in recognizing deficiencies in certain movements, but it is not a valid predictor of injury in population of high school athletes.

The study by Kiesel et al. (2007) focused only on the football players without indicating distinction between contact and non-contact injuries. In the same study, the authors paid attention on establishing cut-off score, without addressing asymmetries which is one of the primary purposes of the FMS®. The study of Chorba et al. (2010) was limited to 38 athletes from three different sports but had a different definition of sports injury than Kiesel et al. (2007).

The main problem is that most of these studies are related to various injuries in different sports, but a negligible number of studies have examined these tests on netball players, especially with the aim to reduce the number of ACL injuries. All of mentioned studies also compared the FMS® score to the number of injuries during the season. The focus of the current study was to investigate if the FMS®, as a basic movement screen, could save time and identify dysfunctional movement patterns that could increase the risk of ACL injury in female netball players. Therefore, the aim of the study is to investigate the effects of the FMS® standardized intervention on dynamic knee stability in female netball players.

Lawrence (2014) proposed a dynamic stability intervention programme based on the FMS® and landing and side stepping tests with the purpose of reducing the ACL injury rate.

They also pointed to the lack of hamstring, calf and gluteal strength as risk factors of ACL injuries. Lawrence (2014) established a strength and conditioning programme that includes lateral step ups, unilateral leg presses, plyometric drills, prone leg curls and dynamic calf raises. While awaiting the research results of this programme, it is necessary to continue research in the field to attempt to reduce the frequency of ACL injuries in netball.

C. AIMS AND OBJECTIVES

The purpose of this study was to implement the FMS testing and intervention in order to create an ACL injury prevention program. Primary aim was to determine the effect of a six-week functional movement intervention on dynamic knee stability and physical performance in female netball players. The secondary aim was to investigate the relationship between FMS®, the dynamic knee stability and performance tests. Therefore, the study outcomes could possibly be used in the prevention of ACL injuries in female netball population.

Within the primary aims, the specific objectives of the study were to:

1. Determine the effects of a six-week functional movement intervention on dynamic knee stability and physical performance in female netball players.

2. Investigate the relationship between FMS®, dynamic knee stability (SLS, DVJ) and performance tests (SLHH and 5-0-5 agility).

D. HYPOTHESES

This study is based on the following hypotheses:

1. A six-week individualized intervention programme based on pre-intervention FMS® scores will significantly improve the dynamic knee stability, athletic performance and FMS® score.
2. The FMS® score will have a significant a correlation with the dynamic knee stability (SLS, DVJ) and athletic performance tests (5-0-5 aglity and SLH test).

Chapter Two

THEORETICAL CONTEXT

A. INTRODUCTION

This chapter is aimed to create the context for the study. Firstly, netball as a sport will be briefly described. Secondly, anterior cruciate ligament (ACL) injuries, mechanism of non-contact ACL injuries and possible risks factors are presented. Finally, the Functional Movement Screen (FMS®), 505 agility test, as well as dynamic knee stability tests such as of a drop vertical jump, single-leg squat, and the single-leg hop-and-hold for distance will be described in more detail.

B. NETBALL

Netball is a popular sport in various countries over the world and is played by both male and female players. Flood and Harrison (2009) reported that netball is played by more than 20 million people worldwide. Participation is mostly amongst female participants and is played at various levels of competition ranging from school to elite international competitions. According to McManus et al. (2006), an estimate of one in seven females in Australia participate in netball on a regular basis. In South Africa, netball is played in schools, universities, clubs, and at regional level. In 2005 it was stated that about 9700 adult netball players play at various levels across the country (Venter, 2005), while Bramley (2007) reported that netball is South Africa's second most popular sport after soccer. As a dynamic and physically demanding game, players need a variety of physical fitness and biomotor abilities, such as dynamic balance, agility, speed, endurance, power, flexibility, cutting manoeuvres, jumping and landing (Reid et al., 2015).

With regard to netball injuries, Pillay and Frantz (2012) designated the knee (28.6%) and ankle (37.5%) as the most frequently injured joints in female netball players during the 2010 season in South Africa. Ferreira and Spamer (2010) reported an injury prevalence of 39% for the ankle and 28% for the knee, respectively, across one season.

The study of Langeveld et al. (2012) showed that most injuries occurred to the ankle (34%), knee (18%) and fingers, hand and wrist (15%) and allocated ligaments as the most injured joint structures.

It is suggested that some netball rules related to footwork, may contribute to ACL injuries. A player may receive the ball with one or both feet on the ground, or jump to catch and land on one or both feet. Further, they are allowed to step or jump with the other or both feet, but must shoot or throw the ball before grounding again (Netball Australia, 2012). These footwork rules have been criticised over the years as possibly contributing to non-contact anterior cruciate ligament (ACL) injuries in netball players (Chong & Tan, 2004).

C. ANTERIOR CRUCIATE LIGAMENT (ACL) INJURIES

1. Introduction

Anterior cruciate ligament (ACL) injury is one of the most serious injuries in sport that can have long-term consequences on other joint structures and cause other pathological knee conditions (Yu & Garrett, 2007). Non-contact ACL injuries usually occur due to different mechanisms of knee loading and require good understanding of the anatomy and biomechanics in order to identify risk factors and to develop preventative programmes (Yu & Garrett, 2007; Markolf et al., 1995).

2. Anatomy and biomechanics of the ACL

The primary role of the anterior cruciate ligament is to restrain anterior translation of the tibia at all degrees of flexion (Liu-Ambrose et al., 2003). The femoral origin of the ACL is on the medial aspect of the lateral femoral condyle (Petersen & Zantop, 2006). The average length of the ACL is 38 mm, and the average width is 11 mm and its attachment site is larger than its central dimensions (Harner et al., 1999). Various descriptions and anatomic reference points of the ACL are present in the literature. (Edwards et al., 2007) divided the ACL into two functional bundles, although many authors do not believe an anatomic separation exists The differentiation of the ACL into two functional bundles, the antero-medial and postero-lateral bundle, seems an oversimplification, but the two bundle description of the fibers of the ACL has widely

8

been accepted. The ACL inserts onto the tibia in the anterior inter-condylar area (AIA), (Petersen & Zantop, 2006). The proprioception of the ACL comes from mechanoreceptors including Ruffini endings, Pacinian corpuscles, and Golgi tendon organ (Mir et al., 2014). Mechanoreceptors from the joint serve to enhance muscle stiffness which is crucial for dynamic joint stability (Riemann & Lephart, 2002).

The primary motion of the knee is flexion and extension in the sagittal plane and according to Fu et al (1993) range of motion averages from 0 to 135 degrees. In order to provide proper mobility and stability during different static and dynamic tasks, good interaction between intra-articular structures and surrounding musculature is essential (Andriacchi & Alexander, 2000). As already noted, the ACL have been described as a primary stabilizer of the tibial antero-posterior translation, but also acts as a secondary stabilizer against internal rotation of the tibia and valgus angulation of the knee (Buoncristiani et al., 2006). The position of the knee joint affects the force transmitted through the ACL bundles. According to Gabriel et al. (2004) there was no difference in stress between bundles at 15 and 30 degrees of flexion. The authors used robotic/universal force-moment sensor (UFS) testing system to test ten cadaveric knees by applying 134N of external load in different knee positions. The greatest force transmitted through antero-medial bundle was at 60 to 90 degrees of flexion, while the greatest force transmitted through the postero-lateral bundle was at maximal extension (Gabriel et al., 2004). The majority of ACL injuries occurs when the knee is maximally extended, which means that the postero-lateral bundle plays a more important role in the biomechanical stability of the knee (Gabriel et al., 2004). Markolf et al. (1995) tested the effects of anterior shear force at the proximal end of the tibia in combination with knee valgus, varus and internal/external moments. ACL loading was recorded from 90 degrees of knee flexion to 5 degrees of hyperextension while the 100N of the anterior shear force were added to cadaver knees. The results of this study showed that ACL loading was greater when anterior shear force was applied combined with knee valgus or varus moments. Therefore, proper stability of the knee in full extension is of crucial importance to athletes whose activities frequently involve jumping, cutting and deceleration (Liu-Ambrose et al., 2003), such as netball players.

3. Neuromuscular imbalances, movement deficiencies and ACL injury risk

Female athletes often land with higher knee abduction moments (valgus torque) and the study by Hewett et al. (2005) showed that a larger knee valgus plays a crucial role in ACL injury prediction. Their study included 205 females from different sports such as basketball, soccer and volleyball. 3D motion analysis was used to measure neuromuscular control (joint moments and angles) during jump-landing tasks. Nine athletes experienced an ACL injury and they had 2.5 times greater knee abduction moments ($p<0.001$) and 20% higher ground reaction force ($p<0.05$) than the uninjured group. Specificity of the dynamic knee valgus to predict ACL injury was 73%, while sensitivity was 78%. Co-activation of the quadriceps and hamstring muscle groups is crucial for providing muscular stability of the knee. The efficient and effective work of these muscles supports the ACL in counteraction of anterior tibial translation (White et al., 2003).

According to Malinzak et al. (2001) and Hewett et al. (1996) female athletes showed greater activity of the quadriceps muscle and less activity of the hamstring muscle group compared to men. Quadriceps dominance increases anterior shear forces to the tibia and ACL (Hewett et al., 2010) and adequate activation of the hamstrings and gastrocnemius is needed to stabilize the knee joint. Compared to men, females showed reduced activity of the hamstrings and asymmetry in the activation of the gastrocnemius during change of direction and landing (Landry et al., 2007). Significant differences in hamstrings strength were also found in the study of Lyons (2001) that evaluated 20 college students (10 males and 10 females). The authors measured isokinetic strength of the quadriceps and hamstrings for flexion and extension using the Biodex System 3. The subjects performed three maximal contractions at each speed with one minute rest between speeds. The results showed less hamstring strength ($p=0.04$) in females and the authors suggested training programmes that targets hamstring strength and activation in order to decrease vulnerability of the ACL. In the study of White et al. (2003), 51 soccer players (26 males and 25 females) were used to evaluate EMG power spectra of the quadriceps and hamstrings muscles during dynamic exercises. Bipolar surface electrodes were attached to the biceps femoris and vastus medialis obliquus muscle and three sets of two-minute bouts of isokinetic knee flexion and extension were performed at 40% of maximal voluntary contraction (MVC).

The study results showed significantly increased quadriceps coactivation ratios in females ($p< 0.01$) during knee flexion. The authors concluded that increased quadriceps coactivation in females may increase anterior tibial load which can affect the integrity of the ACL during athletic activities.

Female athletes whose ligaments absorb significant amounts of ground reaction force rather than muscles during single-leg landing, pivoting, or deceleration, exhibit ligament dominance (Hewett et al., 2010). The proper recruitment of the posterior kinetic chain muscle group is crucial to absorb ground reaction force or it will be absorbed by ligaments which can lead to their injury (Hewett et al., 2010).

Progesterone and estrogen is suggested to play a role in ACL injuries among female athletes in the premenstrual phase by affecting the collagen mechanism and decreasing neuromuscular performance (Wojtys et al., 2002; Slauterbeck et al., 2002; Hewett et al., 2007). According to Wojtys et al. (1998) females are in higher risk of ACL injury during ovulatory phase of the menstrual cycle than during postovulatory phase. The study included 40 female athletes with ACL injuries and 28 of them met the criteria of non-contact injury and regular menstrual periods. The authors found significant relationship between ovulatory phase of the menstrual cycle and the likelihood for an anterior cruciate ligament injury. Hass et al. (2003) analyzed joint kinematics of the lower extremities among 16 prepubescent and 16 postpubescent female recreational athletes during three types of jump (stride jump followed by a static landing, a ballistic vertical jump, and ballistic lateral jump). The results showed that postpubescent athletes had 30% greater extension moment at landing, 4.4 degrees greater knee extension, and 40% greater knee power and greater knee anterior/posterior forces as well as medio-lateral resultant forces.

Stijak et al. (2008) found a greater slope of the lateral tibial plateau and lesser slope of the medial tibial plateau in a group of athletes who sustained an ACL injury, but no other studies supported this evidence. The study consisted of group of patients with ACL lesion and group with patellofemoral pain. MRI and radiography were used to measure tibial slope. The study results showed significantly greater ($p<0.001$) lateral tibial slope in the group of patients with ACL injury. Hughes and Watkins (2006) allocated fatigue as a general risk factor for ACL injuries.

Tamura et al. (2017) investigated the influence of fatigue on dynamic alignment and joint angular velocities of the lower extremities during a single-leg landing in the study that included 34 college female athletes. The fatigue group performed single-leg drop vertical jumps before and after pedalling a bike ergometer at 100 W per minute for five minutes. The study results showed that peak hip flexion and knee flexion angular velocities ($p < 0.05$) increased significantly after the fatigue protocol. The authors of the study suggested that fatigue has a negative impact on the capacity to perform deceleration movements in the lower limb joints during landings.

According to Hewett et al. (2005) and Zazulak et al. (2007) poor neuromuscular control of the lower extremity kinetic chain and poor ability to control trunk position during athletic tasks shows significant relationship with ACL injury incidence in female athletes. In the study of Zazulak et al. (2007), 277 collegiate female athletes were tested for displacement of the trunk after a sudden force release. The athletes were followed for the next three years to track the number of all knee injuries during that period. The trunk response to sudden unloading was measured by electromagnetic device placed on the athlete's back at approximately the T5 level, and the loads were applied by system of pulleys. The athletes were placed in wooden apparatus and sat in semi-seated position. The pelvis and lower limb joints were restraint to prevent any postural adjustments other that spine. Athletes were allowed to perform five trials at 30% of the maximal isometric trunk exertion previously established (108N for males and 72N for females). Flexion, extension and lateral flexion angular displacement were measured at 150 milliseconds after the release. The results of the study showed that ACL ligament injured female athletes (4 of 11 knee injured) demonstrated greater maximum displacement in all three directions than uninjured female athletes ($p = 0.005$). Trunk displacements in all three directions predicted ACL injuries with 83% sensitivity and 76% specificity ($p = 0.002$).

4. ACL injuries in netball

About 66% of all anterior cruciate (ACL) injuries are non-contact injuries (Boden et al., 2000). Research by Hewett et al. (2006) has shown that female athletes had a four to six times greater risk of ACL injury compared to the male counterparts.
Adding to the greater risk, female team sport players also suffer significantly higher rates of ACL injuries than the male athletes in the same sport, with rates of two to ten times higher (Silvers & Mandelbaum, 2007) and two to eight times higher (Arendt & Dick, 1995) being reported.

There is currently limited literature on the number of ACL injuries among female netball players in South Africa compared to Australia and New Zealand. According to Hopper et al. (1995) representation of ACL injuries in Australia was 1.8% of total injuries sustained between 1985 and 1989. 14.8% of hospitalisation related to netball were due to ACL injury (Flood & Harrison, 2006). According to Janssen et al. (2012) netball has a rate of 188 injuries per 100,000 participants in comparison to the annual incidence of ACL injuries of 52 per 100,000 participants in the Australian population. Flood and Harrison (2009) reported 17.2% of hospitalisations due to ACL injury in female netball player population. Hopper et al. (1995) showed lower injury incidence rates of 19 ACL injuries per 100,000 netball players, while Gianotti et al. (2009) reported 47% of non-contact ACL injuries among netball players in New Zealand.

The rupture of anterior cruciate ligament is the most traumatic type of knee injury among netball players, often resulting in early retirement of many players (Hopper et al., 1995). The combination of deceleration, landing and change of direction are frequently implicated in non-contact ACL injury (Hewett et al., 2005), which is characteristic of cutting manoeuvres or one-leg landing in netball (Nagano et al., 2010). During these activities the ACL experiences high loads when anterior directed forces are applied to the tibia (Woo et al., 1998). When a netball player's foot contacts the ground at landing, the player experiences a ground reaction force that has vertical and horizontal (braking) components. Vertical ground reaction forces at landing after performing an attacking movement pattern have been reported to be about four times the player's body weight (Steele & Milburn, 1987).

13

5. Landing in netball and ACL injury risk

Landing in netball has been described as basic component of most netball skills and movements such as leaping to catch a pass, rebounding after an attempted goal or to decelerate the body after a defensive deflection (Steele, 1990). The netball footwork rules have a major influence on landing techniques. A player receiving the ball while in the air is permitted to land either one or two feet. The player then can only take a maximum of one-and-a-half steps while in possession of the ball (Steele & Milburn, 1987).

The player must decelerate rapidly when catches the ball and adopt a position that provides stability so not to affect the footwork rule (Steele & Lafortune, 1989). Stability at this moment is controlled largely by the eccentric work of the lower limb muscles (Hopper et al., 1992). Every time a netball player's foot touches the ground at landing, the player experiences vertical and horizontal ground reaction forces. Steele and Milburn (1987) found that vertical ground reaction forces at landing in netball are in order of four times a player's body weight after performing a typical attacking movement pattern. Ground reaction force follows the centre of mass, and if it is directed laterally to the knee, the ligament dominant athletes are in higher risk of ACL injury during landing due to more frequent manifestation of valgus position (Hewett et al., 2010). Also, peak vertical force at landing is attained very quickly (18-32ms). A player can stop quickly after catching the ball, only by applying an appropriate horizontal braking force (Steele & Lafortune, 1989). According to Steele and Milburn (1987) peak braking forces are high, from 4.2 to 4.6 times player's body weight. Proper recruitment of posterior chain muscles is very important in order to decrease and absorb reaction forces, both vertical and horizontal breaking (Hewett et al., 2010).

The excessive impact forces can adversely affect the musculoskeletal system, and therefore should be reduced (Nigg, 2001). If the player's musculoskeletal system is properly aligned, the body should be able to tolerate these high stresses, but any misalignment or unusual foot placement may lead to injury (Steele & Milburn, 1987). Strategies for muscle activation and recruitment, as well as movement pattern techniques could potentially help to reduce impact forces (Gamble, 2011).

A simple rule change in terms of allowing players to take an extra step after catching the ball could potentially decrease the incidence of knee injuries (Egger,1990), but there is lack of supportive research pertaining to the suggestion. Steele and Milburn (1987) also suggested some rule changes in order to reduce stress caused by high breaking forces. They proposed that players should be allowed more time over which to slow down, thereby reducing the breaking forces required at landing. Steele (1986) suggested that breaking forces can be reduced by throwing higher passes, requiring the player who catches the ball to jumps upwards.

Further analysis on possible modifications lead Steele and Milburn (1988) to conclude that changing the passing technique has a greater benefit on reducing the risk of lower limb injury than changing the footwork rule.

Stuelcken et al. (2016) analyzed videos of 16 ACL injuries during televised games in order to investigate potential mechanism of injury among high level netball players. The authors identified two injury scenarios. In the first scenario a player experienced a perturbation in the air which caused unbalanced landing. In the second scenario a player had good position during grounding but the alignment of the trunk was suddenly altered before the landing was completed. Rotation and lateral bending of the trunk have not been followed by proper alignment of the feet. Knee valgus collapse was found in both scenarios (3/6 Scenario A cases and 5/6 Scenario B).

6. Summary

The literature on ACL injuries is substantial and we have a very good understanding of the mechanics behind the contact and non-contact ACL injuries in sports. Horizontal and vertical forces during landing and cutting movements may be dissipated and better controlled by improving the neuromuscular control of the kinetic chain starting with trunk control and inter and intra limb neuromuscular balance and coordination. Considering that each sport may lead to overdevelopment of specific muscle groups, one of the main tools in ACL injury prevention would be to develop appropriate screening tools for ACL injury risk from comprehensive physical and functional evaluation of players in a specific sport.

6. Summary

The literature on ACL injuries is substantial and we have a very good understanding of the mechanics behind the contact and non-contact ACL injuries in sports. Horizontal and vertical forces during landing and cutting movements may be dissipated and better controlled by improving the neuromuscular control of the kinetic chain starting with trunk control and inter and intra limb neuromuscular balance and coordination. Considering that each sport may lead to overdevelopment of specific muscle groups, one of the main tools in ACL injury prevention would be to develop appropriate screening tools for ACL injury risk from comprehensive physical and functional evaluation of players in a specific sport.

D. SCREENING TOOLS FOR ACL INJURY RISK

1. Introduction

According to Sadoghi et al. (2012), 80% of all ACL injuries are non-contact and could possibly be prevented. Deficits in neuromuscular control of the lower extremities, peculiar to female athletes, are linked to mechanism of ACL injury (Hewett et al., 2005). Modifiable risk factors related to altered neuromuscular control of lower extremities and the trunk have become the focus of recent studies in an attempt to identify athletes at higher risk of ACL injury (Zazulak et al., 2007; Sadoghi et al., 2012).

Simple and practical screening tools which could identify modifiable and non-modifiable risk factors, including neuromuscular imbalances and movement patterns, are needed. These tools could identify athletes at higher risk of injury who could benefit from a pre-participation intervention programme (Boden et al., 2010). Many researchers proposed that sports medicine needs a test that provides a more functional approach to identify imbalances and movement deficiencies (Meeuwisse, 1991).

2. Clinical tests

Passive knee stability tests

Early recognition of the unstable knee that can be caused by ACL or some other ligament injury is essential for determining type of treatment or training models. Although MRI and arthroscopy are the most accurate tests for detecting the integrity of the ACL, some manual clinical tests are used very often due to their reliability, availability, durability and because of these tests are non-invasive and easy to perform (Mulligan et al., 2015). The most commonly used clinical tests for detecting the presence of an ACL injury are the Anterior drawer test, Lachman test and Pivot-shift test (Benjaminse et al., 2006), while frequently used tests for detecting medio-lateral knee instability are valgus stress test and varus stress test (Rossi et al., 2011).

Anterior drawer test

Examination of the integrity of an ACL using the anterior drawer test requires that the patient lies on his back with flexed hip to 45 degrees and knee flexed to 90 degrees while the other leg is resting on the table. The examiner's hands should be placed behind the patient's knee while pulling the tibia forward by applying anterior directed force in order to evaluate tibial translation (Benjaminse et al., 2006). The test is considered to be positive if there is increased anterior tibial motion on the injured side compared to the other. A zero to three mm of anterior tibial movement is considered as normal while grade 1 implies up to 5 mm. Grade 2 represents 5 to 10 mm, and grade 3 more than 10 mm of tibial translation (Benjaminse et al., 2006).

