A critical analysis of two popular field-based movement screens

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Abstract

The Functional Movement Screen (FMS) and the Landing Error Scoring System (LESS) are two of the most commonly used field-based movement screens in the practical setting. The FMS is a series of seven tests that examine movement patterns of the body through assessing an overhead squat, an inline lunge, a hurdle step, two tests of core stability and upper and lower body mobility tests. The LESS is a dynamic drop jump where the landing is assessed and scored. The key purpose of both screens is to identify those who move poorly and may be at increased risk of injury.

Theoretically, the premise behind movement screening as a tool to identify those at increased risk of injury is sound. There is a large body of evidence highlighting that aberrant movements during dynamic tasks, as identified through 3D motion analysis, are associated with increased chance of injury. Therefore, if field-based screens could distinguish similar poor mechanics it may identify those at increased risk of injury.

Despite the theoretical justification and practical use of the FMS and LESS, several topics related to the two screening protocols require investigation. First, there is a lack of evidence examining the relationship between the FMS and LESS. It is unknown whether the FMS and LESS provide similar information to each other or whether they measure different movement variables. Second, there have been no studies investigating the association of injury with the FMS and LESS in the same cohort. Finally, there is a lack of empirical evidence examining the relationship between 3D kinematics during a dynamic task and FMS and LESS scores.
To address these gaps in the literature a series of progressive studies were conducted. First, FMS and LESS scores of 98 participants were correlated against each other. A significant moderate correlation (rho 100 and 21 point = -0.528; -0.487; p< .001) but poor shared variance ($r^2$ 100 and 21 point FMS=0.26 and 0.24 respectively) was reported in this study highlighting that the FMS and LESS measure different movement variables.

The results of this first study highlighted that the FMS and LESS should not be used as a substitute for each other. However, the results could not determine which screen had a greater association with injury. Therefore, a prospective injury study was conducted with 132 military participants undertaking an intensive 16 week fitness regimen. Injury data was recorded daily with this cohort. The results identified that a total FMS score was not a significant predictor of injury. LESS scores of > 5 or having a score of 1 on any FMS test were significantly associated with injury. LESS scores had greater relative risk, sensitivity and specificity (2.2 (95% CI= 1.48-3.34); 71% and 87% respectively) compared to scores of 1 on the FMS (relative risk = 1.32 (95% CI= 1.0-1.7); sensitivity =50% and specificity = 76%).

The final study of this research examined LESS and FMS scores of 52 participants against 3D lower limb kinematics during a drop jump. The results demonstrated that LESS scores could differentiate between poor and acceptable groups at initial contact and maximal displacement for hip flexion, hip adduction, knee valgus and knee rotation. These variables have been associated with injury in previous large prospective and retrospective studies. FMS scores could differentiate maximal hip flexion and knee valgus with a moderate to small effect size (ES= 0.71 and 0.74 respectively) but could not differentiate any other kinematic variables in the sagittal, frontal or transverse plane at the hip or knee at initial contact or maximal displacement. These results highlighted a limited ability of FMS scores to identify those who would perform a drop jump with kinematics associated with increased chance of injury.
The results of this programme of research highlight that the LESS and FMS are reliable screening tools. The two screening tools do not provide the same information and should not be used as a substitute for one another. The LESS has a stronger association with injury compared to the FMS, most likely due to its greater association with aberrant 3D kinematics during dynamic tasks. This research highlights limitations in using the FMS as a standalone screening assessment due to its limited ability to assess dynamic movements. Given the findings presented in this thesis practitioners should incorporate an additional dynamic screen, such as the LESS if using the FMS as their sole assessment of movement ability in order to get a more comprehensive assessment of movement quality and injury risk.

**Keywords:** Functional Movement Screen, Landing Error Scoring System, Pre-participation testing, 3D kinematics, prospective injury association.
Declaration

I hereby declare that the work contained within the current thesis is my own and was completed with the council of my supervisors Dr. Mark Lyons and Prof. Andrew J. Harrison of the Department of Physical Education and Sport Sciences, University of Limerick. This work has not been submitted to any other higher education institution or for any other academic reward within the current institute.

Signed:

__________________________  ____________________________  __________________________
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List of Abbreviations

3D= Three dimensional
AAA= Athletic Ability Assessment
ACL= Anterior Cruciate Ligament
ADD= Additional
ASLR= Active Straight Leg Raise
AT=Athletic training
CSMT= Conditioning Specific Movement Task
ES= Effect size
FMS= Functional Movement Screen
GRF= Ground Reaction force
IC=Initial Contact
ICC= Intra class coefficient
ITB= Iliotibial Band.
ITBFS= Iliotibial Band Friction Syndrome
Kg= Kilogram
Kw= Weighted Kappa
LESS= Landing Error Scoring System
M= Metres
MA= Medical attention
ME= Mean Error
MSc= Master of Science
MSK= Musculoskeletal
OR= Odds Ratio
PFPS= Patellofemoral Pain Syndrome
QAREL= Quality Appraisal of Reliability Studies
ROC= Receiver Operator Characteristics
RR= Risk Ratio
Rot Stab= Rotary Stability
SEM= Standard Error of Measure
Shld Mob= Shoulder Mobility
STROBE= Strengthening of Reporting of Observational Studies in Epidemiology
TJA= Tuck Jump Assessment
TL= Time loss
Yrs= Years
Operational definitions

**Functional Movement Patterns**: Fundamental, comprehensive movement patterns that require adequate muscular strength and symmetry, balance, trunk and core stability, coordination, motor control, flexibility, range of motion, and proximal-to-distal kinetic linking (Cook et al., 2006a, p. 121).