Makhmalbaf et al. (2013) showed high sensitivity of the anterior drawer test (94.4%), with differences between females (72.7%) and males (95%), but without age related sensitivity. Ostrowski (2006) reported the results of eight studies that showed sensitivity values in a range from 0.18 to 0.92 and specificity from 0.78 to 0.98. Kim and Kim (1995) reported 79.6% of positive anterior drawer test in a group of 147 patients with chronic injuries of the arthroscopically proved ACL injuries. The study of Liu et al. (1995) showed similar sensitivity of the anterior drawer test (61%) while Katz and Fingeroth (1986) described the anterior drawer test as a poor diagnostic tool for identifying an ACL injury due to its low sensitivity (40.9%).

Lachman test

The Lachman test is performed in supine position with examiner's one hand on patient's involved femur in 20 to 30 degrees of knee flexion and other hand on posterior tibia. The examiner applies an anteriorly directed force in order to examine anterior translation of the tibia and the test is considered to be positive if 3 to 5 mm of tibial displacement is found compared to the other knee (Benjaminse et al., 2006). Up to 2 mm of tibial translation is assumed as normal result, 6 to 10 mm abnormal and more than 10 mm is considered as abnormal anterior translation of the tibia and indicates an ACL rupture (Benjaminse et al., 2006).

Ostrowski (2006) presented results of nine studies related to specificity and sensitivity of the Lachman test. Sensitivity values were ranging from 0.63 to 0.93 and specificity from 0.55–0.99. Kim and Kim (1995) found very high specificity of the Lachman test (98.6%) among 147 patients with ACL tear proved by arthroscopy. Van der Plas (2005) showed results of 17 studies which dealt with the analysis of sensitivity and specificity of the Lachman test. The authors reported high average values of sensitivity (86%), as well as specificity (91%). Makhmalbaf et al. (2013) also reported high sensitivity of Lachman test (93.5%), as well as Thapa and Lamichhane (2015) who reported 91.42% for sensitivity and 95.55% for specificity. The high specificity could be explained by maximal tension in the ACL seen by Rosenberg and Rasmussen (1984) while examining 20 subjects with no knee pathology using Lachman test. Authors found greater tension of the ACL and less protective muscle activity at degrees of knee flexion than at 90.

Valgus stress test

The valgus stress test is a commonly used test to examine the integrity of the medial collateral ligament and could be performed with a fully extended knee and in 30 degrees of knee flexion (McClure et al., 1989). When performed in full extension, the valgus stress test also provides information about the ACL condition (McClure et al., 1989). In order to create passive abduction of the tibia, the examiner applies medial (valgus) force with one hand on the outside of the knee while holding the ankle with the other hand (Reider, 1996). The grading system from 1 to 3, which is the same as

the FMS® scoring method, is based on the opening of the tibio-femoral joint space. Grade 1 represents from 0 to 5 mm of medial joint space opening, grade 2 assumes 5 to 10 mm and grade 3 more than 10 mm (Hughston et al., 1976).

Only few studies have been done with the aim to investigate reliability, sensitivity and specificity of the valgus stress test. McClure et al. (1989) showed a 68% agreement between examiners with 0.6 of inter-rater reliability when the test was performed in maximal knee extension. With the knee at 30 degrees of knee flexion, inter-rater reliability was 0.16 with 56% intra-examiner agreement. Correlation between MRI results and valgus stress test has been investigated by Mirowitz and Shu (1994) who reported 0.73 for the injuries of the medial collateral ligament which is supported by 96% of sensitivity presented by Garvin et al. (1993) and 86% by Harilainen (1987).

Varus stress test

In order to evaluate lateral knee stability and the integrity of the lateral collateral ligament, practitioners often use the varus stress test that can be performed with the knee in full extension and in 30 degrees of flexion while the patient lying supine (McClure et al., 1989). The test should be carried out with the examiner's one hand on medial side of the patients knee while other hand is holding the ankle. The examiner then applies a varus (lateral) force to the knee and assesses joint opening through the established scoring system from 1 to 3 (Hughston et al., 1976). If the examiner notes 0 to 5 mm of joint opening it means that the patient has a grade 1 ligament strain. Grade 2 represents 5 to 10 mm of joint opening, while grade 3 is more than 10 mm.

Although there is a lack of research related to specificity and sensitivity of the varus stress test, Harilainen (1987) reported 25% of sensitivity, but only among four patients with arthroscopically proved LCL injury. LaPrade (2008) allocated a varus stress test in combination with radiography as an objective and reproducible diagnostic tool to assess lateral compartment of the knee with high intra-observer repeatability (0.99) and high inter-observer reproducibility (0.97).

3. Summary

Passive tests are still widely used in practice despite the evidence in the scientific literature demonstrating their low sensitivity and limited relevance for ACL injury during sport performance. Most of the tests focus on identifying the integrity of the soft tissues and may be relevant for clinical and rehabilitative purposes, but do not sufficiently challenge the neuromuscular control systems which are crucial during sport performance. Therefore, recently more attention is given to functional screening tools including neuromuscular imbalances and movement patters for assessment of risk injury, although passive tests should not be excluded from examining integrity of joint structures.

E. FUNCTIONAL MOVEMENT SCREEN (FMS®)

1. Introduction

The FMS® has been initially introduced by Cook et al., (2006a), with a more recent publication by the authors (Cook et al., 2014a) on research involving the FMS®. The FMS® is currently one of the most well-researched movement screens available. The FMS® has gained a lot of popularity among fitness and sports medicine professionals (Chimera & Warren, 2016) and has become the movement screen of choice in many athletic settings.

2. Purpose of the FMS®

The functional movement screen (FMS®) is accepted as a predictive and reliable tool designed to evaluate the body's kinetic chain and general quality of movement, looking at the areas of deficient mobility and stability (Schneiders et al., 2011). It is intended for individuals who do not have a current injury or pain and its goal is to identify movement pattern limitations in order to prescribe individual corrective exercises to normalize movement before increasing physical demands with training (Cook et al., 2006a).

The FMS® is not designed as a diagnostic tool, it serves a directional role and it is meant to put individuals in positions where imbalances, weaknesses, asymmetries and the movement compensations become noticeable.

After the compensation in movement pattern is found, identifying the primary cause is of vital importance before isolated tests are implemented (Howe & Cushion, 2017).

According to Cook (2017), the kinetic chain could be evaluated by using the "joint by joint approach" that explains the tendency of certain joints to be mobile and other to be stable. Untreated or inappropriately treated previous injury may decrease proprioceptive input which will later have negative effects on mobility and stability, leading to compensatory movement patterns (Cook et al., 2014a). With increasing intensity of physical activity these compensatory movement patterns lead to a poor biomechanics that contributes to greater risk of injury (Chorba et al., 2010). The FMS® has gained a lot of popularity among fitness and sports medicine professionals due to the fact that is easy and quick to administer, doesn't require expensive equipment, and it showed good reliability and consistency in scoring (Chimera & Warren, 2016).

The FMS® is comprised of seven movement tests that have a defined grading system (deep squat, hurdle step, inline lunge, shoulder mobility, active straight leg raise, trunk stability push up, rotary stability) and three clearing exams (impingement clearing test, press up clearing test, posterior rocking clearing test). Each test serves to pinpoint specific areas of movement limitations and asymmetries, and requires proprioception, balance, flexibility, proper range of motion and strength (Kiesel et al., 2007). According to Kiesel et al. (2007), all of the seven movement tests of the FMS® can be used to rate general movement quality, balance and muscle compensations. The authors of the FMS® divided all seven tests into the "big three" (deep squat, hurdle step, in line lunge) and the "small four" (shoulder mobility, active straight leg raise, trunk stability push up, rotary stability) (Chimera & Warren, 2016).

3. Movement tests

The "big three" and ACL injury risk

The first three tests, called "Big three" (Chimera & Warren, 2016), belong to the dynamic stability group of tests and they can be of special relevance for the assessment of the ACL injury risk, because they represent three different common foot positions in sport and daily activities.

Deep squat (DS) test

The deep squat (DS) test challenges total body mechanics assessing bilateral, symmetrical, functional mobility of the hips, knees, ankles, shoulders and thoracic spine (Cook et al., 2006a). The squat probably involves the greatest simultaneous display of stability and mobility of all the tests in the FMS®. The deep squat pattern requires closed-kinetic chain dorsiflexion of the ankles, flexion of the knees and hips, and extension of the thoracic spine, as well as flexion and abduction of the shoulders (Cook et al., 2006a). The optimal performance pattern of the squat has been described as the hips, knees, and ankles being aligned in parallel, with no medio-lateral movement, while the heels remain on the ground at all times (Kritz et al., 2009). Faulty movement patterns such as medio-lateral rotation of the hip, or knee alignment inside or outside the hip during the movement induce increases in the compressive and shear forces at the ankle, knee, and hip joints (Powers, 2010). According to Macrum et al. (2012) limited ankle dorsiflexion can lead to increased foot pronation, internal rotation of the tibia and medial knee displacement during a squatting task. Bell et al. (2008) as well as Kim et al. (2015) reported that restricted ankle dorsiflexion influences dynamic medial knee displacement (knee valgus) during double leg squatting tasks. According to Schoenfeld (2010), a properly performed deep squat requires 15 to 20 degrees of ankle dorsiflexion and 120 degrees of hip flexion. Hemmerich et al. (2006) found that the double leg squat with heels on the ground requires 34 +/- 6 degrees of ankle dorsiflexion. Limited ankle dorsiflexion, an increased Q angle and foot over-pronation could be responsible for a dysfunctional deep squat movement pattern (Stiffler et al., 2015).

Excessive trunk flexion during the deep squat can be a compensatory pattern caused by limited hip flexion (Kritz et al., 2009). Increased knee abduction torque and ligament strain can be the result of compromised dynamic stability of the lower extremities caused by poor neuromuscular control of the trunk during squatting (Zazulak et al., 2005). Butler et al. (2010) conducted a biomechanical analysis of the deep squat test and found that participants who had a score of three exhibited greater hip and knee flexion, as well as the greater extension torque of both joints than the subjects who scored one or two. Individuals can score poorly on the deep squat due to the decreased mobility and stability of the lower limb joints (Butler et al., 2010), which should also be noticeable during the active straight leg raise and trunk stability push-up test (Cook et al., 2006b). Another study related to the deep squat has been conducted by Clifton et al. (2015) with the aim to determine if performance on the deep squat can predict poor total score among 103 collegiate athletes and to determine en refer those who need further assessment. The authors found a positive correlation between the deep squat and adjusted FMS® composite score and proposed further research in order to investigate if the deep squat can predict asymmetries during the other six movement tests of the FMS®.

Hurdle step (HS)

The hurdle step (HS) assesses bilateral functional mobility and stability of the hips, knees and ankles and it is designed to challenge the body's proper stride mechanics during a stepping motion (Cook et al., 2006a). Performing the hurdle step test requires ankle stability of the support knee and hip, as well as maximal closed-kinetic chain extension of the hip. The hurdle step also requires step-leg open-kinetic chain dorsiflexion of the ankle and flexion of the knee and hip (Cook et al., 2006a). Athletes can score poorly due to poor stability while maintaining hip extension with the stance leg and/or poor mobility while performing maximal hip flexion with the step leg (Cook et al., 2006a). Restricted ankle dorsiflexion of the step leg, as well as limited hip flexion and inadequate trunk stability can affect the HS score. The ability of the lumbo-pelvic region to maintain appropriate trunk and hip posture, balance and control during staic and dynamic movement tasks, represents core stability (Mendiguchia et al., 2011).

According to Hewett et al. (2005) and Zazulak et al. (2007), ACL and other injuries of the knee could happen due to poor neuromuscular control (stability) of the trunk muscles. The hurdle step test can serve as good indicator of poor trunk (core) stability and hip imbalances.

In- line lunge (ILL)

The in-line lunge (ILL) test challenges the body's trunk and extremities to resist rotation and maintain proper alignment by placing the body in a position that will focus on the stresses simulated during rotational, decelerating and lateral type movements. This test assesses hip and ankle mobility and stability, quadriceps flexibility, knee stability, trunk (core stability) and thoracic spine and shoulders mobility (Cook et al., 2006a). Poor performance during this test can be the result of inadequate hip mobility of both legs, imbalance between relative adductor weakness and abductor tightness in one or both hips, or poor stability of the stance-leg knee or ankle. Limitations in the thoracic spine region may also affect poor performance on this test (Cook et al., 2006a). Inadequate sensory input and slow muscle response to sudden change of direction, deceleration and landing may influence dynamic knee stability (Zazulak et al., 2007). Dynamic stability of the knee joint can be affected by decreased neuromuscular control and inability to resist hip and trunk rotation which increase hip adduction and internal rotation of the femur resulting in knee valgus (Hewett et al., 2005). Deficiencies in ankle dorsiflexion may cause proximal compensations (Howe, 2017) that can also affect the ILL score.

The "small four" and ACL injury risk

Shoulder mobility *(SM)*

Although the shoulder mobility (SM) test doesn't directly affect biomechanics of lower extremities, it influences the overall FMS® score. Shoulder mobility assess bilateral shoulder range of motion including internal rotation with adduction in one shoulder and external rotation with abduction in the other, as well as scapular mobility and thoracic spine extension (Cook et al., 2006b). Shortening of the pectoralis minor or latissimus dorsi muscles, scapulo-thoracic dysfunction can cause poor performance on the test.

Active straight leg raise (ASLR)

Active straight leg raise (ASLR) test assesses the active flexibility of the hamstring and gastrocnemius-soleus complex of the leg being tested. It also represents active mobility of the flexed hip, and requires adequate extension of the down leg, adequate mobility and flexibility of the elevated leg and appropriate pelvic stabilization prior to and during the leg raise (Cook et al., 2006b). Poor performance during this test can be the result of poor hamstring flexibility, inadequate mobility of the opposite hip and/or poor core stability. Slight flexion of the knee, which can be caused by hamstring shortness or tightness, could potentially increase athlete's propensity for non-contact knee injury (Krosshaug et al., 2006). Inability to hold down leg on the ground could represent hip muscle weakness which is, according to many studies, associated with non-contact knee injuries (Niemuth et al., 2005). Alterations in muscle recruitment, including delayed activation of gluteus maximus, can cause pelvic instability during lower extremity movements (Hungerford et al., 2003). Poor leg raise may be caused by inappropriate pelvic (core) stability and proprioception. Zazulak et al. (2007) reported that impaired trunk proprioception and deficits in trunk control are predictors of knee injury in female athletes. The leg raise can also be affected by gastrocnemius and soleus tightness. Gastrocnemius and soleus tightness reduces the amount of dorsiflexion leading to excessive subtalar joint pronation and tibial internal rotation which will cause femoral internal rotation to increase the Q angle during squat or other dynamic activities (Piva et al., 2005).

Trunk stability push-up (TSPU)

The trunk stability push-up (TSPU) tests spine (trunk) stability in an anterior and posterior plane during a symmetrical closed-chain upper body movement (Cook et al., 2006b). Participants can score poorly usually due to decreased core stability that has been described as a crucial component of fundamental movement patterns (Cook et al., 2006b). Huxel Bliven and Anderson (2013) defined core stability as an interaction between neuromuscular control, local, global and load transfer muscles and specific demands of different movement tasks. Many activities in different sports, such as rebounding in netball and basketball or overhead blocking in volleyball requires good force transfer from upper to the lower extremities provided by trunk stabilizers (Cook et al., 2006b). Lack of symmetrical energy transfer along the kinetic chain in these activities, especially during landing and cutting, represents poor neuromuscular control, which may lead to potentially dangerous knee abduction (valgus) movement (Hewett et al., 2005). The same authors reported significant decrease in incidence of ACL injuries in a group of female athletes who have been undergone to core stability training. Knee abduction moment and hip adduction during landing can be reduced by neuromuscular training program (Hewett et al., 1996). Hence the FMS®, that includes mobility and core stability components, can be improved by corrective exercise program (Kiesel et al., 2011), it seems plausible that improving the overall FMS® score could have positive impact on reducing the number of risk factors related to ACL injury in netball, which is one of the hypotheses of this study.

Rotary stability (RS)

Rotary stability (RS) represents trunk stability and core activation through the reciprocal motions of the upper and lower extremities in transversal and sagittal planes and requires proper neuromuscular coordination and energy transfer (Cook et al., 2006b). As already noted, deficits in core stability may cause certain trunk displacement and perturbations during many athletic activities which makes the athlete more susceptible to ACL injuries (Hewett et al., 1996). Hence the female athletes are at higher risk of the ACL injuries than males due to their tendency to reduced core stability (Ireland et al., 2002) results of several studies related to FMS® support this statement. According to Schneiders et al. (2011), Hotta et al. (2015) and Perry and Koehle (2013) female participants scored less on core stability related tests (trunk stability push-up and rotary stability) than males.

Clearing exams

After shoulder mobility test, a clearing exam called impingement clearing test (ICT) should be performed in order to investigate presence of shoulder impingement. If any painful sensation is present, further clinical diagnostic is needed (Cook et al., 2006b).

Press up clearing test (PUCT), in form of spinal extension, serves as indicator of pain and should be performed after trunk stability push-up test. If an athlete reports any pain during this exam, medical evaluation is necessary (Cook et al., 2006b).

Posterior rocking clearing test (PRCT), in form of spinal flexion shows the presence of pain during this movement task, and must be performed following the rotary stability test (Cook et al., 2006b).

4. Scoring the FMS®

The FMS® scoring consists of four possible scores range from zero to three with the maximum overall score is 21. All the scores, asymmetries and pain should be noted in order to create a "movement profile" of the person which is crucial for rehabilitation, fitness and sport-specific activities (Cook et al., 2014b). If the tested person reports pain anywhere in the body during the movement pattern, a score of zero is given, and the painful area is noted and referred for medical diagnostic (Cook et al., 2014a). A score of one is given if the person is unable to perform the movement pattern even with compensations or is unable to assume starting position for that pattern. If the person is able to perform the required movement pattern with certain compensations a score of two is given (Cook, et al., 2014a). A maximum score of three is given if the person is able to perform movement pattern with no compensatory movements. Five of the seven movement tests in the FMS® examine right and left sides and if any asymmetries between sides are noted, the lower of the two scores from both sides is recorded as the total score for that movement pattern (Cook et al., 2014a).

5. FMS® score and injury risk

To date, multiple studies have been conducted related to FMS® score and injury risk, but there is significantly lack of research on the relationship between FMS® and ACL injuries. The cut-off total score of 14 on the FMS® is widely accepted due to significant correlation with injuries (Kiesel et al., 2007; O'connor et al., 2011; Chorba et al., 2010; Lisman et al., 2013). On the other hand, study of Peate et al. (2007) reported the cut-off score of 16 while Kiesel et al. (2011) used 13 as a failure score. Shojaedin et al. (2014) reported that athletes who scored less than 17 had 4.7 greater chance of suffering an injury of the lower extremities. Possible limitations of these studies could be differences in sample size in terms of nature and number of the participants as well as different definition of injury.

Chorba et al. (2010) found that female collegiate athletes had the greater odds for sustaining the lower extremity injuries according to the six other tests when the shoulder mobility (SM) test did not enter the final result. This result suggests that certain modifications of the FMS® could be useful for the prediction of the specific sport related injuries. Garrison et al. (2015) reported that collegiate athletes with total FMS® score of 14 or below, had at 15 times greater risk of injury. The study of Butler et al. (2013) revealed that firefighters who scored 14 or less on FMS® also had increased risk of injury while Onate et al. (2012) reported that previous injury can be responsible for lower FMS® score. The same authors concluded that participants who scored poorly on FMS® have more chance to become injured. The study of Letafatkar et al. (2014) showed that subjects with score less than 14 were at 11.7 times higher risk of an acute lower extremity injury. Frost et al. (2017) analyzed relationship between FMS® composite score and frontal plane knee motion in a group of 60 healthy firefighters. The authors of the study found that participants with FMS® score lower than 14 exhibit greater frontal plane knee motion. In the study of Hammes et al. (2016), 238 veteran football players older than 32 were recruited and followed during 9 months in order to examine ability of the FMS® to predict injuries in this athletic population. Players with score lower than 10 had significantly higher incidence of injury ($P < 0.05$), but players who scored 14 or more did not have lower injury incidence. The authors found limited suitability of the FMS® to predict injuries in veteran football players.

6. Reliability and validity of the FMS®

Several studies have been done with the aim of investigating the validity and reliability of the FMS®. Shultz et al. (2013) found good test-retest reliability (r=0.6) and excellent reliability for the live versus video testing (0.9), but poor interrater reliability (r=0.38). Study of the Onate et al. (2012) showed high intersession reliability (0.92) for the total score, and 0.98 for the interrater reliability. Teyhen et al. (2012) also found moderate to good interrater (r=0.76) and intrarater (r=0.74) reliability of the FMS®. According to Leeder et al. (2016) FMS® shows high interrater reliability (r=0.90) which is consistent with the study of Minick et al. (2010) that showed similar results (r=0.7-1), and Hotta et al. (2015) who reported excellent interrater reliability (0.92). Gulgin and Hoogenboom (2014) found good to excellent consistency between novice and experience raters (r=0.76-0.94) in the study that included 20 healthy college athletes with average composite score of 14.6 ± 1.9. Schneiders et al. (2011) reported excellent interrater reliability (r=0.70- 1.0) for individual test components as well as for the composite FMS® score (r=0.97). Studies of Gribble et al. (2013) and Smith et al. (2013) showed different reliability between raters with different experience in FMS® testing. According to Gribble et al. (2013) less experienced raters had poor intrarater reliability (r=0.37) while the experienced one had 0.95. Good intrarater reliability (r=0.81-0.91) was found in the study of Smith et al. (2013). Parenteau et al. (2014) reported high interrater reliability (r=0.96), as well as 0.8 reported by Frohm et al. (2011). Excellent interrater (r=0.8) and intrarater reliability (r=0.81) was found in the meta- analysis conducted by Bonazza et al. (2016). The authors also found that subjects who scored less than 14 had 2.74 times higher likelihood of an injury.

To date, multiple studies have been conducted related to FMS® score and injury risk, but there is a significant lack of research on the relationship between FMS® and ACL injuries. The cut-off score of 14 is widely accepted after the study of Kiesel et al. (2007), supported by O'Connor et al. (2011), Chorba et al. (2010), Lisman et al. (2013). On the other hand, study of Peate et al. (2007) reported the cut-off score of 16 while Kiesel et al. (2011) used 13 as a failure score. Shojaedin et al. (2014) reported that athletes who scored less than 17 had 4.7 greater chance of suffering an injury of the lower extremities. Possible limitations of these studies could be differences in sample size in terms of nature and number of the participants as well as different definition of injury.