**Functional Movement Screen**: A screening protocol designed to assess the fundamental movement patterns of an individual by assessing and grading basic locomotor, manipulative, and stabilizing movements (Cook et al., 2006a, p. 123).

**Injury Severity**: “The number of days between the time of the injury and the time at which an individual return to full activity” (O’Connor et al., 2011, p. 2225).

**Injury**: “Any physical complaint, which was caused by a transfer of energy that exceeded the body’s ability to maintain its structural and/or functional integrity, that was sustained by a player during a match or training, irrespective of the need for medical attention or time-loss” (Fuller et al., 2007, p.329).

**Landing Error Scoring System**: A modified field-based drop jump assessment that scores an individual’s landing technique based on a set of 17 criteria that are easily observable to the human eye (Padua et al., 2009, p. 1996).

**Movement Screening**: A qualitative protocol designed for use with apparently healthy, uninjured individuals to primarily assess the ‘quality’ of a movement(s) rather than objective outcomes such as number of repetitions, distance, or time achieved. The movement(s) included should rely on multiple physical qualities to execute correctly, e.g., strength, balance, and flexibility (McCunn et al., 2016, p. 764)
**Time-loss Injury**: “an injury that results in a player being unable to take a full part in future training or match play” (Fuller et al., 2007. p.329).
Publications arising from Programme of Research

Study 1 – "Examining the reliability of the 100 point and 21 point Functional Movement Screen scoring systems."

- Oral presentation at the European College of Sport Science. Vienna 2016

Study 2- "To investigate the inter- and intra-rater reliability of the Landing Error Scoring System with raters using only the standardised instructions."

- Oral presentation at the All-Ireland Post-Graduate Conference. Carlow 2017
- Accepted to Journal of Sports Rehabilitation. June 2019

Study 3 – "To examine the relationship between the Functional Movement Screen and the Landing Error Scoring System in an active male collegiate population."


Study 4 – “An examination of the ability of the Functional Movement Screen and Landing Error Scoring System to predict injury in Military recruits."


Study 5 – "To examine the relationship between field-based screens and 3D kinematic and kinetic data during dynamic movements."

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Thesis overview

This programme of research contains a series of progressively linked studies followed by an overall discussion and conclusion. Four related investigations are reported in this thesis; first, this programme of research examines the inter- and intra-rater reliability of the author conducting and scoring the FMS and LESS (Chapter three). Second, with acceptable reliability for the FMS and LESS established, chapter four examines the relationship between FMS scores and LESS scores (Chapter four). Chapter five investigates the association of injury to FMS and LESS scores in a military cohort undergoing an intensive 16 week fitness training regime (Chapter five). Finally, in order to examine potential reasons for the relationship between the screening protocols and injury, chapter six investigates the relationship between the FMS and LESS and more established 'gold standard' 3D motion analysis of a drop jump. This programme of research finishes with an overall discussion and conclusion that outlines how the key findings of each study link to each other, highlights the overall contributions of new knowledge to the literature and provides practical recommendations based on the results of this programme of research.

The structure of the thesis is detailed briefly below:

- Chapter One: Introductory chapter that sets out the rationale for the programme of research and the overall aims of this research.
- Chapter Two: Review of the literature related to the FMS, LESS and 3D motion analysis of dynamic actions using 3D kinematic data.
- Chapter Three: Examination of the inter- and intra-rater reliability of the LESS and FMS.
- Chapter Four: Field-based study examining whether there is a relationship between FMS scores and LESS scores in a cohort of collegiate athletes.
• Chapter Five: Prospective injury study with a Irish military cohort undergoing an intensive 16 week introductory training block. This study examines the ability of the LESS and FMS to predict injury in this cohort.

• Chapter Six: Investigates the relationship between FMS scores, LESS scores and 3D kinematic data of the lower limbs during a dynamic drop jump action.

• Chapter Seven: Discussion of the wider thesis findings and the individual studies contained therein. This chapter also includes limitations of the programme of research and future research.

• Chapter Eight: Overall conclusions of the programme of research.
Chapter 1

Introduction, Aims and Objectives
1.0 Introduction

The role of sport and physical training in society has become increasingly important in recent years (MacNamara et al., 2010; Meylan et al., 2010). Numerous studies, articles and position statements have highlighted the positive impact that physical training and sport can have on physical and mental well-being (Kraemer et al., 2002; Warburton et al., 2006). In elite sport, the pursuit of improvements has led to the development of more professional approaches and training regimes (Renström et al., 2008; Meylan et al., 2010). Active professions, such as the military, fire-fighters and police are also putting more emphasis on their employees being in peak physical condition to deal with the demands of their chosen profession (Blacker et al., 2008; Teyhen et al., 2014). Billions of euro are lost each year due to days of missed service in active professions and in professional sport injury can lead to loss of form, missed competition or even early retirement from sport (Fuller et al., 2006; Hauret et al., 2010; Teyhen et al., 2014). With the role of physical training and sports participation gaining more importance it is essential that factors that inhibit participation and optimal performance be addressed as comprehensively as possible (Batt et al., 2004; Cook et al., 2006a).

The International Olympic Committee have stressed the need for baseline assessments to be conducted in order to design specific interventions that address individuals’ potential risk factors (Renström et al., 2008; Onate et al., 2010). Pre-participation screening and testing of athletes has long been established as a method of identifying and addressing factors that may predispose an individual to injury (Batt et al., 2004; Cook et al., 2006a). These pre-participation tests should help identify those at increased risk of injury while allowing those with limited risk to undertake the required sport-specific training to excel at their chosen sport or activity (Onate et al., 2010; Batt et al., 2004; Renström et al., 2008). In this way interventions are specific to an individual’s needs and precious resources of time, money and effort are focused towards those who need it most (Renström et al., 2008; Onate et al., 2010).
Traditionally, pre-participation screening has involved manual muscle strength testing and flexibility tests (Batt et al., 2004; Carek, 2008). These tests predominately focus on the strength and flexibility of isolated muscles and/or single joints (Onate et al., 2012; Kiesel et al., 2007). Examples of these type of tests include a Passive Straight Leg Raise to assess hamstring flexibility, a Knee to Wall test for soleus length and individual muscle strength testing. There has been some debate about the validity of this type of testing when assessing potential injury risk in sport due to the obvious disparity in the functioning of the muscle during isolated testing compared to the multi-plane, synergistic manner of muscle functioning during sport (Cook et al., 2006a; Cook et al., 2006b; Kiesel et al., 2007).

Due to potential proposed limitations of isolated strength testing, there has been an increase in the use of movement screening as the main pre-participation method employed in the sport setting (Hewett et al., 2010; McLean et al., 2005; Myer et al., 2008; Cook et al., 2006a; Cook et al., 2006b; Shultz et al., 2011). There have been formalised assessments of movement and posture as early as the 1950’s (Kendall et al., 1952). However, since the early 2000’s, there has been a resurgence in the development of movement screening protocols, possibly due to the static and isolated nature of traditional tests (Cook et al., 2006a). Movement screening can be defined as a method of qualitatively analysing and identifying dysfunction in an individual’s movement patterns (Cook et al., 2006a).

While there are a variety of different movement screens available that vary in the movements they assess, they fundamentally possess similar characteristics. First, they predominantly assess multi-joint, whole body actions. Second, they focus on qualitatively assessing co-ordinated movement patterns. Finally, they may include simpler tests of joint mobility or basic stability to help inform potential reasons for poor performance in the whole body actions (Cook et al., 2006a; Comerford and Mottram, 2012; Giles, 2011). Movement screening assesses the
fundamental movement patterns of the body (Cook et al., 2006a). Fundamental movement patterns are basic movements of the body that require a combination of joint mobility, core stability and co-ordination to be completed successfully (Cook et al., 2006a). It is proposed that examining these fundamental movements may provide an examiner with more insight into how athletes will perform the complex athletic actions required in their sport compared to isolated tests (Kiesel et al., 2007; Lisman et al., 2013).

The Functional Movement Screen (FMS) is one of the most utilised movement screens in the practical and research setting (Agresta et al., 2014; Bodden et al., 2015; Butler et al., 2012, Chapman et al., 2014; Chorba et al., 2010; Dossa et al., 2014; Cook et al., 2006a). The FMS is a simple screen to perform and grade, making it quick and practical to use (Cook et al., 2006a; Cook et al., 2006b). The FMS involves seven tests that examine three different levels of movement difficulty (Cook et al., 2006b; Cook et al., 2010). Three tests, the squat, lunge and hurdle step are described as higher level patterns, which are proposed to examine the three essential foot positions taken up in sport (bilateral jumping, changing direction and running respectively) (Cook et al., 2010). The rotary stability and press up tests are known as transitionary patterns and predominantly assess transverse and sagittal core stability (Cook et al., 2010). Finally, the primitive mobility patterns of the body are assessed by the active straight leg raise and the shoulder mobility tests (Cook et al., 2010).

Proponents of the FMS have described it as a series of “seven tests that utilise a variety of basic positions and movements, which are thought to provide the foundation for more complex athletic movements to be performed efficiently” (Kiesel et al, 2007 pg 148). This rationale for the use of the FMS is widely accepted yet remains largely unsupported in the literature (Kiesel et al, 2007; Cook et al, 2010). The key issue is that it assumes a link between basic movements and the mechanics undertaken in complex athletic actions, such as landing and cutting. There is sufficient research highlighting that poor mechanics during dynamic tasks, such as landing
and cutting increases the risk of lower limb injury (Ford et al., 2003; Hewett et al., 2005; Zazulak et al., 2005; Pollard et al., 2006; Powers, 2010). Therefore, the underlying assumption made by Lisman et al. (2013) and Kiesel et al. (2007) is that scoring poorly on the FMS will identify those who will move poorly in more dynamic tasks and thus be more predisposed to injury (Lisman et al., 2013; Kiesel et al., 2007). However, there is a lack of empirical evidence examining this assumption. Due to this gap in the research, it is apparent that several topics related to the FMS require investigation. First, it is important to examine the relationship between FMS scores and scores of a dynamic, field-based screen, such as the Landing Error Scoring System (LESS). The LESS is a screening assessment that scores an individual’s landing technique based on a set of 17 criteria that are easily observable to the human eye (Padua et al., 2009). The scoring criteria for the LESS have been derived from previous research identifying the specific movements that may contribute to increased risk of injury, in particular ACL injury (Padua et al., 2009). Proponents of the FMS and LESS state that their respective screens provide insights into how athletes will perform dynamic actions required in sport (Padua et al., 2009; Kiesel et al., 2007). Researching the relationship between the FMS and LESS will provide clarification to practitioners as to whether the two screens provide similar information to each other or whether there is no association between them and thus measure different movement variables.