Chorba et al. (2010) found that female collegiate athletes had the greater odds for sustaining the lower extremity injuries according to the six other tests when the shoulder mobility (SM) test did not enter the final result. This result suggests that certain modifications of the FMS® could be useful for the prediction of the specific sport related injuries. The study of Butler et al. (2013) revealed that firefighters who scored 14 or less on FMS® also had increased risk of injury while Onate et al. (2012) reported that previous injury can be responsible for lower FMS® score. The same authors concluded that participants who scored poorly on FMS® have more chance to become injured. The study of Letafatkar et al. (2014) showed that subjects with score less than 14 were at 11.7 times higher risk of an acute lower extremity injury. Frost et al. (2017) analysed relationship between FMS® composite score and frontal plane knee motion in a group of 60 healthy firefighters. The authors of the study found that participants with FMS score lower than 14 exhibit greater frontal plane knee motion.

To date, a few studies have been conducted with aim to determine normative values of the FMS®. Fox et al. (2014) reported average score of 15.6 ± 1.5 for 62 Gaelic football players, which is similar to the findings of Loudon et al. (2014) who reported 15.4 ± 2.4 among 43 runners. The study of Schneiders et al. (2011) showed an average FMS® score of 15.7 ± 1.9 in a group of 209 physically active individuals of both sexes between 18 and 40 years with no recent history of injury. Perry and Koehle (2013) found strong correlation between body mass index, age and level of physical activity with FMS® score. Participants with body mass index higher than 30 scored less on the FMS® compared to participants with lower body mass index.

Several studies have shown that FMS® score could be improved by corrective exercise programme. The Study of (Kiesel et al., 2011) found greater number of NFL players with score more than 14 after intervention as well as the increased number of individuals free of asymmetry. Bodden et al. (2015) found significant increase in the FMS® score and greater number of participants free of asymmetry after the 8 weeks of intervention among MMA fighters. The study of Cowen (2010) showed that yoga classes could improve FMS® score among firefighters. Another interesting study conducted by An et al. (2012), showed that application of kinesiotaping improved score on the hurdle step test (HS) although there was no improvement on deep squat (DS) and in line lunge (ILL) test.

Relationship between FMS® score and strength and flexibility, has been analyzed by Song et al. (2014). The authors found significant improvement in strength and flexibility among high school baseball players after 16 weeks of FMS® corrective exercise programme.

7. Summary

To date, multiple studies have been conducted related to FMS® score and injury risk. According to literature, the FMS® has limited capability for injury prediction. The main problem is that most of these studies are related to various injuries in different sports, with the focus on the cutt off score of 14. Looking only at the total score does not provide clear picture of a person's biomechanics and can not be taken for every sport. It seams that a sport-specific (modified) FMS® test would be stronger injury predictor. Based on the literature FMS® can be considered as screening tool with good reliability and good response to corrective exercise program, but further research is needed in order to investigate if improved FMS® score can reduce injury risk, in particular ACL injury in netball.

F. FMS® AND ATHLETIC PERFORMANCE

1. Introduction

Many people are able to perform different athletic performance tasks but still show certain limitations while tested on FMS®. According to Cook et al. (2006b) those who showed limitations and movement deficiencies on the screen often use compensatory movement patterns during regular sporting activities. Movement compensations could affect biomechanics of the athletic tasks which is risk factor for possible injuries in the future.

FMS® is intended to identify dysfunctional movement patterns (Cook et al., 2006a). Numerous research studies have investigated the relationship between FMS® score and athletic performance.

2. FMS® and athletic performance

Lloyd et al. (2015) investigated relationship between FMS® and performance test in a group of 30 young soccer players aged from 11 to 16 years. The players were assessed for FMS® score, squat jump, reactive strength index protocol, agility and maturation. The authors found significant correlation between FMS® tests (deep squat, in-line lunge, active straight leg raise and rotary stability) and all performance tests while the strongest predictor of squat jump performance was maturation (adjusted R2 = 46%). Venter et al. (2017) found positive correlation between total FMS score and 5-0-5 agility test among 20 university female netball players. Players with higher total FMS® score had better results on 5-0-5 test (ρ=-0.52, p=0.02). The relationship between FMS®, core stability (flexion, extension, right and left lateral) and performance (backward medicine ball throw, T-run, single-leg squat) was investigated by Okada et al. (2011). They found significant correlation between hurdle-step right (r=0.415), shoulder mobility right (r=0.388), push-up (r=0.407) and rotary stability right (r=0.391) with backward medicine ball throw. Significant correlation was found between single-leg squat and shoulder mobility right (r = 0.446) while FMS® did not significantly correlate to core stability. In the study of Mitchell et al. (2015) that included 77 children aged 8-11, positive correlation was found between FMS® total score and core strength (r=0.31; p=0.006).

The relationship between FMS® and athletic performance was investigated in the study of Parchmann and McBride (2011). In a group of 25 National Collegiate Athletic Association Division I golfers (15 men and 10 female), no significant correlation between FMS® and athletic performance tasks was found. A weak correlation existed between FMS® and 10-m sprint times (r =-0.136), 20-m sprint times (r=-0.107), Vertical Jump heights (r=0.249), agility T-test times (r=-0.146), and club head velocity (r=-0.064). The authors of the study concluded that FMS® did not relate to any aspect of athletic performance.

Thirty-two male recreational team sport athletes were assessed in the study of Lockie et al. (2015) in order to investigate relationship between FMS® and multidirectional speed and jump tests. Participants were divided into three groups (higher, intermediate, lower) based on an overall research-grade FMS® score, developed by

Frost et al. (2012), with the aim to investigate whether participants who scored better in the screens, also performed better in the athletic tests. The results showed no significant differences between-group in any of the multidirectional sprint or jump tests. The deep squat (DS) showed a positive correlation with the bilateral vertical and standing broad jump, and the left-leg standing broad and lateral jump (r=0.37-0.52), while the left in-line lunge (ILL) positively correlated with the bilateral and left-leg standing broad jump, and lateral jumps for both legs (r=0.38-0.50). The other study of Lockie et al. (2015) investigated the relationship between lower body screens, FMS® score and multidirectional speed and jumping tasks. The only one significant correlation was found between deep squat (DS) and bilateral vertical jump (r =-0.428) and standing long jump (r =-0.457), as well as between-leg 5-0-5 agility difference (r =-0.423).

3. Summary

Based on current research, FMS® has minimal capabilities for predicting results on the performance in athletic tasks. However, the purpose of the FMS® is to examine the way a person moves through the fundamental movement patterns in order to determine potential compensations that could be seen during performance tasks. In this regard, it seems not useful to compare the FMS® score with performance results and might indicate a need for its modification for the needs of certain sports, as well as for sports performance in general.

G. DYNAMIC KNEE STABILITY TESTS FOR ASSESSING ACL INJURY RISK

1. Single-leg squat (SLS)

The single-leg squat is a frequently used clinical test which assesses neuromuscular control of the lumbo-pelvic region in single-leg stance (Bailey et al., 2010). According to Liebenson (2002), the single-leg squat can be used in order to identify kinetic chain dysfunctions such as knee valgus, foot over-pronation and pelvic control. Kibler et al. (2006) recommended the single-leg squat as a functional tool for evaluating core stability. Previously, the single-leg squat was used as an exercise for improving dynamic balance of the knee (Benn et al., 1998).

Single-leg squat testing scales were described by Mattacola et al. (2004), while Liebenson (2002) did the interpretation of this test as positive or negative result. According to Mattacola et al. (2004), the test is considered to be *excellent* if a subject exhibits at least 65 degrees of hip flexion, valgus/varus angulation of the knee less than 10 degrees, as well as hip abduction/adduction less than 10 degrees. A *good score* meant that he/she met any of the above two scoring criteria. If any one of the above scoring criteria were met, the subject's score was *fair*. If a subject lost balance or fell, none of the criteria were met and test execution was considered to be *poor* (Mattacola et al., 2004).

One of the movement dysfunctions that could be seen during a single-leg squat is femoral adduction or valgus overstrain (Liebenson, 2002a), which contributes to greater risk of ACL injury (Hewett et al., 2005). Increased knee valgus that could be seen in a single-leg squat test includes internal rotation of the femur, knee flexion and abduction and adduction of the hip (Wyndow et al., 2016). According to Zeller et al. (2003), female athletes had four degrees more hip adduction than men during a single-leg test. The same authors proposed that weakness of the gluteus medius muscle could be a reason for increased knee valgus when performing this test, but the study of Dimattia et al. (2005) showed no correlation between SLS and hip abduction strength. Horan et al. (2014) found that poor performance in the single-leg squat test is characterized by a decreased knee flexion angle and an increased frontal plane motion of the knee and hip pointing to other potential structural and anatomical abnormalities that could affect good performance on the test.

Foot over-pronation, which could also be seen in single-leg squat test (Liebenson, 2002), limits dorsiflexion, which further can increase knee valgus during athletic activities (Wyndow et al., 2016). According to Hopper et al. (1994), over-pronation of the foot increases the risk of lower limb injuries in professional netball. Decreased ankle dorsiflexion motion is associated with an increased frontal plane projection angle (Wyndow et al., 2016; Howe & Cushion, 2017) which is widely used for measuring knee valgus during a single-leg squat and other dynamic screening tools. Greater frontal plane projection angles represent higher knee valgus motion which can, as has been mentioned previously, predict female athletes with higher risk of ACL injuries (Myer et al., 2004).

Poor balance during the single-leg squat test, in terms of forward/backward bending, can be caused by inadequate neuromuscular control of the trunk resulting in greater hip internal rotation and adduction and an increased ACL injury risk (Zazulak et al., 2007). Loss of balance, trunk motion, or using the arms to remain in a stable position can also be associated with deficiencies in core stability (Zeller et al., 2003).

Good interrater reliability was found in the study of Weeks et al. (2012) for physiotherapists (r=0.71) and students (r=0.60), in combination with excellent intra-rater reliability for physiotherapist (r=0.81) and good for students (r=0.71) when evaluations of the single-leg squat were done. Poulsen and James (2011) investigated the validity and reliability of frontal plane knee measurements during a single-leg squat done by six physiotherapy students and a computer assessment. Authors of the study found a significant difference in reliability between students (inter-rater r=0.99 and intra-rater r=0.88-0.98) and computer generated measures (inter-rater r=0.38 to 0.94 and intra-rater r=0.68). According to Alenezi et al. (2014) all joint angles (0.85), vertical ground reaction forces (0.90) and torques (0.83) of the lower extremities showed good to excellent consistency during a single-leg squat measured in within-day and between-days assessments. According to these findings, the single-leg squat test can be used as a reliable and valid screening tool in injury prevention and rehabilitation (Ugalde et al., 2015).

2. Drop vertical jump test

Drop vertical jump test was first described by Hewett et al. (2005) as a valid test for assessing biomechanical variables that could increase the risk of ACL injury. The test is usually carried out using 31 cm box and the participants are instructed to step off the box using both feet and immediately perform maximal vertical jump (Pappas et al., 2007). Kinetics and kinematics of the knee during drop vertical jump test can be further assessed by 3D and 2D motion analysis in order to investigate valgus knee alignment and other parameters related to greater ACL injury risk (Hewett et al., 2005). The authors found that 9 from 205 female athletes who sustained an ACL injury displayed increased knee abduction angles and higher ground reaction forces during the drop vertical jump test. Although a 3D motion analysis model is considered the most valid, it is not practical and available to a large athletic population (Myer et al., 2004).

Nilstad et al. (2014) confirmed that real-time observational screening can be used in order to identify knee valgus during drop vertical jump testing. In their study, three sports physiotherapists with different clinical experience assessed frontal plane knee motion during the phases of landing and showed high inter-rater reliability (r=0.70-0.95). Real-time observational screening is easy to implement, does not require special equipment and shows consistency in scoring between raters (Stensrud et al., 2011; Nilstad et al., 2014). The scoring criteria is similar to the FMS scoring model and applies a ranking system from 0 to 2 where 0 means proper knee alignment and control, 1 represents reduced control with one or both knees slightly moving into valgus, and 2 shows poor control with an excessive valgus collapse (Nilstad et al., 2014).

In contrast to the study of Hewett et al. (2005), Krosshaug et al. (2006) investigated five factors proposed as predictors for ACL injury, including knee valgus angle and abduction moment, vertical ground reaction forces, knee flexion angle and medial knee displacement. They found that only greater medial knee displacement was associated with an increased risk of ACL injury among 338 soccer and 372 handball players, and described the drop vertical jump as a poor screening tool. Pollard et al. (2010) investigated the relationship between limited hip and knee flexion and knee valgus during the landing phase among female soccer players. They found that players with lower knee and hip flexion demonstrated 2.2 times increased knee adduction moment in comparison with the high flexion group.

Due to the fact that medio-lateral motion or displacement of the knee includes not only knee valgus but other biomechanical variables such as hip, ankle and trunk motions (Nilstad et al., 2014), Krosshaug et al. (2016) mentioned the need for some other screening tool that represents more biomechanical parameters that can be related to the development of ACL injury. The authors of the same study allocated previous knee injury as a risk factor which correlates to the philosophy of the FMS®. Based on the similar philosophy and scoring method, one of the objectives of this study is to investigate the correlation between total and partial FMS® scores and the results of drop vertical jump test, in order to possibly identify female netball players with higher risk of ACL injury.

3. Summary

Altered dynamic knee stability and valgus collapse has been found in typical ACL injury mechanism. Some of the most common neuromuscular imbalances associated with mechanism of ACL injury, among others, are quadriceps dominance, ligament dominance, leg and trunk dominance (Hewet et al., 2010). All of these imbalances can be responsible for dynamic knee valgus during athletic activities and identification of these faulty movement patterns using the single leg squat and drop jump vertical jump test is essential for the development of the injury prevention programmes.

H. PERFORMANCE TESTS

1. Single-leg hop and hold for distance test

The single-leg hop and hold for distance is a widely used functional test for dynamic knee stability in the prevention and rehabilitation of ACL and other knee injuries, capturing limb asymmetries in jumping activities (Logerstedt et al., 2012). The non-dominant leg is often at greater risk of injury due to the biomechanical variables (Myer et al., 2004). According to Brophy et al. (2010) the non-dominant leg in female athletic population is often exposed to an ACL injury. The single-leg hop-and-hold test displays differences in postural stability, neuromuscular control, strength of the quadriceps muscle and requires coordinated activation of the lower limb muscles (Zouita Ben Moussa et al., 2009). Willigenburg and Hewett (2017) found a significant correlation between FMS® scores and hop distance (r=0.38-0.56, P=0.02) in the study that included 59 collegiate football players. Cates et al. (2009) described the single-leg hop-and-hold test as an inexpensive tool that can be used in order to assess neuromuscular control, limb symmetry, and the strength of the lower leg musculature.

The test is usually performed with participants standing on the tested leg, hopping as far as possible, landing on the same leg and holding the position for three seconds (Daniel et al., 1982). Average distance, from the start to the posterior side of the heel, for the three trials is used to calculate limb symmetry index.

In order to calculate the limb symmetry index, the average distance of the dominant leg should be divided by the non-dominant average score and multiplied by 100 (Fitzgerald et al., 2001). Bahamonde et al. (2012) reported a 10% discrepancy in distance jumped between the dominant and non-dominant leg in favour of dominant limb.

A few studies have been conducted in order to investigate the relationship between the single-leg hop-and-hold test and anterior knee joint laxity. Sernert et al. (1999) reported a low correlation (0.09) measured by the Lachman test, and -0.08 measured by a KT-1000 arthrometer. Eastlack et al. (1999) found no correlation between the single-leg hop test and anterior knee joint laxity. Greenberger and Paterno (1995) and Fitzgerald et al. (2000) proposed that distance in single-leg hop test can be improved by proprioceptive and balance training. Goss et al. (2009) reported that a six week training programme based on functional movements had positive results on the single-leg hop-and-hold test and other dynamic tasks. Many studies showed high reliability of the single-leg hop-and-hold test. Booher et al. (1993) found r=0.97-0.99, Bandy et al. (1994) reported r=0.93, Bolgla and Keskula (1997) reported r=0.96. According to Ageberg et al. (2007) reliability of the single-leg hop-and-hold test was r=0.96, while Ross et al. (2002) found r=0.92. Similar values (r=0.92-0.96) were reported by Greenberger and Paterno (1995) in a group of subjects with no history of lower extremity injury.

Müller et al. (2015) investigated predictive parameters to successfully return to the same level of sport six months after ACL reconstruction. Among 40 athletes, the researchers found that the single-leg hop test had very strong predictive parameters for athletic performance. The authors also reported high sensitivity (0.74) and high specificity (0.88) of the single-leg hop-and-hold for distance test.

Ankle instability can affect knee kinematics during landing and other functional movements (Terada et al., 2014). Sekir et al. (2008) evaluated proprioception and sensorimotor control of the ankle joint using a single-leg approach in the study that included 24 male athletes with unilateral ankle instability. The results showed that testing batteries that include single-leg hopping tests can provide reliable information related to functional instability of the ankle joint.

Although the single-leg hop-and-hold test is usually used to determine limb asymmetry in an injured population, it can be, due to its excellent ability to show asymmetries, used in healthy population in order to investigate athletes at higher risk of ACL injury (Fitzgerald et al., 2001). Based on high reliability, simplicity and high single-leg landing frequency in netball, this test was chosen for this study.

2. 5-0-5 Agility test

The 5-0-5 agility test is a widely used, relatively simple test for assessing change of direction ability for each leg in many sports (Draper & Lancaster, 1985). The test is based on the time required to perform a 180-degree change in direction over a 15m long track with timing gates located at five meters before the end line where the athletes should turn. The timer starts as the athlete passes at 10m and stops at the same spot on the way back, after the turn. The time required to cover five meters before and after turn is recorded, not the first and last 10 meters (Draper & Lancaster, 1985).

Relatively few studies have been conducted in order to examine the reliability of the 5-0-5 test. Stewart et al. (2014) investigated change of direction tests including the 5-0-5 agility test with the aim to determine validity and reliability. A group of 24 male and 20 female physical education students participated in the study. The authors found high intra-class correlation (r=0.88-0.95) and a strong correlation between tests (r=0.84-0.89). Cochrane et al. (2004) reported a r=0.78 intra-class correlation for 5-0-5 agility test in a group of 24 healthy non-competitive athletes. According to Sayers (2015) performance on 5-0-5 agility test is not influenced by limb dominance.

I. ACL INJURY PREVENTION STRATEGY

Many injury prevention programmes implemented in different sports with a focus on modification of biomechanical characteristics have shown positive results in reduction of ACL injuries (Mandelbaum et al., 2005). These programmes consist of different techniques with emphasis on proper landing, cutting and deceleration mechanics, increasing muscle strength of the hip abductors, hamstring and core, as well as improving proprioception and agility (Renstrom et al., 2008).

Hewett et al. (1999) investigated the effects of neuromuscular training on the incidence of knee injuries among two groups of female athletes, one trained before sports participation and one untrained. The results showed a decreased incidence of knee injury in trained female athletes (p=0.01) after specific a six-week plyometric intervention. The incidence of knee injury in the untrained group was 2.4-3.6 higher than in the trained group, while five untrained female athletes sustained an ACL injury and no trained females sustained an ACL injury.

An overall 72% reduction in ACL injuries was achieved by Gilchrist et al. (2008). A sample of 1435 female soccer players participating in 61 teams (NCAA) were included in the study, 852 in a control group and 583 in the intervention group. The intervention programme consisted of neuromuscular control exercises as a part of on-field warm-up. The overall ACL injury rate incidence was 1.7 times less in the intervention group, while non-contact ACL injury rates were 3.3 times less than in control group. A significant reduction of ACL injuries was also found among players with ACL injury history who participated in the intervention group (*p*=0.046). Mandelbaum et al. (2005) investigated the effectiveness of a neuromuscular and proprioceptive training programme in decreasing the incidence of ACL injury in a group of female soccer players between the ages of 14 and18. The intervention lasted two years and consisted of stretching, plyometrics, agility drills, and strengthening programs designed to replace the classic warm-up drills. In the first year of intervention, a reduction of 88% in ACL injuries was noted while in second year there was 74% decrease in ACL injuries.

This is supported by the study of Wingfield (2013) who also found that a neuromuscular training programme reduces the rate of ACL injuries in female soccer players. According to Yoo et al. (2010), who analysed the effectiveness of the ACL injury prevention programs in a meta-analysis of seven cohort studies, neuromuscular training is beneficial for reduction of ACL injuries in young female handball and soccer athletes. The authors found that neuromuscular training programmes were more effective for female soccer athletes younger than 18 if performed pre-season and in-season. LaBella et al. (2011) investigated if a 20-minute neuromuscular warm-up program can be useful in order to reduce lower extremity and ACL injury rates in 1492 high school female basketball and soccer athletes. The program was based on balance, agility, plyometrics and strengthening, as well as on education how to avoid knee valgus during landing. At the end of the intervention, a 56% reduction in overall lower limb injuries was noted compared to control group. There were only two ACL injuries in the intervention group in comparison with six sustained by the players in the control group. The study of Myklebust et al. (2003) also showed that ACL injury incidence could be reduced by specific neuromuscular training. Zazulak et al. (2007) suggested that prevention programmes that include core stability, proprioceptive exercise, correction of body sway and perturbation may potentially decrease the risk of ACL injuries.

Exercise protocols related to ACL injury reduction should focus on balance, plyometrics, strength, agility, warm-up, and flexibility (Yang et al., 2011). The emphasis should be also placed on proper landing technique, avoiding knee hyperextension on landing, strengthening the hamstrings and hip abductors, as well as deceleration (Silvers & Mandelbaum, 2007). These programmes should be implemented six weeks before the season and can be implemented as a 20 minute warm-up sessions (Voskanian, 2013).

J. SUMMARY

The Functional movement screen (FMS®) already has shown positive results in identifying at-risk athletes (Letafatkar et al., 2014; Kiesel et al., 2007; Chorba et al., 2010; O'Connor et al., 2011; Garrison et al., 2015), but there is a lack of research on the relationship between FMS® and ACL injuries. Herring et al. (2006) investigated if the FMS® can be an effective tool for predicting risk of ACL injuries, but results of the study are still pending. Perry (2015) found no correlation between FMS® and the Balance Error Scoring System (BESS). Additionally, the FMS® has not been compared yet to other methods of predicting ACL injury and aim of this study is to compare it with dynamic ACL screening tools.