Screening protocols, such as the LESS and FMS were designed to assess aberrant movement patterns that predispose individuals to injury (Padua et al., 2009; Cook et al., 2006a). There is conflicting and limited evidence related to the ability of the FMS and LESS to predict injury. Regarding the LESS, studies have examined whether the screen can predict ACL injury (Smith et al., 2015; Padua et al., 2015) but there is no empirical evidence investigating whether poor scores on the LESS are associated with overall greater injury risk. With regard to the FMS, a number of early studies reported that a composite score of ≤14 was associated with injury
(Kiesel et al., 2007; Chorba et al., 2010; Letafatkar et al., 2014; Peate et al., 2007; Lehr et al., 2013; Dossa et al., 2014; Kiesel et al., 2014; O’Connor et al., 2011). However, recent empirical studies and meta-analyses have reported limitations in the ability of the FMS to predict injury and others have determined there is in fact no association with injury (Schroeder et al., 2016; Mokha et al., 2016; Bushman et al., 2016; Moran et al., 2017). Furthermore, there is a lack of empirical evidence examining the association of injury of FMS and LESS scores in the same cohort. Therefore, it is apparent that a well-controlled prospective injury study is required to address all these questions. Clarifying the association of the FMS and LESS to injury will allow practitioners to evaluate the effectiveness of both screens as injury prediction tools.

The final gap this programme of research seeks to address is the lack of empirical evidence examining the relationship between FMS scores, LESS scores and lower limb 3D kinematic data obtained during dynamic actions, such as a drop jump. This study will provide insight into the relationship of the FMS and LESS and a valid measurement of dynamic landing. Systematically addressing these elements regarding the FMS and LESS will provide practitioners with much greater clarity regarding the effectiveness and benefit of these pre-participation movement screens.
1.1 Aim and Objectives

Aims of the thesis: To examine the relationship between two field-based screening scores (FMS and LESS), their association with injury and their relationship with lower limb 3D kinematics during a dynamic drop jump.

Objectives:

1. To investigate the inter- and intra-rater reliability of the 21 point and 100 point FMS scoring systems.
2. To examine the inter- and intra-rater reliability of the total score and individual scoring criteria of the LESS with experienced raters.
3. To investigate the relationship between FMS scores and LESS scores.
4. To examine if there is an association between FMS and LESS scores and injury.
5. To explore the relationship between FMS scores, LESS scores and lower limb 3D kinematics during a drop jump.
Chapter 2

Literature Review
2.0 Introduction

The purpose of this literature review is to provide an overview of the relevant research pertaining to functional movement screening in the practical setting. There is a paucity of research comparing the validity of popular movement screens to each other. Furthermore, there is a lack of research examining the potential association between functional screening tests and injury. Finally, there is a lack of empirical evidence regarding the relationship of field-based movement screening to more established 3-dimensional (3D) laboratory methods of movement assessment. Therefore, this review aims to explore the current research available and highlight current gaps that this programme of research will aim to address.

This review is divided into two main sections; the first section examines the research related to field-based movement screens, in particular the FMS developed by Cook (Cook et al., 2006a) and the LESS developed by Padua et al. (2009). The first section of this literature review explores research related to scoring and reliability of the FMS and validity of the screen in relation to predicting injury risk. The section then highlights the lack of research examining the relationship between the FMS and other dynamic field-based movement screens and 'gold standard' 3D kinematic laboratory movement analysis. The second section of this review examines the relevance and importance of comparing functional screening scores with kinematic data derived from 3D analyses and explores why 3D mechanics are considered the gold standard in the evaluation of human movement.

2.1 Search Strategy

A computerise search of five databases was undertaken for this literature review (Sports Discus, CINHAL, Medline, Web of Science, Science Direct) from the respective database’s inception until June 2018. In addition, articles were identified manually by searching the reference list of identified articles in the computerised search.
Appendix 2 outlines the key search terms and associated Prisma Flow diagram utilised to identify; 1. The various movement screens available; 2. Studies related to the FMS and LESS.

2.2- Field-based movement screens

2.2.1 Traditional pre-participation testing

Pre-participation screening of athletes has long been established as a proposed method of identifying and addressing factors that may predispose an individual to injury (Batt et al., 2004; Cook et al., 2006a). Traditionally, pre-participation screening has predominately involved posture assessment, manual muscle strength testing and flexibility tests (Batt et al., 2004; Carek, 2008). The Passive Hamstring test, the Thomas test and Knee to Wall test are examples of muscle length tests for the lower limb (Batt et al., 2004). Manual resistance of muscles using the Oxford Scale have been traditionally used to assess isolated muscle strength (Carek, 2008). The International Olympic Committee have stressed the need for pre-participation assessments to be conducted in order to design specific interventions that address individuals’ potential risk factors (Renström et al., 2008; Onate et al., 2010). These pre-participation tests should help identify those at increased risk of injury while allowing those with limited risk to undertake the required sport specific training to excel at their chosen sport or activity (Onate et al., 2010; Batt et al., 2004; Renström et al., 2008). In this way, interventions are specific to an individual’s needs and precious resources of time, money and effort are focused towards those who need it most (Renström et al., 2008; Onate et al., 2010).

Traditional pre-participation testing is typically conducted in an isolated, single joint manner (Onate et al., 2012; Kiesel et al., 2007). There has been some debate about the validity of this type of testing when assessing potential injury risk in sport due to the obvious disparity in the functioning of the muscle during isolated testing compared to the multi-plane, synergistic manner of muscle functioning during sport (Cook et al., 2006a; Cook et al., 2006b; Kiesel et al., 2007). Therefore, due to the potential limitation of isolated strength testing, there has been
an increase in the use of movement screening as the principal pre-participation method employed in the sport setting (Hewett et al., 2010; McLean et al., 2005; Myer et al., 2008; Cook et al., 2006a; Cook et al., 2006b; Shultz et al., 2011).