Dynamic knee stability is the ability of the knee joint to remain stable when it is exposed to the rapidly changing loads that occur during activity (Williams et al., 2001). Drop vertical jump, single-leg hop-and-hold and single-leg squat are commonly used tests for dynamic stability of the knee in athletes (Hewett et al., 2006; Bailey et al., 2010; Logerstedt et al., 2012). These screening tools were selected based on validity, reliability, and practicality for this study as well as due to the frequency of similar movements in netball and their relationship with netball injury mechanisms. Subjective assessment can be used to screen athletes with poor knee control during single squat as well as during drop vertical jump tests (Stensrud et al., 2011).

Agility has been tested using the 5-0-5 agility test based on its simplicity, reliability and similarity to netball running with quick change in direction.

As mentioned above, there is a lack of research in the field of prediction of the specific injuries in particular sports using the FMS®. There is also unclear whether the biomechanical risk factors associated with ACL injuries in female netball can be identified by the FMS®. Therefore, it would be useful to examine the effects of the FMS® corrective exercise programme on dynamic knee stability in female netball players in order to improve neuromuscular control of the lower extremities and potentially decrease the risk of ACL injuries. The current study was conducted with the purpose to fill the gap in the literature regarding the FMS® and biomechanics of the ACL injury in female netball.

Chapter Three

METHODOLOGY

A. INTRODUCTION

In this chapter, the specific procedures for data collection are firstly described. Secondly, the six-week intervention programme that was applied to the experimental group is explained. The methods used for the statistical analyses concludes the chapter.

B. STUDY DESIGN

The study followed a convenience sample design. Players from a high-level netball club who volunteered to participate in the study were randomly allocated to either the control or the experimental group. The experimental group participated in the intervention programme, in addition to their usual netball and fitness training. The control group continued with their regular fitness and netball training programme. Participants were tested before and after the intervention.

C. EXPERIMENTAL PROCEDURES

1. Place of study and duration of the study

Pre and post-testing was conducted in the Coetzenburg centre, at the Department of Sport Science, Stellenbosch University, which was also the venue for the duration of the six-week intervention programme.

2. Participants

For the study, 31 female university netball players volunteered for participation. Players were included if they were between 18 and 24 years old, with no musculoskeletal injury sustained in the six weeks prior to testing.

Players were excluded if they have sustained an ACL injury in the previous six months or if they were, at the time of testing, undergoing any rehabilitative protocol. Players were requested to abstain from exercise on the day prior to testing and to not use medication like pain killers or anti-inflammatory drugs. During the first visit, players were informed of the testing procedures and received an information sheet with all procedures explained. The researcher was available to answer questions and clarify aspects of the project. During the second visit each participant signed an informed consent prior to the execution of all tests. Ethics approval was obtained from the Research Ethics Committee of Stellenbosch University (SU-HSD-001873), (Apendix no.1).

3. Testing and intervention procedures

Testing was conducted in the Coetzenburg centre, on one of two indoor netball courts, covered with a synthetic surface. All testing for a specific player was completed on the same day. Players booked a testing session of an hour during the day, based on their academic availability. Players were tested at the start of the second half of the netball season. The movement patterns did not require maximum physical effort and performance tests were of short duration, therefore, fatigue due to an hour of intermittent testing on the same was not a concern. The players were asked to wear comfortable athletic clothes and netball trainers for testing. Pre-testing was done over two consecutive days and all 31 players were successfully tested during that time. When players arrived at the testing facility, anthropometric measurements were taken firstly, followed by the FMS®. FMS® was done without a warm-up (Cook, 2010) in the following order: Deep squat, Hurdle step, In-line lunge, Shoulder mobility, Impingement clearing test (ICT), Active straight leg raise, Trunk stability push up, Press up clearing test (PUCT), Rotary stability, and the Posterior rocking clearing test (PRC).

To prepare for physical testing, players went through a five-minute warm-up protocol which included: jogging, rope jumping and dynamic stretches. The warm-up was led by a research assistant with experience in strength and conditioning.

Drop vertical jump and single-leg squat tests were performed after FMS testing.

The first performance test was the single-leg hop test for distance. Players were given as much time as they wanted between each jump. However, if a player had to perform more than five jumps in an attempt to stabilise on one leg, their test was void. The second performance test was 5-0-5 agility test.

The intervention period lasted six weeks, during which time the experimental group had 18 sessions supervised by the researcher. Post-testing was conducted over three days, due to academic obligations of some of the players.

D. TESTS AND MEASUREMENTS

1. Anthropometrics

The players were asked to take off their shoes and stand on the scale for measurement of body weight using an electronic scale (SECA robusta 813, Hamburg, Germany) Standing height was measured using a stadiometer (SECA 213, Hamburg, Germany). Measurements were done by an ISAK (Level 1) qualified Biokineticist according the set protocol.

2. FMS® testing procedure

FMS® has been shown to be a reliable screening tool designed to evaluate movement patterns with high interrater (r=0.81) and intrarater (r=0.81) reliability (Bonazza et al. 2016). A Standard FMS® KIT (Functional Movement Systems, Inc., Chatham, VA, USA) was used to test all seven movement patterns. The FMS® kit contains a 2m x 6cm board, a 152.4cm dowel, two small dowel pieces and a hurdle with a movable horizontal bar or elastic string (Figure 3.1).

All FMS® assessments were done by the same researcher. The researcher is a qualified physiotherapist, as well as an internationally qualified Level 2 FMS® instructor with many years of experience in testing high-level athletes on the FMS®. The researcher performed the pre- and post-testing FMS® procedures, as well as the intervention programme. The researcher was therefore not blinded to the groups, but did not have prior knowledge of the level of the players or the teams for which they were playing.

Figure 3.1: FMS® kit

In the FMS® assessment, movement quality was rated from 1 to 3, based on following criteria:

Score of 3: Player was able to perform movement pattern without compensations.
Score of 2: Player was able to perform movement pattern with certain compensations. *Score of 1*: Player was unable to perform movement pattern.

Netball players in the current study had no previous experience of being tested on the FMS®. Before each movement pattern was performed, the researcher explained the movement to be performed. Standardized verbal instructions were given to the players and they had the opportunity to communicate with the researcher to clarify uncertainties. Three attempts for each movement was given to the individual and the best of three was scored using the official FMS® score sheet (Appendix no. 2). Because of the functionality of the movement patterns of the FMS®, three attempts are sufficient for familiarisation. When the player performed perfectly on the first attempt (correct without any compensations), a score of three was given and there was no need for further attempts. If asymmetries were noted between the left and right side during testing, a lower score of the two sides is recorded and is counted toward the total for that movement pattern.

Scoring criteria for the seven movement patterns are shown in Tables 3.2 to 3.8. FMS® has been conducted in the following order:

Deep squat: The player's feet were aligned and placed shoulder width apart in the sagital plane. The dowel rested on the top of the head while a 90 degree angle between shoulders and elbows were adjusted. The player was then asked to press the dowel overhead and squat into deepest possible position with heels on the ground, head facing forward and maximally pressed dowel and hold the position for 1 second. This task was repeated three times and if a score of three was not achieved, the player was asked to perform the same task with 2 x 6cm board under the heels.

Figure 3.2: Deep squat

Table 3.1: Deep squat scoring criteria

Score of 3	Score of 2 2x6 board under heels	Score of 1 2x6 board under heels
Upper torso is parallel with tibia or toward vertical Femur below horizontal Knees are aligned over feet Dowel aligned over feet	Upper torso is parallel with tibia or toward vertical Femur below horizontal Knees are aligned over feet Dowel aligned over feet	Tibia and upper torso are not parallel Femur is not below horizontal Knees are not aligned over feet Dowel not aligned over feet

Hurdle step: The players started with feet together and toes touching the board. The tibial tuberosity was taken as a landmark for positioning the height of the hurdle. The dowel was positioned across the shoulders and players were asked to step over the hurdle, touch the ground with the heel and return it to previous position. The players were allowed to choose which leg to start with. This movement was performed three times on each side, and moving leg was scored. Lesser total score was given if asymmetries between sides were noted.

Figure 3.3: Hurdle step

Table 3.2: Hurdle step scoring criteria

Score of 3	Score of 2	Score of 1
Hips, knees and ankles remain aligned in sagittal plane Minimal to no movement noted in lumbar spine Dowel and hurdle remain parallel	Alignment is lost between hips, knees and ankles Movement is noted in lumbar spine Dowel and hurdle do not remain parallel	Contact between foot and hurdle Loss of balance is noted

In-line lunge: The player placed the toes of one foot on the zero mark of the FMS® board and heel of the foot in front in line with opposite foot (started in the narow base lunge position).

48

Previously measured tibial tuberosity height was used to determine the distance from heel to toe. The dowel was placed behind subject's back, touching the sacrum, thoracic spine and occiput. The player grasped the dowel at the cervical spine by the hand opposite to the foot in front. The other hand was grasped the dowel behind lumbar spine. The player was then asked to descent into a lunge lowering the back knee to touch the board just behind the heel of the front foot and return to starting position.

Figure 3.4: In-line lunge

Table 3.3: In-Line lunge scoring criteria

Score of 3	Score of 2	Score of 1
Dowel contacts remain with lumbar spine extension	Dowel contacts do not remain with lumbar extension	Loss of balance is noted
No torso movement is noted	Torso movement is noted	
Dowel and feet remain in sagittal plane	Dowel and feet do not remain in sagittal plane	
Knee touches board behind heel of front foot	Knee does not touch board behind heel of front foot	

Shoulder mobility (SM): Hand length was determined by measuring the distance from the distal wrist crease to the tip of the third digit. The player was then asked to make a fist with each hand with fingers across the thumb. The player assumed a position of maximal abduction, flexion and external rotation with upper arm and maximal adduction, extension and internal rotation with arm down. During the test the hands remained closed and placed on the back. The player achieved this position in one smooth motion while standing with feet close together while the examiner measures distance between closest points of both fists. The shoulder mobility test was performed three times bilaterally. Following the SM test, the impingement clearing test (ICT) was performed in order to exclude any presence of shoulder impingement. The ICT was performed in following manner:

The participant placed her hand on opposite shoulder and attempted to point the elbow upward. If there was pain during this movement, the score of zero would be given for the SM test.

Figure 3.5: Shoulder mobility   **Figure 3.6: ICT**
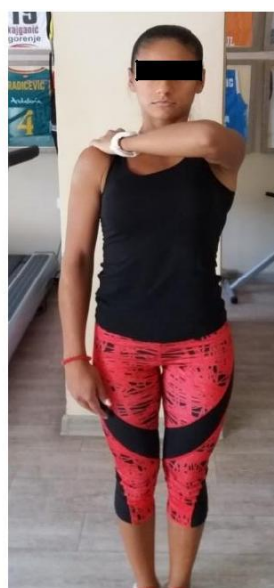
Table 3.4: Shoulder mobility scoring criteria

Score of 3	Score of 2	Score of 1
Fists are within one hand length	Fists are within one and a half hand lengths	Fists are not within one a half hand lengths

Active straight leg raise: The player assumed a supine position with arms in 90 degrees of abduction and palms pointed upward and head lying flat on the floor. The board was placed at the back of the knees. The mid-point between anterior superior iliac spine and mid- point of the patella was identified, and the dowel was placed at this point. The player was then asked to raise test leg as far as possible with the knee into full extension and the ankle dorsiflexed. The opposite knee remained in contact with the board during test with the ankle dorsiflexed. If the medial malleolus of the test leg went past the dowel, the score of three was given for that leg.

Figure 3.7: Active straight leg raise

Table 3.5: Active straight leg raise scoring criteria

Score of 3	Score of 2	Score of 1
Ankle/dowel resides between mid-thigh and ASIS	Ankle/dowel resides between mid-thigh and mid-patella/joint line	Ankle/dowel resides below mid-patella/joint line

Trunk stability push-up (TSPU): The player was lying in prone position with the feet together. The hands were placed shoulder with apart with thumbs aligned with the chin. The player was then asked to perform one push-up with fully extended knees and ankle dorsiflexed (toes on the floor). The body should be lifted as a unit with no lag in the lumbar spine for the score of three. If the player could not perform the task from this position, the hands were lowered to the line with the clavicle.

A Press-up clearing test (PUCT) was performed after the TSPU test in order to exclude pain during spinal extension. The PUCT was performed in following manner:

The player performed a press-up movement in prone position. If there was pain associated with this movement the score of zero would be given for TSPU test.

Figure 3.9: Press-up clearing test

Figure 3.8: Trunk stability push-up

Table 3.6: Push up scoring criteria:

Score of 3	Score of 2	Score of 1
Perform 1 repetition with thumbs aligned with chin	Perform 1 repetition with thumbs aligned with clavicle	Unable to perform 1 repetition with thumbs aligned with clavicle

Rotary stability: The player assumed a quadruped starting position with the board between hands, knees and toes. The shoulders, hips, knees and ankles were at 90 degrees angle, while the thumbs and knees were in contact with the board. The player was asked to flex the shoulder and extend hip on the same side, and then to extend the shoulder and flex the knee so the elbow and knee touched over the board before returning to starting position. This was performed three times on both sides. If criteria for a maximum score was not achieved the player tried a diagonal pattern using the opposite shoulder and hip in the same manner.

Figure 3.10: Rotary stability

Following the rotary stability test players were performed posterior rocking clearing test (PRCT) to exclude pain during spinal flexion in following manner:

The participant first assumed a quadruped position, then sat on their heels with their chest touching the floor and arms reaching out as far as possible. If there was pain associated with this movement the score of zero would be given.

Figure 3.11: Posterior rocking clearing test

Table 3.7: Rotary stability scoring criteria:

Score of 3	Score of 2	Score of 1
Perform one correct unilateral repetition while keeping spine parallel to board Knee and elbow touch in line over the board	Perform one correct diagonal repetition while keeping spine parallel to board	Inabilitytoperform diagonal repetition

3. Performance tests

5-0-5 Agility test

The 5-0-5 test is used for assessing agility in many sports (Draper & Lancaster 1985) with 0.78 intra-class correlation showed by Cochrane et al. (2004). See Figure 3.1 for the lay-out of the test. Timing gates (BROWER timing systems, Utah, USA) were placed in the line of cones and raised to a height of one meter. Players were then asked to stand at the starting point and when they were ready to sprint to the turning line, between timing gates, turn and sprint back to the starting line. They were asked to perform two trials per leg, to turn on the left and right foot. The fastest time (recorded to 0.1s) over the five meters for each leg was recorded as score.
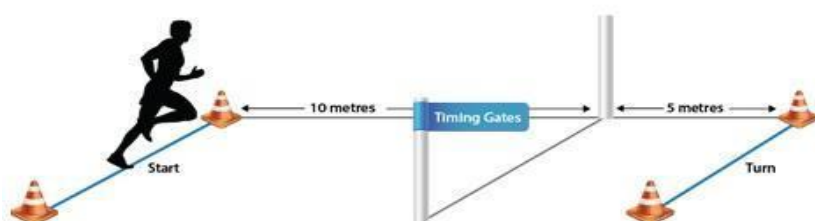

Figure 3.12: Lay-out of the 5-0-5 Agility test

Single-leg hop (and hold for distance (SLHH)

SLH assesses dynamic knee stability and neuromuscular control commonly required in netball and basketball (Greenberger & Paterno, 1995).

Many authors found high reliability (above r=0.92) of the single-leg hop for distance test (Bandy et al., 1994; Bolgla & Keskula, 1997; Ageberg et al., 2007).

SLH was performed while the participant stood on the tested leg with the great toe on the starting line and hands placed on hips. A standard tape measure (15m long) was placed on the floor with starting line marked by chalk. After they received an explanation of the test, the players were asked to hop as far as possible and land on the same leg. They were required to stick the landing, i.e. keep the position for three seconds upon landing. The distance hopped from starting line to the heel at landing was recorded (Bolgla & Keskula, 1997). Three trials were given for the each participant, and the best of the three jumps to the nearest 0.1 cm was used for analysis. Differences between left and right leg (i.e. Lymb symmetry index) were also used for analysis (Fitzgerald et al., 2001). If the player was unable to hold balance for three seconds or if the opposite leg touched the ground the trial was repeated. The score of zero was given to the player who was unable to hold balance during each trial, even with repeated attempts.

4. Dynamic knee stability tests

Drop vertical jump (DVJ)

Real-time observation and subjective assessment of the DVJ was performed by the researcher. Grading criteria from literature was used to analyse performance on the drop vertical jump test (Stensrud et al., 2011; Nilstad et al., 2014). According to Stensrud et al. (2011) this method of knee control evaluation showed high intra-rater reliability, as well as good to excellent agreement in comparison with 2D video analysis (r=0.83–0.89).

Tibial tuberosities was previously marked using coloured paper stickers. Players stood with their feet shoulder width apart and they were then asked to hop off the 31 cm box with both feet at the same time and immediately perform maximal vertical jump and raising both arms as if they were jumping for a ball. The task was demonstrated to players and each subject was given two practices trials. If players jumped off the box instead of stepping off, or if they lowered the foot below the level of box before stepping off that trial was considered invalid and they were asked to repeat. Three valid trials

were performed and used for analysis. Players were allowed to take as much time needed between jumps although all athletes did not take more than 30 seconds between trials. All players completed jumps within five trials. See table 3.8 for the DVJ scoring criteria.

Table 3.8: DVJ scoring criteria

Score of 3	Score of 2	Score of 1
Perform DVJ with proper knee alignment (straight line from tibial tuberosity to the mid toes of the foot) No valgus collapse No medio-lateral side to side knee movement	Knee missalignment with left or right knee moving medially into slight valgus Small medio-lateral side to side movement during task.	Poor knee alignment with one or both knees moving into significant amount of valgus Medio-lateral side to side movement during task.

Single-leg squat (SLS) test

The single-leg squat test was conducted in order to assess neuromuscular control, dynamic knee stability and core strength (Okada et al., 2011; Liebenson, 2002) which is necessary during landing, running and cutting in netball and some other sports (Claiborne et al., 2006; Zeller et al., 2003). The single-leg squat had good inter-rater reliability (r=0.71) and excellent intra-rater reliability (r-0.81) for physiotherapists (Weeks et al., 2012). See table 3.9 for the DVJ scoring criteria.

Table 3.9: Single-leg squat (SLS) scoring criteria

Score of 3	Score of 2	Score of 1
At least 65 degrees of hip flexion Less than 10 degrees of valgus/varus angulation of the knee Less than 10 degrees of hip abduction/adduction	Any two of the criteria for the score of 3 were met	Any one of the criteria for the score of 3 was met

The participants were asked to place their hands on their hips and stand on one leg and flex the opposing knee to 90 degrees. They were then asked to squat to at least 65 degrees of hip flexion and return to the starting position. The protocol was demonstrated to familiarize the participants with the depth of the squat. Visual inspection was used to estimate whether the participants were able to squat to at least 65 degrees of hip flexion (Ugalde et al., 2015).

E. INTERVENTION PROGRAMME

After the testing was completed, results were evaluated in order to create the six-week intervention programme. The intervention programme was designed by the researcher, based on functional limitations identified through the FMS® assessment. The six-week intervention consisted of FMS® specific corrective exercises that progressed through three stages of functionality according to the standardised FMS® corrective algorithm. Exercises were designed to correct dysfunctional movement patterns that focused on the mobility, static stability (static motor control) and dynamic stability (dynamic motor control) according to limitations or shortcomings identified in players. The corrective exercise algorithm, as recommended by Cook (2010) had the primary focus on mobility patterns and asymmetries and then moved onto stability patterns. The experimental group was divided into two subgroups based on their FMS® results. The first group included players with score of one for ASLR and SM test and they started with mobility exercises. The other group had score of one on the TSPU test and started with static stability exercises (Cook, 2017). The name of the mobility exercises, their level and functionality are shown in the Table 3.10, with static exercises in Table and 3.11.

All the corrective exercise sessions were instructed and supervised by the researcher. Players performed three sessions per week (between 30 and 40 minutes long) prior to each netball session. Equipment used during the sessions included yoga mats, rubber bands, swiss balls, foam rollers, wooden sticks and kettlebells. The intervention was carried out on the same indoor netball courts where the pre-testing and post-testing were done. Both groups were instructed by the researcher how to properly perform each exercise and how to breathe and control every movement. Abdominal breathing was used during sessions.

PNF techniques such as hold-relax and contract relax were implemented into mobility exercises in order to improve flexibility of the muscles and mobility of the joints.

Table 3.10: Mobility exercises.

Mobility	
Stage 1	Active straight leg raise with core activation (4 sets, 6 repetitions) Leg lowering 1 (4 sets, 6 repetitions) Hip flexor stretch from half kneeling position (4 sets, 6 repetitions, 10 sec)
Stage 2	Leg lowering 2 (4 sets, 6 repetitions) Leg lock bridge (4 sets, 6 repetitions) Deadlift patterning (4 sets, 6 repetitions)
Stage 3	Leg lowering 2 (4 sets, 6 repetitions) Straight leg bridge (4 sets, 6 repetitions) Single-leg deadlift patterning RNT (4 sets, 6 repetitions)

Table 3.11: Static stability exercises

Static stability	
Stage 1	Quadruped rock with core activation (4 sets, 6 repetitions) Plank with knee flexion (4 sets, 6 repetitions) Rolling pattern (4 sets, 6 repetitions)
Stage 2	Hard roll (4 sets, 6 repetitions) Plank with leg extension (4 sets, 6 repetitions) Elevated push-up (4 sets, 6 repetitions)
Stage 3	Push-up walk out (4 sets, 6 repetitions) Half turkish get up (4 sets, 6 repetitions) Push-up (4 sets, 6 repetitions)

F. STATISTICAL ANALYSIS

Statistical analyses were completed using Statistica v. 13 (Dell Inc., Round Rock, TX, USA). Mean and standard deviation were presented for participants characteristics, FMS® and performance variables for each group. A one-way ANOVA was used to asses the differences between groups for all variables. Significance for all tests was set at p <0.05. All tests were analyzed for normality with a Shapiro – Wilk test.

To test the effect of the six-week intervention on FMS® score, dynamic knee stability tests and performance (objective 1, 2 and 3, respectively), a one-way ANOVA was used to assess the differences between pre- and post-intervention for all variables, as well as between intervention and control groups. Significant differences were analyzed using LSD post-hoc.

To test the relationship between FMS® score, dynamic knee stability tests and performance (objectives 1, 2 and 3), a Pearson Correlation was completed (set at $p < 0.05$). Considering that several variables were categorical, after consulting with a statistician, correlation analysis was appropriate considering that variables are ordinal rather than nominal.

The initial FMS® evaluation was video-recorded for re-evaluation purposes to determine intra-rater reliability, as the FMS® score might have been affected by the training programme in which players were participating at that time. The intra-rater reliability was computed on 10 out of 31 randomly selected participants (32%). The reliability was evaluated by computing intra-class correlation coefficient (ICC) using 2-way mixed-effects model (Koo and Li, 2016) and Cronbach's alpha on total FMS® score.

Chapter Four

RESULTS

A. INTRODUCTION

The primary objectives of this study was firstly, to determine the effect of a six-week functional movement intervention on dynamic knee stability and physical performance in a cohort of netball players. The secondary aim was to investigate the relationship between FMS®, dynamic knee stability (SLS, DVJ) and performance tests (SLHH, 5-0-5). This section of the thesis reports on the results from the study according to the objectives set out.

B. PARTICIPANTS CHARACTERISTICS

A total of thirty-one (31) female netball players participated in the study and were randomly assigned into an experimental (n=12) and a control (n=19) group. Shapiro-Wilk's tests determined that all data were normally distributed. The descriptive statistics given in **Table 4.1** show no differences between groups in terms of age, height and weight.

Table 4.1. Participants characteristics and differences between groups

	N = 31 (mean ± SD)	Control (n=19) (mean ± SD)	Experimental (n=12) (mean ± SD)	*P* value
Age (yrs)	19.9 ± 1.5	19.8 ± 1.5	20.0 ± 1.5	0.71
Height (cm)	174.7 ± 6.5	175.6 ± 6.7	173.3 ± 6.3	0.35
Weight (kg)	70.0 ± 7.7	70.5 ± 8.1	69.3 ± 7.4	0.67

There were also no differences pre-intervention in functional movement screen relative to total FMS® score and individual FMS® tests (**Table 4.2**).

However, significant differences were noted between left and right side during in-line lunge test ($p<0.01$)and shoulder mobility ($p<0.01$) where participants scored higher for the right than the left side, independent of the groups. Similar differences was also noted during the hurdle step, although the differences were not statistically significant (p= 0.056).

Table 4.2. Differences in FMS evaluation between groups

	Control (mean ± SD)	Experimental (mean ± SD)	*p value*
Deep squat	1.6 ± 0.5	1.7 ± 0.4	0.35
Hurdle step*	1.8 ± 0.7	1.6 ± 0.7	0.31
In-line lunge*	1.8 ± 0.4	1.7 ± 0.4	0.81
Shoulder mobility*	2.6 ± 0.5	2.8 ± 0.6	0.31
Active straight leg raise*	2.1 ± 0.9	1.7 ± 1.0	0.22
Trunk stability push-up	1.6 ± 0.8	1.3 ± 0.8	0.33
Rotary stability*	1.9 ± 0.2	2.0 ± 0.0	0.44
Total FMS score	13.7 ± 2.4	13.0 ± 1.6	0.40

* tests that are done bilaterally

In addition, no pre-intervention differences were noted between groups in vertical jump, squat and agility tests (**Table 4.3**). Although no bilateral differences were noted for single-leg squat and 5-0-5 agility test, participants jumped significantly longer with their dominant leg during single-leg hop-and-hold test (p=0.05).

Intra-rater reliability

The reliability analysis showed good intra-rater reliability based on ICC = 0.775 and Cronbach's alpha = 0.752, as categorized by Koo and Li (2016).

Table 4.3. Differences between group in squat, single-leg lunge and agility test

	Control (mean ± SD)	Intervention (mean ± SD)	*p value*
Drop-vertical jump	1.79 ± 0.86	2.0 ± 0.95	0.53
Single-leg squat – left	1.74 ± 0.93	1.58 ± 0.67	0.63
Single-leg squat – right	1.68 ± 0.95	1.58 ± 0.67	0.75
Single-leg hop-hold – DL (cm)	157.2 ± 24.9	145.9 ± 15.5	0.17
Single-leg hop-hold – NDL (cm)	140.1 ± 54.2	142.9 ± 15.1	0.86
5-0-5 – left (sec)	2.61 ± 0.13	2.67 ± 0.14	0.28
5-0-5 – right (sec)	2.62 ± 0.12	2.67 ± 0.13	0.37

C. INFERENTIAL ANALYSIS

1. Effects of the intervention

The results demonstrate a significant effect of the six-week intervention programme (**Figure 1**). Firstly, FMS® score was significantly higher post-intervention ($p<0.001$) (i.e. time effect), and there was a significant increase ($p<0.01$) in the score of the experimental group, while the control's group FMS® score remained unchanged (i.e. group*time effect).
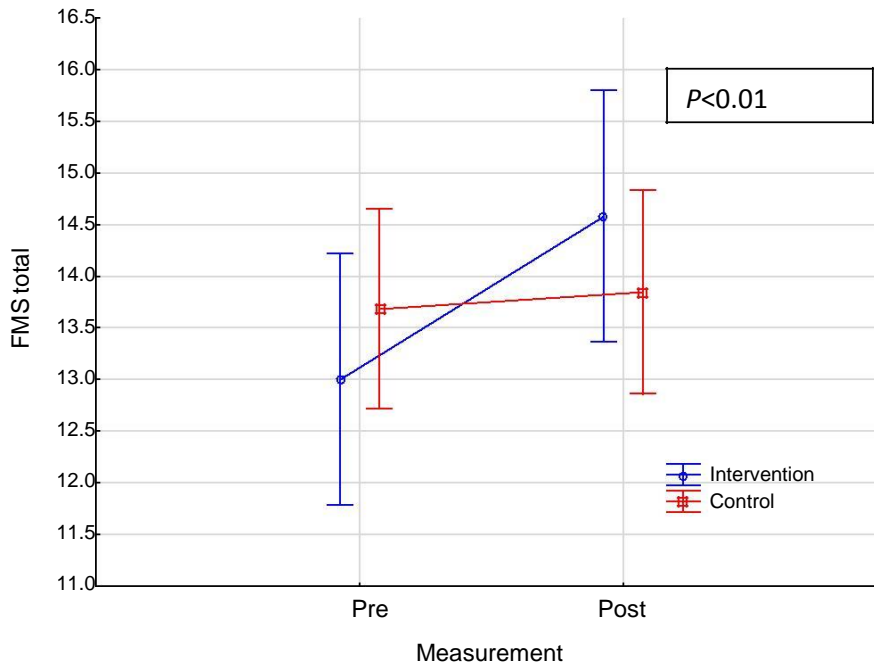
Figure 4.1. Differences in mean FMS® score between groups after the six-week intervention with 95% CI.

Figure 4.2 depicts the changes between individual FMS® tests across the time period and between groups. It is notable that scores on the deep squat, in-line lunge and active straight leg raise improved significantly in both groups, while only group*time effect was noted for the trunk stability push-up test (TSPU). Shoulder mobility and rotary trunk stability were scored 2.6 and 2.8 for all participants in pre- and post-testing. Interestingly, bilateral differences remained after the intervention for in-line lunge ($p=0.04$), shoulder mobility ($p<0.01$), while the difference in hurdle step was also noteworthy, although not statistically significant ($p=0.056$).
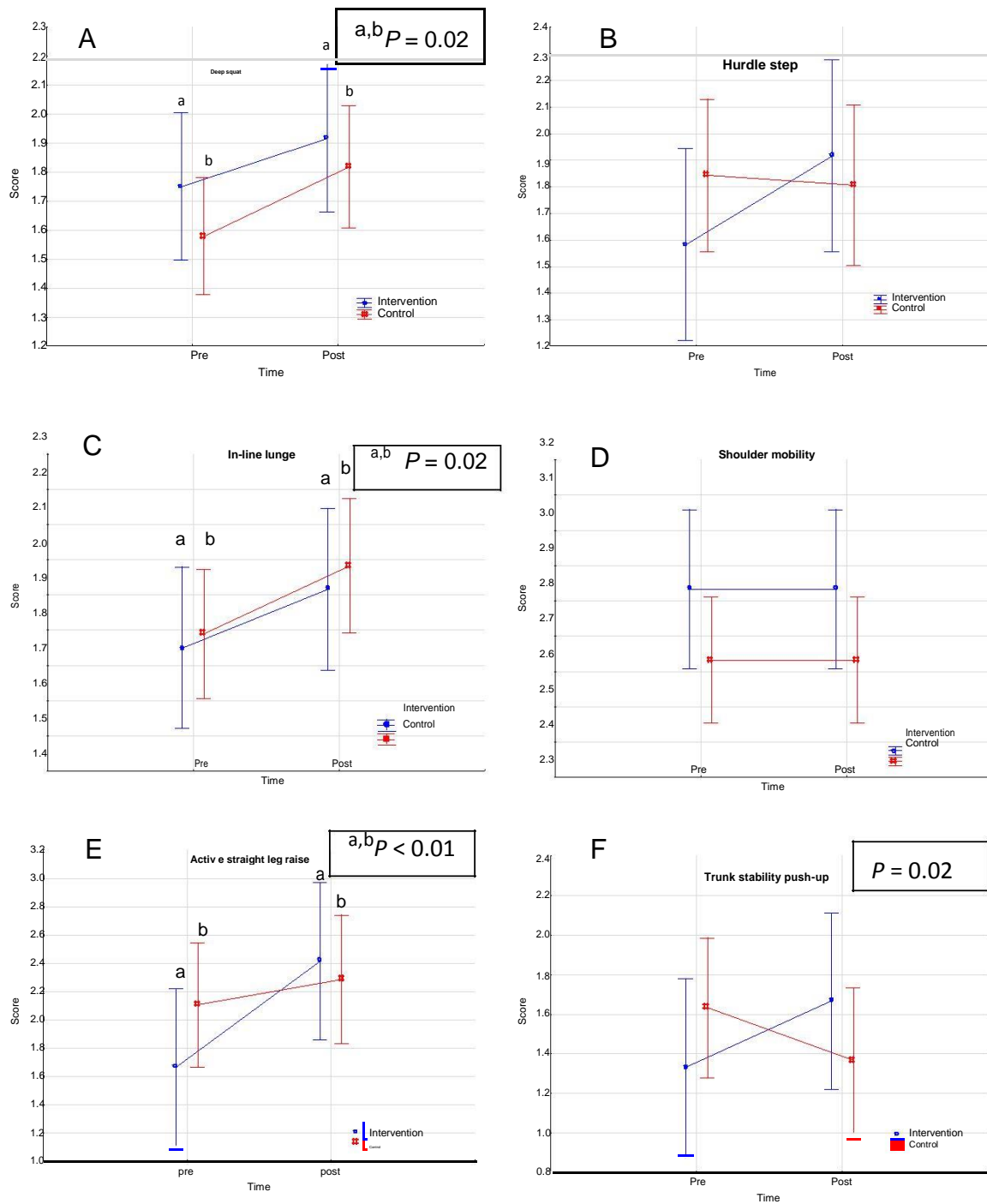
Figure 4.2. Differences in the individual FMS® tests between groups, pre- and post-intervention

There were no significant differences in any of the performance tests ($p > 0.05$). Additional analysis for 5-0-5 agility test, single-leg hop-and-hold and single-leg squat show no significant differences between left and right side, hence no bilateral effect was found.
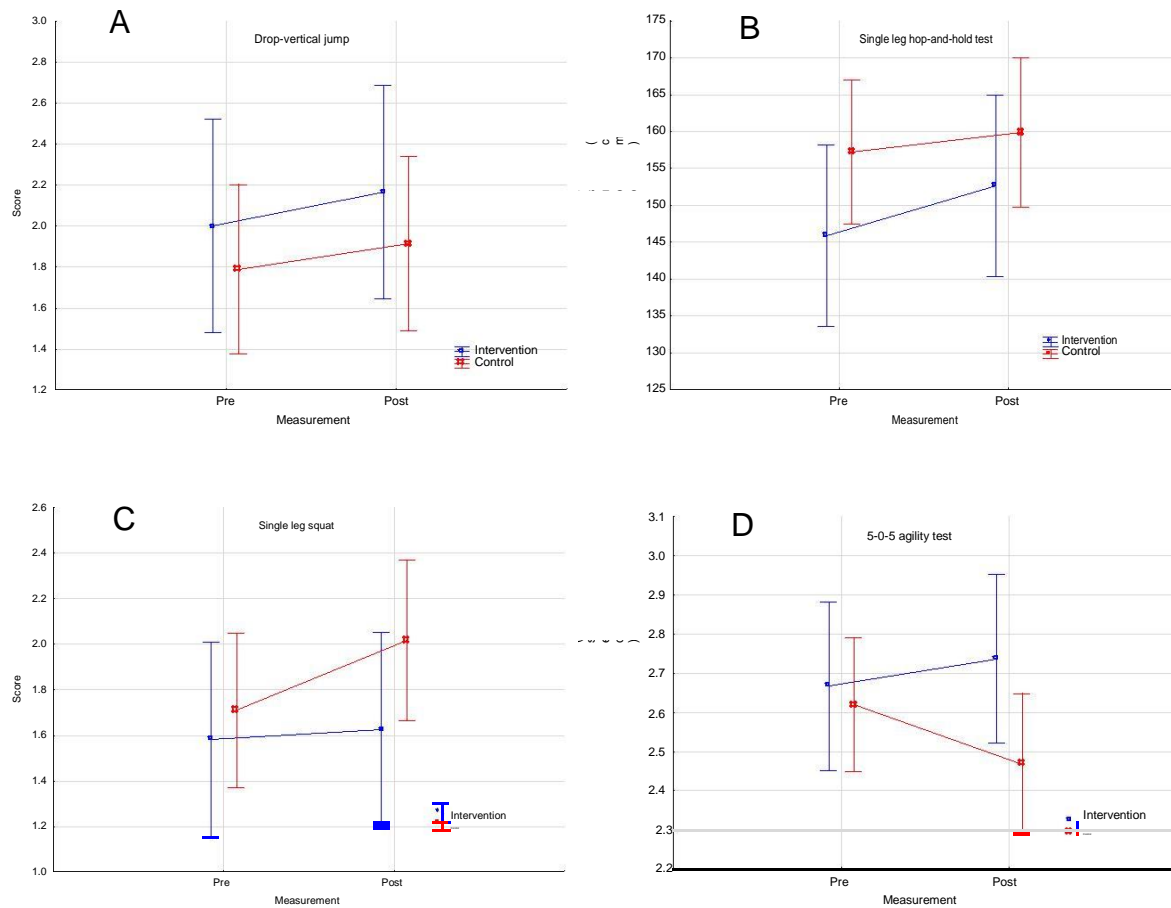
Figure 4.3. Differences in performance tests between groups, before and after the intervention

66

D. RELATIONSHIP BETWEEN FMS®, DYNAMIC KNEE STABILITY AND PERFORMANCE TESTS

The results (**Table 4.4**) demonstrate a moderate significant correlation between the FMS® total score and single-leg hop, as well as the 5-0-5 agility test when performed with the dominant leg. Testing on the non-dominant leg also indicated a potential significant relationship (p=0.06), although statistically not significant. After the intervention there was no significant relationship between the FMS® total score and performance tests.

Table 4.4. Pearson correlation between FMS® total score and performance tests

|	SLH_{DL}	SLH_{NDL}	DVJ	SLS_R	SLS_L	$5\text{-}0\text{-}5_R$	$5\text{-}0\text{-}5_L$
Pre-intervention							
$FMS_{pre\text{-}test}$	0.48**	0.34^X	0.03	0.05	0.15	-0.37*	-0.34^X
Post-intervention							
$FMS_{post\text{-}test}$	0.37^X	0.33	0.04	0.21	0.14	-0.17	-0.17

** <0.01; *<0.05; ^{X}0.06

Regarding the relationship between individual FMS® scores and performance tests, only significant relationships in pre- and post-testing were found between the hurdle step (HS) and single-leg hop-and-hold tests (SLHH) (r=0.35, p=0.05 and r=0.39, p=0.04, respectively). Yet, when considering differences in hop distance relative to HS score (**Figure 4.4**), no significant differences existed between groups pre-intervention, while there was a significant increase in hop distance at post-intervention. It is likely that large inter-subject variability indicated by the large 95% confidence interval has made an impact on the significance of the results.
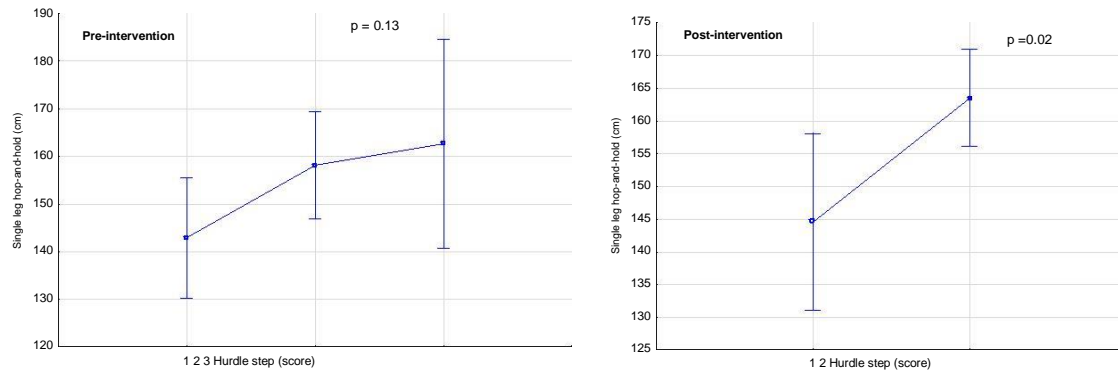
Figure 4.4. Difference in single-leg hop-and-hold test relative to hurdle step score in pre- and post-intervention

Considering that several significant correlations between individual FMS® and performance were noted only in either pre- or post-intervention, it is likely that the intervention had an impact on the relationship between variables. These associations will be addressed in the discussion section. In addition, multiple Pearson correlations found several additional significant relationships between individual FMS® score and performance tests, but these were largely random correlations between tests whose associations are not functionally related.

Chapter Five

DISCUSSION AND CONCLUSION

A. INTRODUCTION

The primary aim of the study was to determine effects of the functional movement intervention (FMS® standardized corrective exercise program) on dynamic knee stability and performance in female netball players. The secondary aim was to investigate potential relationship between FMS®, dynamic knee stability and performance tests. These aims stem from the high incidence of ACL injuries in female netball players, and the potential of FMS® to identify functional impairments that may predispose athletes to injury. The results will be discussed with regard to these stated objectives in the order of aims and objectives presented in Chapter One.

B.PARTICIPANTS FMS® AND PERFORMANCE SCREENING

There were no significant differences between groups in anthropometric characteristics and age (**Table 4.1.**). The results also showed no differences in total and individual FMS® scores between experimental (13.0 ± 1.6) and control group (13.7 ± 2.4). Significant differences were noted only between sides during the in-line lunge and shoulder mobility tests where participants from both groups had higher scores for the right side.

The participants in the current study had lower total FMS® scores compared to the results from other studies. Schneiders et al. (2011) reported a composite FMS® score of 15.6 ± 2.0 for the 108 university female athletes who participated in different sports. The total FMS® score among university female athletes was 16.3± 1.2 in the study conducted by Letafatkar et al. (2014), while Chorba et al. (2010) found 14.3±1.77 in a group of 38 Division II female collegiate athletes participating in soccer, volleyball, and basketball. Similar results were found in the study of Venter et al. (2017) who reported 14.50±3.80 in the group of 20 female university netball players. The lower FMS® total score in the current study may be the result of the diversity of the group of netball players.

Most players from the club were involved, which included players from lower teams and higher teams. The difference in physical fitness between players of the first and second team may be the reason for lower FMS® score in comparison with other studies. Also, netball is a quadriceps dominant sport. A quad dominant athletes often show lower FMS® score due to forward lean, decreased hip flexion and increased frontal plane knee excursion on the deep squat test. Lower score on the ASLR as a result of innactive posterior kinetic chain muscle groups can also affect the total FMS® score.

No differences were found between groups in single-leg squat, drop vertical jump and agility. Also, no bilateral differences were noted for 5-0-5 agility and single-leg squat test. These findings could be explained by the fact that all participants of the study play the same sport. A significant difference was only noted for SLHH test (p=0.05) where participants jumped further with their dominant leg. These findings are similar to the results found in the study of Bahamonde et al. (2012) who reported that participants had 10% difference in the distance jumped with dominant leg.

C. EFFECT OF A SIX-WEEK INTERVENTION ON FMS®, DYNAMIC KNEE STABILITY TESTS AND PERFORMANCE TESTS

1. Effect of 6-week intervention on FMS®

The results indicate that the six week intervention programme improved the total FMS® score of the experimental group, while the control group did not significantly improve over the same period. Therefore, adding functional exercises to strength and conditioning programmes may improve the player's functional ability as assessed by the FMS®. These results are in agreement with previous studies who also found similar improvements after a standardized FMS®-based intervention programme in an athletic population. Kiesel et al. (2011) showed that the total FMS® score among 62 NFL players could be improved by a standardized intervention programme. A 31 players exhibited asymmetries between left and right side at pre-intervention testing. Following the seven-week off-season intervention programme, 41 players were free of asymmetry and 39 with a score >14 compared to 7 that had a score >14 at baseline.

The authors of the study concluded that a standardized intervention programme had positive effects on improving fundamental movement characteristics. Simmilar results were found in the study of Bodden et al. (2015) that included 25 MMA fighters.

The fighters who followed a FMS® standardized intervention programme significantly improved their FMS® score (p=0.05). Findings from the current study correlates with the results from the mentioned studies. The experimental group in the current study had significantly higher FMS® scores (p<0.01) at the end of six-week intervention programme.