2.2.2 Movement Screening

As early as the 1950's, there have been formalised assessments of movement and posture (Kendall et al., 1952). However, since the early 2000's, there has been a resurgence in the development of movement screening protocols, possibly due to the static and isolated nature of traditional tests (Cook et al., 2006a). Movement screening can be defined as a method of qualitatively analysing and identifying dysfunction in an individual’s movement patterns (Cook et al., 2006a). The current review of the literature revealed several movement screens that fit with this definition. A description of these screens is outlined in Table 1.

The movement screens identified in this chapter vary in the movements they assess; however, they fundamentally possess similar characteristics. First, they predominantly assess multi-joint, whole body actions. Second, they focus on qualitatively assessing co-ordinated movement patterns. Finally, they may include more simple tests of joint mobility or basic stability to help inform potential reasons for poor performance in the whole body actions (Cook et al., 2006a; Comerford and Mottram, 2012; Giles, 2011). Movement screens are designed to examine the quality of a movement pattern rather than score objective measures, such as mass, time achieved, distance or number of repetitions. The movement(s) included should rely on multiple physical qualities to execute correctly, e.g., strength, balance, and flexibility (McCunn et al., 2016). The various movement screens identified in this research were assessed for methodological quality by the Applied Research Model for Sport Sciences (ARMSS)(Bishop, 2008).
The ARMSS includes eight stages of research that can be divided into three key objectives (Bishop, 2008). The first objective (stages 1-2) relates to a description of the problem and how the research may provide a solution (Kraus et al., 2014; Bishop, 2008). In the case of movement screening, this includes studies examining reliability, clinical commentaries and factor analyses (Kraus et al., 2014). The second objective relates to examining the validity of the movement screens in relation to factors such as performance and injury risk (Bishop, 2008). The third objective examines the effectiveness of the movement screens in the real world setting (Bishop, 2008). Controlled intervention studies and large scale correlation studies are included in this third objective (Bishop, 2008). The ARMSS scores of each movement screen are outlined in Table 1.
<table>
<thead>
<tr>
<th>Screen Name</th>
<th>No. of Sub-tests</th>
<th>Name of Subtests</th>
<th>ARMSS level (Rationale for score)</th>
<th>Protocol description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Functional Movement Screen</td>
<td>7</td>
<td>Overhead squat, Inline lunge, Hurdle, Rotary stability, Press up, Active straight leg raise, Shoulder mobility</td>
<td>7/8 (Descriptive/ Reliability/ Prospective injury/ RCT Studies)</td>
<td>Cook et al. (2006a)</td>
</tr>
<tr>
<td>Landing Error Scoring System</td>
<td>1</td>
<td>Drop jump</td>
<td>6/8 (Descriptive/ Reliability/ Concurrent Validity/ Prospective injury)</td>
<td>Padua et al. (2009)</td>
</tr>
<tr>
<td>Physical Competency Assessment</td>
<td>5</td>
<td>Lunge, Push up, Back squat</td>
<td>1/8 (Reliability study)</td>
<td>Giles (2011)</td>
</tr>
<tr>
<td>Performance Matrix</td>
<td>9</td>
<td>Double leg swing</td>
<td>1/8 (Reliability study)</td>
<td></td>
</tr>
<tr>
<td>--------------------</td>
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<td>------------------</td>
<td>------------------------</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Single leg quarter squat</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Split squat</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Lateral stair hop</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>One arm wall push</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>Plank and Lateral twist</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>Rotary stability test</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Bridge and heel lift</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Shoulder internal rotation</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Tuck Jump</th>
<th>1</th>
<th>Repeated tuck jump</th>
<th>3/8 (Reliability/ RCT)</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Single leg Squat Screens</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>• Single leg squat</td>
<td>1</td>
<td>Single leg half squat</td>
<td>3/8 (Reliability/ Concurrent Validity studies)</td>
</tr>
<tr>
<td>• Single leg mini-squat</td>
<td>1</td>
<td>Single leg quarter Squat</td>
<td>Ageberg et al. (2010)</td>
</tr>
<tr>
<td>• Unilateral single leg functional tasks</td>
<td>2</td>
<td>Single leg half squat</td>
<td>Yamazaki et al. (2010)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Lateral step up</td>
<td>Chmielewski et al. (2007)</td>
</tr>
<tr>
<td>Athletic Ability Assessment</td>
<td>9</td>
<td>Prone plank</td>
<td></td>
</tr>
<tr>
<td>-----------------------------</td>
<td>---</td>
<td>-------------</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Lateral side plank</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Overhead squat</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Single-leg squat off box</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Walking lunge</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Single-leg forward hop</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Lateral bound</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Push ups</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Chin ups</td>
<td></td>
</tr>
<tr>
<td>Condition Specific Movement Task</td>
<td>6</td>
<td>Overhead squat</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Romanian deadlift</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Single-leg squat</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Double-leg to single-leg landing</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sprint (40 m)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Countermovement jump</td>
<td></td>
</tr>
<tr>
<td>Overhead Squat Screen</td>
<td>1</td>
<td>Overhead Squat</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>2/8 (Descriptive/Reliability Study)</td>
<td></td>
</tr>
<tr>
<td>Modified FMS</td>
<td>9</td>
<td>Overhead squat</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>2/8 (Descriptive/Reliability Study)</td>
<td></td>
</tr>
</tbody>
</table>

McKeown et al. (2014)