Improvement in the total FMS® score were primarily due to significant improvements in ASLR and TSPU tests. Significant improvements in the mentioned individual FMS® tests are probably due to the fact that the FMS® corrective exercises always started with mobility (ASLR) and static stability (TSPU) movement patterns described in FMS® manual (Cook, 2010). Doing these exercises regularly probably gave the players enough exposure and repetition over the course of the intervention period with enough time to improve. On the other hand, the intervention programme in the current study lasted six weeks with three sessions per week, while previously mentioned studies included seven- and eight-week intervention programmes with four sessions per week. The shorter duration of the intervention programme and one session less per week may be a reason why other FMS® tests did not improve.

The ASLR test significantly improved following the intervention programme which included corrective strategies for the ASLR movement pattern. Decreased lumbo-pelvic stability in combination with decreased hip flexion may cause pelvic anterior rotation, forcing the hamstring to lenghten more which could give false representation of the hamstring shortness or tightness and consenquently affect the ASLR score (Burton, 2015). According to Moreside and Mcgill (2012), proximal stability of the pelvis may increase distal mobility of the lower limbs. The concept of proximal stability for distal mobility is integrated into ASLR corrective exercise programme. One of the implemented exercise was the "Active straight leg raise with core activation". Core activation was initiated by pulling a rubber band before disassociating the legs, therefore helping to stabilize the lumbo-pelvic unit to prevent anterior rotation of the pelvis and increasing the leg raise (Burton, 2015).

The TSPU test also improved significantly after the six-week intervention programme based on the standardized corrective algorithm for that movement pattern. The TSPU test represents a participant's core activation and stability (Cook et al., 2006b) and all the exercises applied in the intervention programme were designed to activate trunk (core) muscles and distribute power between upper and lower body parts which may be the reason for a better score after the intervention.

2. Effect of the six-week intervention on dynamic knee stability tests

The purpose of the FMS® is to detect and correct basic movement patterns before implementing a specific fitness or injury prevention programme (Cook et al., 2014a). Improvement in the ASLR score should lead to higher mobility and stability of the hips, which is crucial for knee control during landing and cutting in netball. Improvement of the TSPU test represents increased energy transfer along the kinetic chain which is important for knee stability during different athletic activities (Hewett et al., 2005). Some FMS® corrective exercises used in the second and third phase of the ASLR movement pattern correction are "The leg lock bridge" and "Single-leg deadlift RNT" (**Table 3.10)**. The leg lock bridge exercise develops the hamstrings, and gluteal strength, as well as hip stability (Post-Run Core: The Leg-Lock Bridge, 2017). The single-leg deadlift exercise engages the gluteal and hamstring muscles while standing on one leg (Johnson, 2017). Both exercises develop neuromuscular control through a load transfer between local and global stabilizers, which, according to Hewett et al. (1996), can reduce knee abduction moment (knee valgus) during athletic tasks. The RNT concept uses dynamic work in one part of the body to cause a perturbation through torque generated when external force is applied. In the case of the single leg deadlift exercise, pulling the knee inward results in activation of the hip abductors to prevent valgus collapse. A longer intervention period, that includes this concept, could potentially lead to a significant improvement in dynamic knee stability. Despite this potential relationship between the FMS® and kinematics of the knee, the results in the current study showed no significant effect of the intervention on the dynamic knee stability measured in the single-leg squat and drop vertical jump. In the FMS® corrective exercise hierarchy, mobility and static stability should be corrected first (Cook, 2010). The above mentioned exercises are used to correct static stability, but only when the progress in mobility is noticed.

The RNT (Reactive Neuromuscular Training) concept within ASLR correctives may be a key link to improve the dynamic knee stability. Depending on the pre-testing ASLR score, some players took more time to improve their mobility not leaving them enough time for exercising static stability which could explain the weak effect of the intervention on dynamic knee stability.

3. Effect of six-week intervention on performance tests

A positive correlation between total the FMS® score and SLHH test was found after the intervention programme. Significant correlations were found between the total hurdle step (HS) score and SLHH test before and after the intervention. As noted, improvement in the total FMS® score is largely due to the advancement in the ASLR movement pattern that includes hamstring flexibility. Although an ASLR corrective exercise programme does not only include static streching, improvements in ASLR test are, among other, due to increased hamstring flexibility. These findings are in agreement with results of Ross (2007) who also found improvement in the SLH test after the 15-day hamstring stretching programme in a group of thirteen cadets enrolled at a military academy.

Song et al. (2014) found improvements in performance after the standardized FMS® corrective exercises programme that was conducted three times per week for 16 weeks. The authors found changes in strength and flexibility among high school baseball players after the intervention. Unlike the above study, the intervention period in the current study lasted considerably shorter, which could be the reason for statistically minor changes in other performance tests.

D. RELATIONSHIP BETWEEN FMS® AND PERFORMANCE TESTS

A positive correlation was found in the current study between overall FMS® score and 5-0-5 agility and single-leg hop test when performed with the dominant leg. Athletes with higher FMS® score had faster times in 5-0-5 test (r=-0.37) and longer jump distances in SLHH test (0.48). A positive correlation was also noted between total hurdle step (HS) score and SLHH score. These results are in agreement with those of Venter et al. (2017), who also found a significant correlation between FMS® and 5-0-5 agility test (r=-0.52) in a group of 20 university female netballers, as well as with those of Lockie et al. (2015) who reported (r=-0.423). The overall FMS® score in the current study was also associated with single-leg hop distance test (r=0.48), which coincides with the results of the study conducted by Willigenburg and Hewett (2017) who reported (r= 0.38 - 0.56).

A possible explanation for the positive correlation between FMS® and agility found in the current study perhaps lies in some components of the FMS®, such as core activation and stability. Quickly activated trunk (core) muscles are important to decrease shear forces that affect the spine during multidirectional tasks (Okada et al., 2011) such as change of direction found in the 5-0-5 agility test.

On the other hand, Okada et al. (2011) found no relationship between FMS® and core stability in 28 healthy recreational athletes both men and female. The authors found only a moderate relationship between the FMS® and T-test for agility and an overhead medicine ball throw for performance. Parchmann and McBride (2011) also reported no significant correlation between FMS® and performance among 15 men and 10 female National Collegiate Athletic Association Division I golfers. A weak correlation existed between FMS® and 10-m sprint time (r= -0.136), 20-m sprint time (r= -0.107), vertical Jump height (r= 0.249), agility T-test time (r= -0.146), and club head velocity (r= - 0.064).

E. RELATIONSHIP BETWEEN FMS® AND DYNAMIC KNEE STABILITY TESTS

The results of the current study did not show significant relationships between FMS® and dynamic knee stability tests (ACL screening tools). It is difficult to compare results of the current study to other research as the researcher is unaware of any other published study to date which has tested the FMS® and ACL screening tools in similar manner, especially in netball.

Similarities in the biomechanical requirements of the FMS® test and dynamic knee stability tests should show closer relationship between these tests, which is one of the hypotheses of this study. All of the seven FMS® tests assess mobility and stability of the athletes. The deep squat (DS), hurdle step (HS) and in-line lunge (ILL) require proper mobility of the ankles, hips and knees as well as the adequate core activation and stability (Cook et al., 2006b). Poor result on the DS test could be result of an excessive forward lean, which according to Nuckols (2013) represents neuromuscular imabalance, called quadriceps dominance. According to Hewett et al. (2010) quadriceps dominance is a characteristic of female athletes and increases the risk of ACL injury. Decreased ankle dorsiflexion can influence dynamic knee valgus during squating (Kim et al., 2015) which is one of the main risk factors for ACL injuries (Hewett et al., 2005). The two of the most commonly used valgus detection tests are the DVJ and SLS that also represent neuromuscular control of the lower extremities and core activation of the trunk muscles.

Nevertheless, during the SLS test participants are using trunk (core) muscles isometricaly contracted to maintain an upright position that represents muscle endurance, while core activation measured by TSPU of the FMS® represents quick, explosive activation of the trunk muscles to stabilize the pelvis and spine. The differencies between muscle contractions during FMS® tests such as TSPU and RS and SLS test may be one of the reasons why a link between these tests has not been found.

F. CONCLUSION

The primary finding of the current study is that the FMS® scores in female netball players could be improved by a standardized corrective exercise programme. The results of the current study showed positive correlations between total FMS® score and SLHH test, as well as the HS and SLHH when performed with the dominant leg. A positive correlation was also found between total FMS® score and 5-0-5 agility test. On the other hand, there was no significant correlation between FMS® and SLS and DVJ tests (dynamic knee stability tests). Although the results showed a positive correlation between ASLR test and SLS after the intervention, the six-week FMS®-based corrective exercise programme did not significantly improve performance on the SLS and DVJ test.

In fact, FMS® is a subjective screening tool designed to assess the quality of the basic movement patterns and to identify weak links in the kinetic chain (Cook et al., 2006b). Although the FMS® requires certain mobility of the joints and proper core activation, which is also needed for knee stability during athletic activities, it seems that different muscular activity and neuromuscular control are required in order to accomplish movement tasks in FMS® and ACL screening tools. Single-leg stance, which is represented in many ACL screening tools, is required in only one FMS® test (HS). Other tests within the FMS® are performed in a lying, quadruped and double leg stance position. The difference in the test positions may be one of the reasons why no close relationship was found between FMS® and ACL screening tools. Also, the short duration of the intervention can explain why there was no significant improvement in ACL screening tools and performance tests.

However, the advantage of the FMS® is that it is relatively easy to conduct and the exercise program based on the FMS® score does not require expensive equipment that makes it available to most sports clubs. A functional movement intervention based on the FMS® assessment could be a possible tool to include in an ACL preventative programme in netball players. Previous research has demonstrated the existence of discernable groups of athletes that may benefit from injury prevention interventions like ACL programmes.

Further investigation of the relationship between FMS® and the mechanism of ACL injuries would be of great importance for reducing the injury incidence in the female netball.

The current study can serve as a guidline for the future research in the field of ACL injury prevention in netball.

G. STUDY LIMITATIONS

In the current study one of the limitations was the small number of participants, especially in the intervention group. Two players from the experimental group stopped playing netball, which certainly reduced the statistical power. Due to the timeline within the netball club where players were affiliated, the intervention programme only lasted six weeks with three sessions per week.

Also, video analysis was not used to determine angles during SLS and DVJ, and only a three-point scoring system were used for most tests.

H. STUDY DELIMITATIONS

A single researcher conducted all the of the FMS® testing, dynamic knee stability and performance tests. The researcher was FMS® 1 and 2 certified physiotherapist and he supervised the participants during intervention. Only healthy netball players with no recent injuries participated in this study.

I. RECOMMENDATIONS FOR FUTURE RESEARCH

It is necessary to create normative values of the FMS® for female netball players for comparison with similar sports and to follow the potential changes in score during season. It could be possible to compare FMS® assessments with three-dimensional motion analysis such as the Landing Error Score (LESS) in order to get a more accurate picture of the knee missalignment during dynamic tasks. If the FMS® would have a strong correlation with LESS, it would facilitate the early detection of athletes with potentially higher risk of ACL injury.

REFERENCES

Ageberg, E., Zätterström, R., & Moritz, U. (2007). Stabilometry and one-leg hop test have high test-retest reliability. *Scandinavian Journal of Medicine & Science in Sports*, 8(4):98–202.

Alenezi, F., Herrington, L., Jones, P., & Jones, R. (2014). The reliability of biomechanical variables collected during single leg squat and landing tasks. *Journal of Electromyography and Kinesiology*, 24(5):718–721.

An, H.M.O., Miller, C., Mcelveen, M., & Lynch, J. (2012). The Effect of kinesio tape® on lower extremity functional movement screen TM scores*. International Journal of Exercise Science*, 1:196-204.

Andriacchi, T.P. & Alexander, E.J. (2000). Studies of human locomotion: past, present and future*. Journal of Biomechanics*, 33(10):217–224.

Anon, (2017). *Post-Run Core: The leg-lock bridge* - Brooks blog. Available at: http://talk.brooksrunning.com/blog/2017/07/07/post-run-core-the-leg-lock-bridge/

Arendt, E. & Dick, R. (1995). Knee injury patterns among men and women in collegiate basketball and soccer. *The American Journal of Sports Medicine*, 23(6):694–701.

Bahamonde, R., Weyer, J., Velotta, J., & Middleton, A. (2012). *Effects of leg dominance on the single leg hop functional test test in non-injured adults*. 30th Annual Conference of Biomechanics in Sports – Melbourne.

Bandy, W.D., Rusche, K.R., & Tekulve, F.Y. (1994). Reliability and limb symmetry for five unilateral functional tests of the lower extremities. *Isokinetics and Exercise Science,* 4(3):108–111.

Bailey, R., Selfe, J., & Richards, J. (2010). The single leg squat test in the assessment of musculoskeletal function: A review. *Physiotherapy Ireland*, 31(1):18-23.

Bardenett, S., Micca, J., DeNoyelles, J., Miller, S., Jenk, D., & Brooks, G. (2015). Functional movement screen normative values and validity in high school athletes:

Can the FMS be used as a predictor of injuries. *The International Journal of Sports Physical Therapy*,10(3): 303.

Bell, D.R., Padua, D.A., & Clark, M.A. (2008). Muscle strength and flexibility characteristics of people displaying excessive medial knee displacement. *Archives of Physical Medicine and Rehabilitation*, 89(7):1323–1328.

Benjaminse, A., Gokeler, A., & Van der Schans, C.P. (2006). Clinical diagnosis of an anterior cruciate ligament rupture: A meta-analysis. *Journal of Orthopaedic & Sports Physical Therapy*, 36(5):267–288.

Benn, C., Forman, K., Mathewson, D., Tapply, M., Tiskus, S., Whang, K., & Blanpied, P. (1998). The effects of serial stretch loading on stretch work and stretch-shorten cycle performance in the knee musculature. *Journal of Orthopaedic & Sports Physical Therapy*, 27(6): 412-422.

Bodden, J.G., Needham, R.A., & Chockalingam, N. (2015). The Effect of an intervention program on functional movement screen test scores in mixed martial arts athletes. *Journal of Strength and Conditioning Research*, 29(1): 219–225.

Boden, B.P., Dean, S., Feagin, J.A., & Garrett, W.E. (2000). Mechanisms of anterior cruciate ligament injury. *Orthopedics*, 23(6):573–578.

Boden, B.P., Sheehan,F.T., Torg, J.S., & Hewett, T. E. (2010). Noncontact anterior cruciate ligament injuries: mechanisms and risk factors. *The Journal of the American Academy of Orthopaedic Surgeons,* 18(9):520–527.

Bolgla, L.A. & Keskula, D.R. (1997). Reliability of lower extremity functional performance tests. *Journal of Orthopaedic & Sports Physical Therapy*, 26(3):138–142.

Bonazza, N.A., Smuin, D., Onks, C.A., Silvis, M.L., & Dhawan, A. (2016). Reliability, validity, and injury predictive value of the functional movement screen: A systematic review and meta-analysis. *The American Journal of Sports Medicine*,45(3): 725-732.

Booher, L.D., Hench, K.M., Worrell, T.W., & Stikeleather, J. (1993). Reliability of three single-leg hop tests. *Journal of Sport Rehabilitation*, 2(3):165–170.

Brophy, R., Silvers, H.J., Gonzales, T., & Mandelbaum, B.B. (2010). Gender influences: the role of leg dominance in ACL injury among soccer players. *British Journal of Sports Medicine*, 44(10):694–697.

Buoncristiani, A.M. Tjoumakaris, F.P., Starman, J.S., Ferretti, M., & Fu, F.H. (2006). Anatomic double-bundle anterior cruciate ligament reconstruction. *The Journal of Arthroscopic & Related Surgery*, 22(9):1000–1006.

Butler, R.J., Plisky, R.J., Southers, C., Scoma, C., & Kiesel, K.B. (2010). Biomechanical analysis of the different classifications of the functional movement screen deep squat test. *Sports Biomechanics*, 9(4):270–279.

Butler, R.J., Contreras, M., Burton, L.C., Plisky, P.J., Goode, A., & Kiesel, K. (2013). Modifiable risk factors predict injuries in firefighters during training academies. *Work*, 46(1):1–7.

Burton, L. (2010). *Active Straight Leg Raise (ASLR) Progressions | Functional Movement Systems.* [Online]. Available at: https://www.functionalmovement.com/articles/Corrections/2010-09-15_active_straight_leg_raise_aslr_progressions.

Cates, W. & Cavanaugh, J. (2009). Advances in rehabilitation and performance testing. *Clinics in Sports Medicine*, 28(1):63–76.

Chappell, J.D., Yu, B., Kirkendall, D., Garrett, W.E., & Hill, C. (2002). A Comparison of Knee Kinetics between Male and Female Recreational Athletes in Stop-Jump Tasks. *American Journal of Sports Medicine*, 30(2):261–267.

Chimera, N.J. & Warren, M. (2016). Use of clinical movement screening tests to predict injury in sport. *World Journal of Orthopedics*, 7(4):202.

Chong, R.W.W. & Tan, J.L. (2004). Rising trend of anterior cruciate ligament injuries in females in a regional hospital. *Annals of the Academy of Medicine*, 33(3):298–301.

Chorba, R., Chorba, D., Bouillon, L., Overmyer, C., & Landis, J. (2010). Use of a functional movement screening tool to determine injury risk in female collegiate athletes. *North American Journal of Sports Physical Therapy,* 5(2):47–54.

Claiborne, T., Armstrong, C., Gandhi, V., & Pincivero, D. (2006). Relationship between hip and knee strength and knee valgus during a single leg squat. *Journal of Applied Biomechanics*, 22(1):41–50.

Clifton, D.R., Grooms, D.R., & Onate, J.A. (2015). Overhead deep squat performance predicts functional movement screen score*. International Journal of Sports Physical Therapy*, 10(5):622–627.

Cochrane, D., Legg, S., & Hooker, M. (2004). The short-term effect of whole-body vibration training on vertical jump, sprint, and agility performance. *Journal of Strength and Conditioning Research*, 18(4):828-832.

Cook, G., *Balance, Posture and Movement*. Available at: https://www.functionalmovement.com/files/imagebyname?fileName=506a_Cook and Plisky - Balance%2C Posture and Movement_V2.pdf

Cook, G., Burton, L., & Fields, K. (2005). *The Functional Movement Screen and Exercise Progressions Manual* 84. Available at: http://isd194.org/lakeville-south/download/communications_master/Athletics:Activities/Athletic Trainer/FMSManual(2).pdf.

Cook, G., Burton, L., & Hoogenboom, B. (2006a). Pre-participation screening: the use of fundamental movements as an assessment of function - part 1. *North American Journal of Sports Physical Therapy*,1(2):62–72.

Cook, G., Burton, L., & Hoogenboom, B. (2006b). Pre-participation screening: the use of fundamental movements as an assessment of function - part 2*. North American Journal of Sports Physical Therapy*, 1(3):132–139.

Cook, Gray. (2017). *Expanding on the Joint-by-Joint Approach*. [Online] Available at: http://graycook.com/?p=35.

Cook, G., Burton, L., Hoogenboom, B., & Voigt, M. (2014a). Functional movement screening: The use of fundamental movement as an assessment of function. Part 1. *The International Journal of Sports Physical Therapy*, 9:(396).

Cook, G., Burton, L., Hoogenboom, B., & Voigt, M. (2014b). Functional movement screening: The use of fundamental movement as an assessment of function. Part 2. *The International Journal of Sports Physical Therapy*, 9:549.

Cowen, V.S. (2010). Functional fitness improvements after a worksite-based yoga initiative. *Journal of Bodywork and Movement Therapies*, 14(1):50–54.

Daniel, D., Malcolm, L., Stone, M., Perth, H., Morgan, J., & Riehl, B. (1982). Quantification of knee stability and function. *Contemporary Orthopaedics*,5:83-91.

Draper, J. & Lancaster, M. (1985). The 505 test: A test for agility in the horizontal plane. *Australian Journal of Science and Medicine In Sport*, 17(1):15-18.

DiMattia, M., Livengood, A., Uhl, T., Mattacola, C., & Malone, T. (2005). What are the validity of the single-leg-squat test and its relationship to hip-abduction strength? *Journal of Sports Rehabilitation*, 14:108-123.

Eastlack, M.E., Axe, M.J., & Snyder-Mackler, L. (1999). Laxity, instability, and functional outcome after ACL injury: copers versus noncopers. *Medicine and Science in Sports and Exercise*, 31(2):210–215.

Edwards, A., Bull, A.M.J., & Amis, A.A. (2007). The Attachments of the fiber bundles of the posterior cruciate ligament: An anatomic study. *Arthroscopy: The Journal of Arthroscopic & Related Surgery*, 23(3):284–290.

Egger, G. (1990). Sports injury in Australia: Causes, costs and prevention. A report to the National Better Health Program.

Ferreira, M.A. & Spamer, E.J. (2010). Biomechanical, anthropometrical and physical profile of elite university netball players and the relationship to musculoskeletal injuries. *South African Journal for Research in Sport, Physical Education, and Recreation*, 32(1):57–67.

Fitzgerald, G.K., Axe, M.J., & Snyder-Mackler, L. (2000). The efficacy of perturbation training in nonoperative anterior cruciate ligament rehabilitation programs for physical active individuals. *Physical Therapy*, 80(2):128–140.

Fitzgerald, G., Lephart, S.M., Hwang, J. H., & Wainer, M.R.S. (2001). Hop tests as predictors of dynamic knee stability. *Journal of Orthopaedic & Sports Physical Therapy*, 31(10):588-597

Flood, L. & Harrison, J. (2006). *Hospitalised basketball and netball injuries*. AIHW National Injury Surveillance Unit. South Australia

Flood, L. & Harrison, J.E. (2009). Epidemiology of basketball and netball injuries that resulted in hospital admission in Australia, 2000-2004. *The Medical Journal of Australia*, 190(2):87–90.

Fong, C., Blackburn, J., Norcross, M., McGrath, M., & Padua, D. (2011). Ankle-dorsiflexion range of motion and landing biomechanics. *Journal of Athletic Training*, 46(1):5–10.

Ford, K.R., Myer, G.D., & Hewett, T.E. (2003). Valgus knee motion during landing in high school female and male basketball players. *Medicine and Science in Sports and Exercise,* 35(10):745–1750.

Fox, D., O'Malley, E., & Blake, C. (2014). Normative data for the functional movement screenTM in male Gaelic field sports*. Physical Therapy in Sport*, 15(3):194–199.

Frohm, A., Heijne, A., Kowalski, J., Svensson, P., & Myklebust, G. (2011). A nine-test screening battery for athletes: a reliability study*. Scandinavian Journal of Medicine and Science in Sports*, 22(3): 306-315.