Parsonage et al. (2014)

Noda and Verscheure, (2009)

Frohm et al. (2011)
<table>
<thead>
<tr>
<th>Inline lunge</th>
<th>Reliability Study</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hurdle</td>
<td></td>
</tr>
<tr>
<td>Rotary stability</td>
<td></td>
</tr>
<tr>
<td>Press up</td>
<td></td>
</tr>
<tr>
<td>Active straight leg raise</td>
<td></td>
</tr>
<tr>
<td>Shoulder mobility</td>
<td></td>
</tr>
<tr>
<td>Seated rotation test</td>
<td></td>
</tr>
<tr>
<td>Single leg squat</td>
<td></td>
</tr>
</tbody>
</table>
2.2.3 Description of movement screens

2.2.3.1 Physical Competency Assessment, and Performance Matrix

The Performance Matrix originally developed by Comerford and Mottram (2012) and involves a series of nine tests examining different levels of movement difficulty. **All tests are performed with no external load. The tests range from simple flexibility and core stability assessments to more complex actions, such as the split squat and bilateral squat assessments.** There has been one intra- and inter-rater reliability study conducted on the screen. The results of this study revealed substantial inter-rater reliability (ICC=0.81) and excellent intra-rater reliability for both of the experienced raters (ICC=0.96 and 0.88)(Portney and Watkins, 2008). In the case of the Physical Competency Assessment there have been no reliability or validity studies conducted and with the Performance Matrix there is a lack of validation studies. For these reasons, both screens were not considered for use in this research programme.

2.2.3.2 Single leg squat

To date, five studies have examined the reliability of a single leg squat screen. However, the protocols and designs of these single leg squat studies vary considerably. The squatting action varied in terms of squat depth (half vs. quarter squat), starting position (on a step vs. on the ground) and protocol used (e.g. hand position during the squat). The scoring criteria across the five studies were similar and involved scoring knee alignment and pelvic level during the squat descent.

The reliability of the single leg squat screens ranged from poor to substantial (kappa values=0.13-0.80) (Portney and Watkins, 2008). Potential reasons for the varied reliability may be the lack of a definitive protocol and scoring criteria. Reliability and set criteria should be established for the single leg squat before validity trials can proceed. Therefore, for the
purposes of this programme of research the single leg squat was not considered an appropriate
field-based movement screen.

2.2.3.3 Athletic Ability Assessment (AAA) and Conditioning Specific Movement Task
(CSMT)

The AAA is a series of nine movement tests and the CSMT is a rugby specific movement
screen involving six tests (McKeown et al., 2014; Parsonage et al., 2014). The AAA is scored
out of 117 possibly allowing for greater sensitivity across participant’s movement quality. The
CMST is scored out of 4 similar to the FMS and was developed to assess young rugby union
player’s ability to join academy programmes. Both tests involve the same co-founders
(McKeown et al., 2014; Parsonage et al., 2014) and as such, have considerable overlap. The
tests within both screens involve measures of core stability, weighted and non-weighted
movement patterns, such as a plank hold, lunge with 20 kg bar and an unloaded overhead squat
(McKeown et al., 2014; Parsonage et al., 2014).

Currently, only the developers have examined the inter- and intra-rater reliability of both
screens. McKeown et al. (2014) reported excellent intra- and inter-rater reliability for the total
score of the AAA (ICC values of 0.97 (90 % CI 0.92–0.99) and 0.96 (90 % CI 0.94–0.98),
respectively). With respect to the CSMT, Parsonage et al. (2014) reported moderate to excellent
reliability for all six of the tests, with inter-rater kappa values ranging from 0.62-1.00 and intra-
rater kappa values from 0.61-1.00. While the reliability of these tests is encouraging, additional
reliability trials by independent researchers and more validation tests are required.

2.2.3.4 Tuck Jump Assessment (TJA)

The TJA requires a participant to undertake repeated tuck jumps for 10 seconds and was
developed by Myer et al. (2008) based on 3D kinematic analysis of drop jump landing (Myer
et al., 2008). The repeated jumps allow for the assessor to examine foot, knee and trunk motion,
overall technique and fatigability in the plyometric activity (Myer et al., 2008). The TJA is the
only movement screen identified that contains a repeated plyometric jump and as such may have increased utility in the sports setting especially where jumping and landing are key elements. A description of the scoring criteria is illustrated in Figure 1.
There have been limited studies examining the reliability and validity of the TJA. Two such studies have examined the reliability of the TJA and have reported conflicting results (Dudley et al., 2013; Herrington et al., 2013). Herrington et al. (2013) using five males and five females reported excellent agreement (93%) between two experienced raters and a high Kappa score of 0.88. In contrast, Dudley et al. (2013) reported poor to moderate reliability for the TJA with intra- and inter-rater reliability ICC’s of 0.44 and 0.72 respectively. There are several possible reasons for the differences in the reliability reported. First, Dudley et al. (2013) scored 40 participants compared to only 10 in the study by Herrington et al. (2013). The higher reliability in the Herrington et al. (2013) study may have been due to possible recall bias by being able to remember participant’s previous scores due to the small number of participants involved (Hopkins, 2008). Another potential reason for the discrepancy in results may be because in the
study by Herrington et al. (2013) one of the raters was also a co-founder of the TJA. Therefore, the raters may have had more expertise and insight into scoring the TJA than the raters in the study by Dudley et al. (2013).