Frost, D., Beach, T., Campbell, T., Callaghan, J., & McGill, S. (2017). Can the functional movement screenTM be used to capture changes in spine and knee motion control following 12 weeks of training*? Physical Therapy in Sport*, 23:50–57.

Frost, D., Beach, T., Callaghan, J., & McGill, S. (2012). Using the functional movement screenTM to evaluate the effectiveness of training. *Journal of Strength and Conditioning Research*, 26(6):1620–1630.

Fu, F., Harner, C., Johnson, D., Miller, M., & Woo, S. (1993). Biomechanics of knee ligaments: Basic concepts and clinical application. *Journal of Bone & Joint Surgery*, 75(A):1716-1721.

Gabriel, M., Wong, E., Woo, S., Yagi, M., & Debski, R. (2004). Distribution of in situ forces in the anterior cruciate ligament in response to rotatory loads. *Journal of Orthopaedic Research*, 22(1):85–89.

Gamble, P. (2011). Physical preparation for netball – Part 1: Needs analysis and injury epidemiology*. UK Strength & Conditioning Association*, 22:10–15.

Garrison, M., Westrick, R., Johnson, M., & Benenson, J. (2015). Association between the functional movement screen and injury development in college athletes. *International Journal of Sports Physical Therapy*, 10(1):21–28.

Garvin, G.J., Munk, P.L., & Vellet, A.D. (1993). Tears of the medial collateral ligament: magnetic resonance imaging findings and associated injuries. *Canadian Association of Radiologists journal = Journal l'Association canadienne des radiologistes*, 44(3):99– 204.

Gianotti, S., Marshall, S., Hume, P., & Bunt, L. (2009). Incidence of anterior cruciate ligament injury and other knee ligament injuries: A national population-based study. *Journal of Science and Medicine in Sport*, 12(6):622–627.

Gilchrist, J., Mandelbaum, B., Melancon, H., Ryan, G., Silvers, H., Griffin, L., Watanabe, D., & Dick, R. (2008). A randomized controlled trial to prevent noncontact anterior cruciate ligament injury in female collegiate soccer players. *The American Journal of Sports Medicine*, 36(8):1476–1483.

Goss, D., Christopher, G., Faulk, R., & Moore, J. (2009). Functional training program bridges rehabilitation and return to duty*. Journal of Special Operations Medicine : a peer reviewed journal for SOF medical professionals*, 9(2):29–48.

Greenberger, H. & Paterno, M. V. (1995). Relationship of knee extensor strength and hopping test performance in the assessment of lower extremity function. *Journal of Sports Physical Therapy,* 22(5):202-206.

Nuckols, G. (2013). *Forward lean in the squat – is knee-dominant or hip-dominant better for moving more weight?* – Bret Contreras. Available at: https://bretcontreras.com/forward-lean-in-the-squat-is-knee-dominant-or-hip-dominant-better-for-moving-more-weight/

Gribble, P., Brigle, J., Pietrosimone, B., Pfile, K., & Webster, K. (2013). Intrarater reliability of the functional movement screen. *Journal of Strength and Conditioning Research*, 27(4):978–981.

Gulgin, H. & Hoogenboom, B. (2014). The functional movement screening (fms)TM: an inter-rater reliability study between raters of varied experience. *International Journal of Sports Physical Therapy*, 9(1):14–20.

Hammes, D., Aus der Fünten, K., Bizzini M., & Meyer, T. (2016). Injury prediction in veteran football players using the functional movement screenTM. *Journal of Sports Sciences*, 34(14):1371-1379.

Harilainen, A. 1987. Evaluation of knee instability in acute ligamentous injuries. *Annales chirurgiae et gynaecologiae*, 76(5):269–273.

Harner, C., Baek, G., Vogrin, T., Carlin, G., Kashiwaguchi, S., & Woo, S. (1999). Quantitative analysis of human cruciate ligament insertions. *Arthroscopy: The Journal of Arthroscopic & Related Surgery*, 15(7):741–749.

Hass, C., Schick, E., Chow, J., Tillman, M., Brunt, D., & Cauraugh, J. (2003). Lower extremity biomechanics differ in prepubescent and postpubescent female athletes during stride jump landings. *Journal of Applied Biomechanics*, 19(2):139–152.

Hemmerich, A., Brown, H., Smith, S., Marthandam, S., & Wyss, U. (2006). Hip, knee, and ankle kinematics of high range of motion activities of daily living. *Journal of Orthopaedic Research*, 24(4):770–781.

Herring, D., Cherry, K., Stedge, H., Herring, D., Cherry K., & Stedge, H. (2006). *Predictive value of the functional movement screen as it relates to anterior cruciate ligament injury.* Cedarville University. Cedarville, USA.

Hewett, T., Myer ,G., Ford, K., Heidt, R., Colosimo, A., McLean, S., van den Bogert, A., & Paterno, M. (2005). Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes: A prospective study. *American Journal of Sports Medicine*, 33(4):492–501.

Hewett, T., Stroupe, A., Nance, T., & Noyes, F. (1996). Plyometric training in female athletes. *The American Journal of Sports Medicine*, 24(6):765–773.

Hewett, T., Ford, K., Hoogenboom, B., & Myer, G. (2010). Understanding and preventing ACL injuries: current biomechanical and epidemiologic considerations - update 2010. *North American Journal of Sports Physical Therapy*, 5(4):234–251.

Hewett, T.E., Myer, G.D., & Ford, K.R. (2006). Anterior cruciate ligament injuries in female athletes. *The American Journal of Sports Medicine*, 34(2):299–311.

Hewett, T.E., Zazulak, B.T., & Myer, G.D. (2007). Effects of the menstrual cycle on anterior cruciate ligament injury risk. *The American Journal of Sports Medicine*, 35(4):659–668.

Hewett, T., Lindenfeld, T., Riccobene, J.V., & J., Noyes, F. (1999). The effect of neuromuscular training incidence on knee injury in female athletes. *American Journal of Sports Medicine,* 27(6):699-706.

Hopper, D., Lo, S., Kirkham, C., & Elliott, B. (1992). Landing patterns in netball: analysis of an international game. *British Journal of Sports Medicine*, 26(2):101-106.

Hopper, D., Bryant, A., & Elliott, B. (1994). Foot types and lower limb injuries in elite netball players. *Journal of the American Podiatric Medical Association*, 84(7):355–62.

Hopper, D.M., Hopper, J.L., & Elliott, B.C. (1995). Do selected kinanthropometric and performance variables predict injuries in female netball players? *Journal of Sports Sciences,* 13(3):213–222.

Horan, S., Watson, S., Carty, C., Sartori, M., & Weeks, B. (2014). Lower-limb kinematics of single-leg squat performance in young adults. *Physiotherapy Canada,* 66(3):228–233.

Hotta, T., Nishiguchi, S., Fukutani, N., Tashiro, Y., Adachi, D., Morino, S., Shirooka, H., & Nozaki, Y. (2015). Functional movement screen for predicting running injuries in 18- to 24-year-old competitive male runners. *Journal of Strength and Conditioning Research*, 29(10):2808–2815.

Howe, L. & Cushion, J. E. (2017). A problem-solving process to identify the origins of poor movement. *Origins of poor movement*, (44):7-15.

Hughes, G. & Watkins, J. (2006). A risk-factor model for anterior cruciate ligament injury. *Sports Medicine*, 36(5):411–428.

Hughston, J., Andrews, J., Cross, M., & Moschi, A. (1976). Classification of knee ligament instabilities. Part I. The medial compartment and cruciate ligaments. *The Journal of Bone and Joint Surgery,* 58(2):159-172.

Hungerford, B., Gilleard, W., & Hodges, P. (2003). Evidence of altered lumbopelvic muscle recruitment in the presence of sacroiliac joint pain. *Spine*, 28:593–1600.

Huston, L., Vibert, B., Ashton-Miller, J., & Wojtys, E. (2001). Gender differences in knee angle when landing from a drop-jump. *American Journal of Knee Surgery*, 14(4):215-219.

Huxel Bliven, K.C. & Anderson, B.E. (2013). Core stability training for injury prevention. *Sports Health*, 5(6):514–522.

Ireland, M.L. (2002). The female ACL: Why is it more prone to injury? *Orthopedic Clinics of North America*, 33(4):637–651.

Bramley, J. (2007). *Netball players: best educated in the country* | IOL Sport. Available at: https://www.iol.co.za/sport/more-sport/netball-players-best-educated-in-the-country-576660.

Janssen, K., Orchard, J., Driscoll, T., & van Mechelen, W. (2012). High incidence and costs for anterior cruciate ligament reconstructions performed in Australia from 2003-2004 to 2007-2008: time for an anterior cruciate ligament register by Scandinavian model? *Scandinavian Journal of Medicine & Science in Sports*, 22(4):495–501.

Johnson, J. (2017). *Straight-Leg Dead Lift Exercises* | Livestrong.com. Available at: http://www.livestrong.com/article/358949-straight-leg-dead-lift-exercises/

Lawrence, J. (2014). Dynamic stability intervention program reducing the ACL injury rate of Singapore netballers. [Online] Available at: http://netballabudhabi.com/wp/wp-content/uploads/2015/09/CAP_Dynamic-Stability-Intervention-Prog_Netball-Singapore_Updated-21.11.14.pdf.

Katz, J.W. & Fingeroth, R.J. (1986). The diagnostic accuracy of ruptures of the anterior cruciate ligament comparing the Lachman test, the anterior drawer sign, and the pivot shift test in acute and chronic knee injuries. *The American Journal of Sports Medicine*, 14(1):88–91.

Kibler, W., Ben, Press, J., & Sciascia, A. (2006). The role of core stability in athletic function. *Sports Medicine*, 36(3):189–198.

Kiesel, K., Plisky, P., & Butler, R. (2011). Functional movement test scores improve following a standardized off-season intervention program in professional football players. *Scandinavian Journal of Medicine and Science in Sports*, 21(2):287–292.

Kim, S-H., Kwon, O-Y., Park, K-N., Jeon, I-C., & Weon, J-H. (2015). Lower extremity strength and the range of motion in relation to squat depth. *Journal of Human Kinetics*, 45:59–69.

Kim, S. & Kim, H. (1995). Reliability of the anterior drawer test, the pivot shift test, and the lachman test. *Clinical Orthopaedics and Related Research*, (317):237–242.

Koo, K. T., & Li, Y.M. (2016). A guideline of selecting and reporting intraclass correlation coefficients for reliability research. *Journal of Chiropractic Medicine,* 15(2): 155-163.

Kritz, M., Cronin, J., & Hume, P. (2009). The bodyweight squat: A movement screen for the squat pattern. *Strength and Conditioning Journal*, 31(1):76–85.

Krosshaug, T., Nakamae, A., Boden, B., Engebretsen, L., Smith, G., Slauterbeck, J., Hewett, T., & Bahr, R. (2006). Mechanisms of anterior cruciate ligament injury in basketball: Video analysis of 39 cases. *The American Journal of Sports Medicine*, 35(3):359–367.

Krosshaug, T., Steffen, K., Kristianslund, E., Nilstad, A., Mok, K-M., Myklebust, G., Andersen, T.E. et al. (2016). The vertical drop jump Is a poor screening test for ACL injuries in female elite soccer and handball players. *The American Journal of Sports Medicine*, 44(4):874–883.

Kiesel, K., Plisky, P., & Voight, M. (2007). Can serious injury in proffesional football be predicted by a preseason functional movement screen*? North American Journal of Sports Physical Therapy*, 2(3):147-158.

LaBella, C., Huxford, M., Grissom, J., Kim, K., Peng, J., & Christoffel, K. (2011). Effect of neuromuscular warm-up on injuries in female soccer and basketball athletes in urban public high schools. *Archives of Pediatrics & Adolescent Medicine*, 165(11):1033.

Landry, S.C., McKean, K.A., Hubley-Kozey, C.L., Stanish, W.D., & Deluzio, k.J. (2007). Neuromuscular and lower limb biomechanical differences exist between male and female elite adolescent soccer players during an unanticipated side-cut maneuver. *The American Journal of Sports Medicine*, 35(11):1888–1900.

Langeveld, E., Coetzee, F.F., & Holtzhausen, L.J. (2012). Epidemiology of injuries in elite South African netball players. *South African Journal for Research in Sport, Physical Education and Recreation*, 34(2):83–93.

LaPrade, R.F., Ly, T.V., & Griffith, C. (2008). The external rotation recurvatum test revisited: Reevaluation of the sagittal plane tibiofemoral relationship. *American Journal of Sports Medicine*, 36(4):709.

Leeder, J.E., Horsley, I.G., & Herrington, L.C. (2016). The inter-rater reliability of the functional movement screen within an athletic population using untrained raters. *Journal of Strength and Conditioning Research*, 30(9):2591-2599.

Lephart, S., Fitzgerald, G., Lephart, S., Hwang, J., Wainner, R., Fitzgerald, G., Lephart, S., & Hwang, J. et al. (2001). Hop tests as predictors of dynamic knee stability. *Journal of Orthopaedic & Sports Physical Therapy,* 31(10):588–597.

Letafatkar, A., Hadadnezhad, M., Shojaedin, S., & Mohamadi, E. (2014). Relationship between functional movement screening score and history of injury. *International Journal of Sports Physical Therapy*, 9(1):21–27.

Liebenson, C. (2002a). Functional exercises. *Journal of Bodywork and Movement Therapies*, 6(2):14–116.

Liebenson, C. (2002b). Squats and lunges for "Core" Stability. *Journal of Bodywork and Movement Therapies,* 6(4):255–256.

Lisman, P., O'Connor, F.G., Deuster, P.A., & Knapik, J.J. (2013). Functional movement screen and aerobic fitness predict injuries in military training. *Medicine and Science in Sports and Exercise.* 45(4):636–643.

Liu-Ambrose, T., Taunton, J.E., MacIntyre, D., McConkey, P., & Khan, K.M. (2003). The effects of proprioceptive or strength training on the neuromuscular function of the ACL reconstructed knee: a randomized clinical trial. *Scandinavian Journal of Medicine & Science in Sports,* 13(2):115–123.

Liu, S.H., Osti, L., Henry, M., & Bocchi, M. (1995). The diagnosis of acute complete tears of the anterior cruciate ligament. Comparison of MRI, arthrometry and clinical examination. *The Journal Of Bone And Joint Surgery,* 77(B):586-588.

Livingston, K.E., Clifford, S.N., Campbell, M., Garner, S., Maggi, E., & Sweeney, J. Kean (2016). Examination of the relationship between passive and dynamic measures of lower extremity stability in division III athletes, EATA professional. University, Union.

Lloyd, R.S., Oliver, J.L., Radnor, J.M., Rhodes, B.C., Faigenbaum, A.D., & Myer, G.D. (2015). Relationships between functional movement screen scores, maturation and physical performance in young soccer players. *Journal of Sports Sciences*, 33(1):11– 19.

Lockie, R., Schultz, A., Callaghan, S., Jordan, C., Luczo, T., & Jeffriess, M. (2015). A preliminary investigation into the relationship between functional movement screen scores and athletic physical performance in female team sport athletes. *Biology of Sport*, 32(1):41–51.

Lockie, R., Robert, G., Schultz, A.B., Jordan, C.A., Callaghan, S.J., Jeffriess, M.D., & Luczo, T.M. (2015). Can selected functional movement screen assessments be Used to identify movement deficiencies that could affect multidirectional speed and jump performance? *Journal of Strength and Conditioning Research*, 29(1):95–205.

Lockie, R., Jalilvand, F., Jordan, C., Callaghan, S., Jeffriess, M., Luczo, T., & Schultz, A. (2015). Research-grade scoring for the functional movement screen and relationships with athletic performance tests in team sport athletes. *Journal of Athletic Enhancement*, 4(1):8.

Logerstedt, D., Grindem, H., Lynch, A., Eitzen, I., Engebretsen, L., Risberg, M.A., Axe, M.J., & Snyder-Mackler, I. (2012). Single-legged hop tests as predictors of self-reported knee function after anterior cruciate ligament reconstruction. *The American Journal of Sports Medicine*, 40(10):2348–2356.

Loudon, J., Parkerson-Mitchell, A., Hildebrand, L., & Teague, C. (2014). Functional movement screen scores in a group of running athletes. *Journal of Strength and Conditioning Research* , 28(4):909-913.

Lyons, M.E. (2006). Isokinetic Hamstring : Quadriceps strength ratio in males and females : Implications for ACL injury. *The Osprey Journal of Ideas and Inquiry*, 1(1):2001–2008.

Macrum, E., Bell, D.R., Boling, M., Lewek, M., & Padua, D. (2012). Effect of limiting ankle-dorsiflexion range of motion on lower extremity kinematics and muscle-activation patterns during a squat. *Journal of Sport Rehabilitation*, 21(2):144–150.

Makhmalbaf, H., Moradi, A., Ganji, S., & Omidi-Kashani, F. (2013). Accuracy of lachman and anterior drawer tests for anterior cruciate ligament injuries*. Archives Of Bone And Joint Surgery,* 1(2): 94-97.

Malinzak, R., Colby, S., Kirkendall, D., Yu, B., & Garrett, W. (2001). A comparison of knee joint motion patterns between men and women in selected athletic tasks. *Clinical Biomechanics,* 16(5):438–445.

Mandelbaum, B.R., Silvers, H.J., Watanabe, D.S., Knarr, J.F., Thomas, S.D., Griffin , L.Y., Kirkendall, D.T., & Garrett, W. (2005). Effectiveness of a neuromuscular and proprioceptive training program in preventing anterior cruciate ligament injuries in female athletes: 2-year follow-up. *American Journal of Sports Medicine*, 33(7):1003–1010.

Markolf, K.L., Burchfield, D.M., Shapiro, M.M., Shepard, M.F., Finerman, G.A.M., & Slauterbeck, J.L. (1995). Combined knee loading states that generate high anterior cruciate ligament forces. *Journal of Orthopaedic Research,* 13(6):930–935.

Mattacola, C.G., Livengood, A.L., DiMattia, M.A., & Uhl, T.L. (2004). "Dynamic trendelenburg": Single-leg-squat test for gluteus medius strength. *Athletic Therapy Today,* 9(1):24–25.

McClure, P.W., Rothstein, J.M., & Riddle, D.L. (1989). Intertester reliability of clinical judgments of medial knee ligament integrity*. Physical Therapy,* 69(4):268–275.

McManus, A., Stevenson, M.R., & Finch, C.F. (2006). Incidence and risk factors for injury in non-elite netball. *Journal of Science and Medicine in Sport*, 9(1–2):119–124.

Meeuwisse, W.H. (1991). Predictability of sports injuries. What is the epidemiological evidence? *Sports Medicine* (Auckland, N.Z.), 12(1):8–15.

Mendiguchia, J. Ford, K.R., Quatman, C.E., Alentorn-Geli, E., & Hewett, T.E. (2011). Sex differences in proximal control of the knee joint. *Sports Medicine,* 41(7):541–557.

Minick, K.I., Kiesel, K.B., Burton, L., Taylor, A., Plisky, P., & Butler, R.J. (2010). Interrater reliability of the functional movement screen. *Journal of Strength and Conditioning Research*, 24(2): 479–486.

Mir, S.M., Talebian, S., Naseri, N., & Hadian M.R., (2014). Assessment of knee proprioception in the anterior cruciate ligament injury risk position in healthy subjects: A Cross-sectional Study. *Journal of Physical Therapy Science*, 26(10):1515– 1518.

Mirowitz, S.A. & Shu, H.H. (1994). Mr imaging evaluation of knee collateral ligaments and related injuries: Comparison of T1-weighted, T2-weighted, and fat-saturated T2-weighted sequences—correlation with clinical findings. *Journal of Magnetic Resonance Imaging,* 4(5):725–732.

Mitchell, U.H., Johnson, A.W., & Adamson, B. (2015). Relationship between functional movement screen scores, core strength, posture, and body mass index in school children in moldova. *Journal of Strength and Conditioning Research*, 29(5):1172-1179.

Moreside, J.M. & Mcgill, S.M. (2012). Hip joint range of motion improvements using three different interventions. *Journal of Strength and Conditioning Research*, 26(5):1265–1273.

Mulligan, E., McGuffie, D., Coyner, K., & Khazzam, M. (2015). The reliability and diagnostic accuracy of assessing the translation endpoint during the Lachman test. *The International Journal of Sports Physical Therapy*, 10(1):52.

Munro, A., Herrington, L., & Comfort, P. (2012). Comparison of landing knee valgus angle between female basketball and football athletes: Possible implications for anterior cruciate ligament and patellofemoral joint injury rates. *Physical Therapy in Sport*, 13(4):259–264.

Müller, U., Krüger-Franke, M., Schmidt, M., & Rosemeyer, B. (2015). Predictive parameters for return to pre-injury level of sport 6 months following anterior cruciate ligament reconstruction surgery. *Knee Surgery, Sports Traumatology, Arthroscopy*, 23(12): 3623-3631.

Myer, G.D., Ford, K.R., & Hewett, T.E. (2004). Rationale and clinical techniques for anterior cruciate ligament injury prevention among female athletes. *Journal of Athletic Training,* 39(4):352–364.

Myklebust, G., Engebretsen, L., Braekken, I.H., Skjølberg, A., Olsen, O.E., & Bahr, R. (2003). Prevention of anterior cruciate ligament injuries in female team handball players: a prospective intervention study over three seasons. *Clinical Journal of Sport Medicine : official journal of the Canadian Academy of Sport Medicine,* 13(2):71–78.

Nagano, Y., Fukano, M., Itagaki, K., Li, S., Miyakawa, S., & Fukubayashi, T. (2010). Influence of lower limb clinical physical measurements of female athletes on knee motion during continuous jump testing. *The Open Sports Medicine Journa*l, 4:134–139.

Netball Australia, 2012. Official Rules of Netball. Online. Avalaible at: http://netball.com.au/wp-content/uploads/2014/07/Official-Rules-of-Netball_Revised-2012.pdf.

Niemuth, P.E., Johnson, R. J., Myers, M.J., & Thieman, T.J.P. (2005). Hip muscle weakness and overuse injuries in recreational runners. Clinical Journal of Sport Medicine. *Clinical Journal of Sport Medicine*, 15(1):14-21.

Nigg, B.M. (2001). The role of impact forces and foot pronation: A new paradigm. *Clinical Journal of Sport Medicine*, 11:2-9.