Regarding the TJA, there is a paucity of evidence examining its association with injury. There is a distinct lack of prospective or retrospective injury studies and there have been no studies examining the TJA’s relationship to established lower limb 3D kinematics associated with increased injury risk, such as knee valgus, hip flexion etc. Therefore, due to these current limitations with the TJA this programme of research decided to use the more established, LESS test as its dynamic field-based screen.

2.3 The Functional Movement Screen

The FMS involves seven tests that examine three different levels of movement difficulty (Cook et al., 2006b; Cook et al., 2010). Three tests, the squat, lunge and hurdle are described as higher level patterns, which are proposed to examine the three essential foot positions taken up in sport (bilateral jumping, changing direction and running respectively) (Cook et al., 2010). The rotary stability and press up tests are known as transitionary patterns and predominantly assess transverse and sagittal core stability of the body (Cook et al., 2010). Finally, the primitive, mobility patterns of the body are assessed by the active straight leg raise and the shoulder mobility tests (Cook et al., 2010). In addition to the seven tests, there are three pain clearing tests, which help out rule the possibility of back or shoulder pain (Cook et al, 2010). A full description of how to conduct and score the seven tests and three clearing tests are included in Appendix 3 and illustrated in Figure 2.
The 7 FMS tests: Overhead squat; Lunge; Hurdle, Shld Mob; RotStab, Press-up and ASLR in order from top right to bottom left.

2.3.1 Scoring system and factorial analysis

Traditionally, each of the seven FMS sub-tests are scored out of three with a score of zero indicating the subject experienced pain in one of the screens or had pain in one of the clearing tests (Cook et al., 2006a; 2006b). A score of one is given if the subject cannot complete a screen or if they have compensations when performing an easier, modified version of the original screen (Cook et al., 2006a). A participant scores a two if they can perform the original screen but have some compensations in the movement or if they can perform an easier, modified version perfectly without fault (Cook et al., 2010). Finally, a three is awarded if the participant can perform the screen perfectly without compensation (Cook et al., 2006a). As there are seven tests, the maximum score available is 21 and the lowest possible score for an athlete not
reporting pain is seven (Cook et al., 2006a; 2006b). The specific scoring criteria for each of the individual screens are described in Table 2 (Okada et al., 2011).
Table 2- Scoring criteria for the FMS scoring system. Table from Okada et al. (2011 pg 253).

<table>
<thead>
<tr>
<th>Tests</th>
<th>3 points</th>
<th>2 points</th>
<th>1 point</th>
<th>0 points</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overhead squat</td>
<td>Upper torso is parallel with tibia or toward vertical.</td>
<td>Meet criteria of 3 points with 2 x 6 board under heels.</td>
<td>Tibia and upper torso are not parallel.</td>
<td>If pain is associated with any portion of this test.</td>
</tr>
<tr>
<td></td>
<td>Femur is below horizontal.</td>
<td>Knees are not aligned over feet.</td>
<td>Femur is not below horizontal. Knees are not aligned over feet. Lumbar flexion is noted.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Knees are aligned over feet.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Dowel is aligned over feet.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hurdle step</td>
<td>Hips, knees and ankles remain aligned in sagittal plane.</td>
<td>Alignment lost between hips, knees and ankles.</td>
<td>Contact between foot and hurdle occurs.</td>
<td>If pain is associated with any portion of this test.</td>
</tr>
<tr>
<td></td>
<td>Minimal to no movement is noted in lumbar spine.</td>
<td>Movement is noted in lumbar spine.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Dowel and hurdle remain parallel.</td>
<td>Loss of balance is noted.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>In-line lunge</td>
<td>Minimal to no torso movement is noted.</td>
<td>Movement is noted in torso.</td>
<td>Loss of balance is noted.</td>
<td>If pain is associated with any portion of this test.</td>
</tr>
<tr>
<td></td>
<td>Feet remain in sagittal plane on 2 x 6 board.</td>
<td>Feet do not remain in sagittal plane.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Knee touches 2 x 6 board behind heel of front feet.</td>
<td>Knee does not touch behind heel of front foot.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shoulder mobility</td>
<td>Fists are within 1 hand length.</td>
<td>Fists are within 1.5 hand length.</td>
<td>Loss of balance is noted.</td>
<td>If pain is associated with any portion of this test.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Fists are not within 1.5 hand length.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>If pain is associated with any portion of this test and/or during shoulder stability screen.</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Active</strong></td>
<td><strong>Straight-leg-raise</strong></td>
<td>Dowel resides between mid-thigh and anterior superior iliac spine.</td>
<td>Dowel resides between mid-thigh and joint line of knee.</td>
<td>Dowel resides below joint line.</td>
</tr>
<tr>
<td>---</td>
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<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td><strong>Trunk-stability push-up</strong></td>
<td>Males perform 1 repetition with thumbs aligned with top of head.</td>
<td>Subjects perform 1 repetition in modified position. Male-thumbs aligned with chin. Female-thumbs aligned with chest.</td>
<td>Subjects are unable to perform 1 repetition in modified position.</td>
<td>If pain is associated with any portion of this test. If pain is noted during lumbar extension.</td>
</tr>
<tr>
<td></td>
<td>Females perform 1 repetition with thumbs aligned with chin.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Rotary stability</strong></td>
<td>Subjects perform 1 correct repetition while keeping torso parallel to board and elbow and knee in line with board.</td>
<td>Subjects perform 1 correct diagonal flexion and extension lift while maintaining torso parallel to board and floor.</td>
<td>Subjects are unable to perform diagonal repetition.</td>
<td>If pain is associated with any portion of this test. If pain is noted during lumbar flexion.</td>
</tr>
</tbody>
</table>
The original 21 point scoring system related to the FMS has been criticised due to its very broad categories (Frost et al., 2012; Waldron et al., 2015). For example, if an athlete can complete a screen with compensation they receive a score of two. The degree of compensation or number of faults does not impact on the scoring. Therefore, two athletes could score a two on the FMS who have very different levels of movement patterns (Frost et al., 2012). This broad scoring may also not be sensitive enough to detect significant differences in movement patterns (Frost et al., 2012; Waldron et al., 2015), and has been attributed to the low sensitivity reported in a number of studies examining the relationship between FMS scores and injury risk (O’Connor et al., 2011; Kiesel et al., 2007; Kiesel et al., 2014). With regards implementing interventions, the broad scoring system may lack precision in detailing specific movement compensations for each pattern tested (Butler et al., 2012, Hickey et al., 2010). This may result in a less focused intervention, whereas a more detailed scoring system may allow interventions to focus specifically on the weakest part of a movement pattern (Butler et al., 2012; Hickey et al., 2010).