Nilstad, A., Andersen, T.E., Kristianslund, E., Bahr, R., Myclebust, G., Steffen, K., & Krosshaug, Tron. (2014). Physiotherapists can identify female football players with high knee valgus angles during vertical drop jumps using real-time Observational Screening. *Journal of Orthopaedic & Sports Physical Therapy*,44(5): 358-365.

O'Connor, F.G., Deuster, P., Davis, J., Pappas, C.G., & Knapik, J.J. 2011. Functional movement screening. *Medicine & Science in Sports & Exercise*, 43(12):2224–2230.

Okada, T., Huxel, K.C., & Nesser, T.W. (2011). Relationship between core stability, functional movement, and performance. *Journal of Strength and Conditioning Research,* 25(1):252–261.

Onate, J.A., Dewey, T., Kollock, R.O., Thomas, K.S., Van Lunen,B.L., DeMaio, M., & Ringleb, S. (2012). Real-time intersession and interrater reliability of the functional movement screen. *Journal of Strength and Conditioning Research*, 26(2):408–415.

Ostrowski, J.A. (2006). Accuracy of 3 diagnostic tests for anterior cruciate ligament tears. *Journal of Athletic Training*, 41(1):120–121.

Otago, L. & Peake, J. (2007). The role of insurance data in setting priorities for netball injury prevention strategies. *Journal of Science And Medicine In Sport*, 10(2):105–109.

Pappas, E., Hagins, M., Sheikhzadeh, A., Nordin, M., & Rose, D. (2007). Biomechanical differences between unilateral and bilateral landings from a jump: Gender differences. *Clinical Journal of Sports Medicine*, 17(4):263-268.

Parchmann, C.J. & McBride, J.M. (2011). Relationship between functional movement screen and athletic performance. *Journal of Strength and Conditioning Research*, 25(12):3378–3384.

Parenteau-G, E., Gaudreault, N., Chambers, S., Boisvert, C., Grenier, A., Gagné, G., & Balg, F. (2014). Functional movement screen test: A reliable screening test for young elite ice hockey players. *Physical Therapy in Sport*, 15(3):169–175.

Peate, W., Bates, G., Lunda, K., Francis, S., & Bellamy, K. (2007). Core strength: A new model for injury prediction and prevention. *Journal of Occupational Medicine and Toxicology*, 2(3):1-9.

Perry, F.T. & Koehle, M.S. (2013). Normative data for the functional movement screen in middle-aged adults. *Journal of Strength and Conditioning Research*, 27(2):458–462.

Perry, J. (2015). *Correlations between the functional movement screen (FMS), the balance error scoring system (BESS)*, and injury. Unpublished thesis. Winthrop University. Rock Hill, USA.

Petersen, W. & Zantop, T. (2006). Anatomy of the anterior cruciate ligament with regard to Its two bundles*. Clinical Orthopaedics and Related Research*, 454:35-47

Pillay, T. & Frantz, J.M. (2012). Injury prevalence of netball players in South Africa: The need for in jury prevention. *South African Journal of Physiotherapy*, 68(3):7–10.

Piva, S.R., Goodnite, E.A., & Childs, J.D. (2005). Strength around the hip and flexibility of soft tissues in individuals with and without Patellofemoral pain syndrome. *Journal of Orthopaedic & Sports Physical Therapy*, 35:793-801.

Pollard, C.D., Sigward, S.M., & Powers, C.M. (2010). Limited hip and knee flexion during landing is associated with increased frontal plane knee motion and moments*. Clinical Biomechanics*, 25 (2):142-146.

Poulsen, D.R. & James, C.R. (2011). Concurrent validity and reliability of clinical evaluation of the single leg squat. *Physiotherapy Theory and Practice*, 27(8):586–594.

Powers, C. (2010). The influence of abnormal hip mechanics on knee injury: A biomechanical perspective*. Journal Of Orthopaedic & Sports Physical Therapy*, 40(2):42-51.

Reid, D.A., Vanweerd, R.J., Larmer, P.J., & Kingstone, R. (2015). The inter and intra rater reliability of the netball movement screening tool*. Journal Of Science And Medicine In Sport / Sports Medicine Australia,* 18(3):353-357.

Reider, B. 1996. Medial collateral ligament injuries in athletes. *Sports Medicine,* 21(2):147–156.

Renstrom, P., Ljungqvist, A., Arendt, E., Beynnon, B., Fukubayashi , T., Garrett, W., Georgoulis, T. et al. (2008). Non-contact ACL injuries in female athletes: an International Olympic Committee current concepts statement. British *Journal of Sports Medicine*, 42(6):394–412.

Riemann, B.L. & Lephart, S.M. (2002). The sensorimotor system, Part II: The role of proprioception in motor control and functional joint stability. *Journal of Athletic Training,* 37(1):80–84.

Rosenberg, T.D. & Rasmussen, G.L. (1984). The function of the anterior cruciate ligament during anterior drawer and lachman's testing. *The American Journal of Sports Medicine,* 12(4):318–322.

Ross, M. (2007). Effect of a 15-Day pragmatic hamstring stretching program on hamstring flexibility and single hop for distance test performance. *Research in Sports Medicine*, 15(4):271–281.

Ross, M.D., Langford, B., & Whelan, P.J. (2002). Test-retest reliability of 4 single-leg horizontal hop tests. *Journal of Strength and Conditioning Research*, 16(4):617–622.

Rossi, R., Dettoni, F., Bruzzone, M., Cottino, U., D 'elicio, D.G., & Bonasia, D.E. (2011). Clinical examination of the knee: know your tools for diagnosis of knee injuries. *Sports Medicine, Arthroscopy, Rehabilitation, Therapy & Technology*, 3(25), 331-336.

S.H. L, L. O, M., H, L. B., Liu, S., Osti L., Henry, M., & Bocchi, L. (1995). The diagnosis of acute complete tears of the anterior cruciate ligament. *The Journal Of Bone And Joint Surgery,* 7-B:586-588.

Sadoghi, P., von Keudell, A., & Vavken, P. (2012). Effectiveness of anterior cruciate ligament injury prevention training programs. *The Journal of Bone and Joint Surgery-American Volume*, 94(9):769–776.

Sayers, M.G.L. (2015). Influence of test distance on change of direction speed test results*. Journal of Strength and Conditioning Research*, 29(9):2412–2416.

Schneiders, A., Davidsson, A., Hörman, E., & Sullivan, S. (2011). Functional movement screen normative values in a young, active population. *International journal of sports physical therapy, 6(2): 75.*

Schoenfeld, B. (2010). Squatting kinematics and kinetics and their application to exercise performance. *Journal of Strength and Conditioning Research*, 24(12):3497–3506.

Sekir, U., Yildiz, Y., Hazneci, B., Ors, F., Saka, T., & Aydin, T. (2008). Reliability of a functional test battery evaluating functionality, proprioception, and strength in recreational athletes with functional ankle instability. *European journal of physical and rehabilitation medicine*, 44(4):407–415.

Sernert, N., Kartus,J., Köhler, K., Stener, S., Larsson, J., Eriksson, B.I., Karlsson, J., & (1999). Analysis of subjective, objective and functional examination tests after anterior cruciate ligament reconstruction. *Knee Surgery, Sports Traumatology, Arthroscopy*, 7(3):160–165.

Shojaedin, S., Letafatkar, A., Hadadnezhad, M., & Dehkhoda, M. (2014). Relationship between functional movement screening score and history of injury and identifying the predictive value of the FMS for injury. *International Journal of Injury Control and Safety Promotion*, 21(4):355–360.

Shultz, R., Anderson, S., Matheson, G., Marcello, B., & Besier, T. (2013). Test-retest and interrater reliability of the functional movement screen. *Journal of Athletic Training*, 48(3):331–336.

Sigward, S.M. & Powers, C.M. (2007). Loading characteristics of females exhibiting excessive valgus moments during cutting. *Clinical Biomechanics,* 22(7):827–833.

Silvers, H.J. & Mandelbaum, B.R. (2007). Prevention of anterior cruciate ligament injury in the female athlete. *British journal of sports medicine*, 41(1):52-59.

Slauterbeck, J., Fuzie, S., Smith, M., Clark, R., Xu, K., Starch, D., & Hardy D. 2002. The menstrual cycle, sex hormones, and anterior cruciate ligament injury. *Journal of athletic training*, 37(3):275–278.

Smith, C., Chimera, N., Wright, N., & Warren, M. (2013). Interrater and Intrarater Reliability of the Functional Movement Screen. *Journal of Strength and Conditioning Research*, 27(4):982–987.

Song, H., Woo, S., So, W., Kim, K., Lee, J., & Kim, J. (2014). Effects of 16-week functional movement screen training program on strength and flexibility of elite high school baseball players. *Journal of Exercise Rehabilitation*, 10(2):124–130.

Soomro, N., Sanders, R., Hackett, D., Hubka, T., Ebrahimi, S., Freeston, J., & Cobley, S. (2016). The efficacy of injury prevention programs in adolescent team sports. *The American Journal of Sports Medicine*, 44(9):2415–2424.

Steele, J. & Milburn, P. (1987). Ground reaction forces on landing in netball. *Journal of Human Movement Studies*,13:399–410.

Steele, J.R. (1986). A kinetic and kinematic analysis of netball landing technique : implications for injury prevention. National Library of Australia.

Steele, J.R. (1990). Biomechanical factors affecting performance in netball. Implications for improving performance and injury reduction. *Sports Medicine*, 10(2):88–102.

Steele, J.R. & Lafortune, M.A. (1989). A kinetic analysis of footfall patterns at landing in netball. *Human Movement and Sports Science*:101–112.

Steele, J.R. & Milburn, P.D. (1988). Effect of different synthetic sport surfaces on ground reaction forces at landing in netball. *International journal of sport biomechanics*, 4(2):130-145.

Stensrud, S., Myklebust, G., Kristianslund, E., Bahr, R., & Krosshaug, T. (2011). Correlation between two-dimensional video analysis and subjective assessment in evaluating knee control among elite female team handball players. *British Journal of Sports Medicine*, 45(7);589–595.

Stewart, P.F., Turner, A.N., & Miller, S.C. (2014). Reliability, factorial validity, and interrelationships of five commonly used change of direction speed tests. *Scandinavian Journal of Medicine & Science in Sports*, 24(3):500–506.

Stiffler, M., Pennuto, A., Smith, M., Olson, M., & Bell, D. (2015). Range of motion, postural alignment, and LESS score differences of those with and without excessive medial knee displacement. *Clinical Journal of Sport Medicine*, 25(1):61–66.

Stijak, L., Herzog, R.F., & Schai, P. (2008). Is there an influence of the tibial slope of the lateral condyle on the ACL lesion? *Knee Surgery, Sports Traumatology, Arthroscopy*, 16(2):112–117.

Stuelcken, M., Mellifont, D., Gorman, A., & Sayers, M. (2016). Mechanisms of anterior cruciate ligament injuries in elite women's netball: a systematic video analysis. *Journal of Sports Sciences*, 34(16):1516–1522.

Tamura, A., Akasaka, K., Otsudo, T., Shiozawa,J., Toda, Y., & Yamada, K. (2017). Fatigue influences lower extremity angular velocities during a single-leg drop vertical jump. *Journal of physical therapy science*, 29(3):498–504.

Terada, M., Harkey, M.S., Wells, A.M., Pietrosimone, B.G., & Griblle, P.A. (2014). The influence of ankle dorsiflexion and self-reported patient outcomes on dynamic postural control in participants with chronic ankle instability, *Gait & Posture*, 40(1):193 – 197.

Teyhen, D., Shaffer, S., Lorenson, C., Halfpap, J., Donofry, D., Walker, M., Dugan, J., & Childs, J. (2012). The functional movement screen: a reliability study. *The Journal of orthopaedic and sports physical therapy*, 42(6):530-540.

Thapa, S.S. & Lamichhane A.P. (2015). Accuracy of Lelli test for anterior cruciate ligament tear. *Journal of Institute of Medicine*, 37(2): 91-94.

Ugalde, V., Brockman, C., Bailowitz, Z., & Pollard, C. (2015). Single leg squat test and Its relationship to dynamic knee valgus and injury risk screening. *The journal of injury function and rehabilitation* , 7:229–235.

Van der Plas, C. (2005). Fysische diagnostiek - de waarde van enkele gebruikelijke tests voor het aantonen van een voorstekruisbandruptuur: meta-analyse. *Ned Tijdschr Geneeskd*, 8149(2):83-88.

Venter, R. 2005. Physical and physiological profiles of Boland netball. *South African Journal for Research in Sport, Physical Education and Recreation*, 17(2):3–7.

Venter, R., Masterson, C., Tidbury, G., & Krkeljas, Z. (2017). The relationship between functional movement screening and performance tests in high-level university female netball players. *South African Journal for Research in Sport, Physical Education and Recreation*, 32(32):57-67.

Voskanian, N. (2013). ACL Injury prevention in female athletes: review of the literature and practical considerations in implementing an ACL prevention program. *Current reviews in musculoskeletal medicine*, 6(2):158–163.

Weeks, B.K., Carty, C.P., & Horan, S.A. (2012). Kinematic predictors of single-leg squat performance: a comparison of experienced physiotherapists and student physiotherapists. *BMC Musculoskeletal Disorders*, 13(1):207.

White, K., Lee, S., Cutuk, A., Hargens, A., & Pedowitz, R. (2003). EMG power spectra of intercollegiate athletes and anterior cruciate ligament injury risk in females. *Medicine & Science in Sports & Exercise*, 35(3):371–376.

Williams, G., Chmielewski, T., Rudolph, K., Buchanan, T., & Snyder-Mackler, L. (2001). Dynamic knee stability: Current theory and implications for clinicians and scientists. *Journal of Orthopaedic & Sports Physical Therapy*, 31(10):546–566.

Willigenburg, N. & Hewett, T.E. (2017). Performance on the functional movement screen Is related to hop performance but not to hip and knee strength in collegiate *Football Players. Clinical Journal of Sport Medicine*, 27(2):119-126.

Wingfield, K. (2013). Neuromuscular training to prevent knee injuries in adolescent female soccer players. *Clinical Journal of Sport Medicine*, 23(5):407–408.

Wojtys, E., Hutston, L., Lindenfeld, T., & Hewett, T. (1998). Association between the menstrual cycle and anterior cruciate ligament injuries in female athletes. *The American Journal of Sports Medicine*, 26(5):614–619.

Wojtys, E. Huston, L., Boynton, M., Spindler, K., & Lindenfeld, T. (2002). The Effect of the menstrual cycle on anterior cruciate ligament injuries in women as determined by hormone levels. *The American Journal of Sports Medicine*, 30(2):182–188.

Wyndow, N., De Jong, A., Rial, K., Tucker, K., Collins, N., Vicenzino, B., Russell, T., & Crossley, K. (2016). The relationship of foot and ankle mobility to the frontal plane projection angle in asymptomatic adults. *Journal of Foot and Ankle Research*, 9(1):3.

Yang, C., Lee, G., Kim, J., Lee, Y,. Shin, I., Kwon, Y., Lee ,S., Yoo, J. et al. (2011). The anterior cruciate ligament injury prevention program: A Meta-Analysis. *Biomechanics in Sports Portuguese Journal of Sport Sciences*, 29(11):679-682.

Yoo, J., Lim, B., Ha, M., Lee, S., Oh, S., Lee, Y., & Kim, J. (2010). A meta-analysis of the effect of neuromuscular training on the prevention of the anterior cruciate ligament injury in female athletes. *Knee Surgery, Sports Traumatology, Arthroscopy*, 18(6):824– 830.

Yu, B. & Garrett, W.E. (2007). Mechanisms of non-contact ACL injuries. *British journal of sports medicine*, 41(1):47-51.

Zazulak, B., Hewett, T., Reeves, N., Goldberg, B., & Cholewicki, J. (2007). Deficits in neuromuscular control of the trunk predict knee injury risk: A Prospective Biomechanical-Epidemiologic Study. *The American Journal of Sports Medicine*, 35(7):1123–1130.

Zazulak, B., Ponce, P., Straub, S., Medvecky, M., Avedisian, L., & Hewett, T. (2005). Gender comparison of hip muscle activity during single-leg landing. *Journal of Orthopaedic & Sports Physical Therapy*, 35:292-299.

Zeller, B.L., McCrory, J.L., Kibler, B.W., & Uhl, T.L. (2003). Differences in kinematics and electromyographic activity between men and women during the single-legged squat. *The American Journal of Sports Medicine*, 31(3): 449-456.

Zouita Ben Moussa, A., Zouita ,S., Dziri, C., & Ben Salah, F. (2009). Single-leg assessment of postural stability and knee functional outcome two years after anterior cruciate ligament reconstruction. *Annals of Physical and Rehabilitation Medicine*, 52(6):475–484.

APPENDICES

Appendix 1

UNIVERSITEIT·STELLENBOSCH·UNIVERSITY
jou kennisvennoot • your knowledge partner

STELLENBOSCH UNIVERSITY
CONSENT TO PARTICIPATE IN RESEARCH

Correlation between FMS® and ACL screening tests and the effects of a six-week intervention to improve the test results

You are asked to participate in a research study titled "Correlation between FMS® and ACL screening tests and the effects of a six-week intervention to improve the test results". The study is part of the master thesis, and conducted by Dimitrije Kovac, a physiotherapist. You were selected as a possible participant in this study because you are a university netball player, older than 18 and currently do not have any known injuries.

1. PURPOSE OF THE STUDY

This study is designed to identify female netball players who are at the risk of ACL injuries using FMS®. screen test and ACL-specific clinical tests. Furthermore, the results of the tests will be used to create an ACL injury prevention exercise program in order to limit incidence of ACL injuries in netball.

2. PROCEDURES

If you volunteer to participate in this study, we would ask you to do the following things according to the following schedule:

FMS® functional movement screen consisting of 7 movement tests (deep squat, hurdle step, inline lunge, shoulder mobility, active straight leg raise, trunk stability push up, rotary stability) and 3 clearing exams (spinal flexion, spinal extension, shoulder flexion with internal rotation).

The time required for the test: 10 - 15 minutes.

Dynamic knee stability tests- single leg hop and hold test, vertical drop jump, single leg squat

The time required for the test: 10 minutes

Performance tests: 5-0-5 test. The athlete runs from the 15 meter marker towards the line (run in distance to build up speed) and through the 5 m markers, turns on the line and runs back through the 5 m markers

Single leg hop and hold for distance test.

The time required for the test: 10 minutes.

Total length of time per person: 30-40 minutes.

You will be required to wear comfortable athletic clothing and athletic shoes (tekkies

3. POTENTIAL RISKS AND DISCOMFORTS

You may feel a slight fatigue but without risk to health. If you experience any larger discomfort or pain during the test you should inform the investigator, and stop the test. All precautions will be taken to ensure the minimal risk to injury during testing.

4. POTENTIAL BENEFITS TO SUBJECTS AND/OR TO SOCIETY

Identification of netball players who have a higher potential risk of ACL injuries is essential to reducing the incidence of the same. Prevention programs may increase netball players careers, improve team performance through less injury time, and financial cost due to rehabilitation.

Future research on injury prevention may use the results to further develop screening strategies and prevention programs for other sports.

5. PAYMENT FOR PARTICIPATION

You will not receive any payment for participating in this study.

6. CONFIDENTIALITY

Any information that is obtained in connection with this study and that can be identified with you will remain confidential and will be disclosed only with your permission or as required by law. Confidentiality will be maintained by using your data only under participant ID, and not your name or any identifying information. Data will be stored on investigator private password protected computer, and available only to the PI, study leader, and any legal entities. The results of this study may be published in the scientific journal, however, the results will be published as group (i.e. sample) statistics rather than individual data, which will not be linked to your individual.

7. PARTICIPATION AND WITHDRAWAL

Your participation is voluntary, and you may withdraw at any time without consequences of any kind. You may also refuse to answer any questions you don't want to answer and still remain in the study.

8. IDENTIFICATION OF INVESTIGATORS

If you have any questions or concerns about the research, please feel free to contact research supervisor, professor Ranel Venter on the phone number 808 4721, primary investigator Dimitrije Kovac 21 808 9241.

9. RIGHTS OF RESEARCH SUBJECTS

You may withdraw your consent at any time and discontinue participation without penalty. You are not waiving any legal claims, rights or remedies because of your participation in this research study. If you have questions regarding your rights as a research subject, contact Ms Clarissa Graham (cgraham@sun.ac.za; 021 808 9183) at the Division for Research Development.

SIGNATURE OF RESEARCH SUBJECT OR LEGAL REPRESENTATIVE

By signing bellow, I indicate that I fully understand my rights if I choose to participate in this study. Information was conveyed to me in a language that I fully understand, and I was given an opportunity to ask questions, and these were answered to me with my satisfaction.

I hereby consent voluntarily to participate in the above study. I have been given a copy of this form.

_____

Name of Subject/Participant

_____

Name of Legal Representative (if applicable)

_____   _____

Signature of Subject/Participant or Legal Representative Date

Appendix 2

THE FUNCTIONAL MOVEMENT SCREEN
SCORING SHEET

NAME _____ DATE _____ DOB _____

ADDRESS _____

CITY, STATE, ZIP _____ PHONE _____

SCHOOL/AFFILIATION _____

SSN _____ HEIGHT _____ WEIGHT _____ AGE _____ GENDER _____

PRIMARY SPORT _____ PRIMARY POSITION _____

HAND/LEG DOMINANCE _____ PREVIOUS TEST SCORE _____

TEST		RAW SCORE	FINAL SCORE	COMMENTS
DEEP SQUAT				
HURDLE STEP	L			
	R			
INLINE LUNGE	L			
	R			
SHOULDER MOBILITY	L			
	R			
IMPINGEMENT CLEARING TEST	L			
	R			
ACTIVE STRAIGHT-LEG RAISE	L			
	R			
TRUNK STABILITY PUSHUP				
PRESS-UP CLEARING TEST				
ROTARY STABILITY	L			
	R			
POSTERIOR ROCKING CLEARING TEST				
TOTAL				

Raw Score: This score is used to denote right and left side scoring. The right and left sides are scored in five of the seven tests and both are documented in this space.

Final Score: This score is used to denote the overall score for the test. The lowest score for the raw score (each side) is carried over to give a final score for the test. A person who scores a three on the right and a two on the left would receive a final score of two. The final score is then summarized and used as a total score.