To address these potential limitations, a 100 point scoring scheme was devised for the FMS (Butler et al., 2012; Hickey et al., 2010). This scale scores individual criteria for each of the seven tests giving a score which more accurately identifies specific limitations in each movement pattern (Hickey et al., 2010; Butler et al., 2012). The developers of the 100 point system have proposed that it allows greater sensitivity in detecting movement deficits and improves intervention specificity (Butler et al., 2012; Hickey et al., 2010). However, the 100 point system has not been widely used and has not been compared to the 21 point scoring scale. Therefore, it is apparent that more research is required to determine which system is best to use in the research and practical settings. This research programme will use both scoring systems related to the FMS to determine which one may be more appropriate in the research and sporting setting.
2.3.2 Reliability of the FMS

Before examining the validity of any screening tool it is important that the tool is firstly established as reliable (Apeldoorn and Kamper, 2014). At the time of this literature review, thirteen studies had been published examining the intra-rater and/or inter-rater reliability of both the final score and/or the component tests within the FMS. There have also been three systematic reviews/meta-analyses (Moran et al., 2017; Bonazza et al., 2016; Cuchna et al., 2016) examining the reliability of the FMS and one literature review (Kraus et al., 2014). In addition to examining the reliability of the FMS, some of the key elements that may influence reliability, such as experience of the testers, methods used and participant group examined were also reviewed.

The quality of the reliability studies were assessed using the Quality Appraisal of Reliability Studies (QAREL)(Lucas et al., 2010). While the QAREL was also utilised to appraise the quality of FMS studies in the systematic review by Cuchna et al. (2016), there is no widely accepted quality appraisal tool used with respect to reliability studies (Lucas et al., 2010). This differs to randomised control trials where both the PEDro Scale (deMorton, 2009) and the Oxford Centre of Evidenced-based Levels of Evidence (Atkins et al., 2004) are accepted quality appraisal systems. The QAREL is a novel tool that has been designed to assess the quality of reliability studies (Lucas et al., 2013; Lucas et al., 2010) with a checklist consisting of 11 criteria that examine; participant appropriateness, rater appropriateness, various forms of rater blinding, participant blinding, procedure accurately followed, scoring conducted correctly and appropriate statistical analysis employed (Apeldoorn and Kamper, 2014). For criteria that were not applicable (for example, rater blinding with a study only examining intra-rater reliability) the criteria was excluded and the QAREL score marked out of 10. Table 3 outlines how many criteria were applicable for each study and converts the QAREL score into a percentage for Table 4. The results of the QAREL checklist are presented in Table 3.
The quality of the studies ranged from 66 to 93%. Common weaknesses in study quality included; (1) failure to provide adequate measures to reduce bias, in particular utilising more than one pair of examiners (2) having only one testing session (3) providing limited information regarding rater characteristics (4) using non-certified novice raters and (5) failure to fully describe participants’ training age and/or schedule (Table 3).
Table 3- Quality appraisal of FMS reliability studies

<table>
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<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Participants</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>2. Raters</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>3. Raters blinded to other raters</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>4. Raters blinded to previous findings</td>
<td>Yes</td>
<td>N.A</td>
<td>N.A</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>N.A</td>
<td>Yes</td>
<td>N.A</td>
<td>N.A</td>
<td>No</td>
<td>N.A</td>
</tr>
<tr>
<td>7. Raters blinded to additional cues not part of test</td>
<td>U</td>
<td>U</td>
<td>U</td>
<td>U</td>
<td>U</td>
<td>U</td>
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</tr>
<tr>
<td>8. Order of examination varied</td>
<td>No</td>
<td>N.A</td>
<td>N.A</td>
<td>Yes</td>
<td>No</td>
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<td>Yes</td>
<td>N.A</td>
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<td>N.A</td>
<td>No</td>
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<td></td>
<td>Stability of variable being measured</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
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<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
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</tr>
<tr>
<td>10.</td>
<td>Test applied correctly and interpreted appropriately</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>11.</td>
<td>Appropriate statistical measurement</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td></td>
</tr>
</tbody>
</table>

**SCORE**


N.A= Not Applicable; U=Unclear
An outline of all included studies is presented in Table 4 but as a general overview, 12 of the 13 studies included in this review reported that the FMS has good to moderate inter-rater and intra-rater reliability (Frohm et al., 2012; Schneiders et al., 2011; Gribble et al., 2013; Gulgin and Hoogenboom, 2014; Leeder et al., 2016; Minick et al., 2010; Onate et al., 2012; Smith et al., 2013; Teyhen et al., 2012; Waldron et al., 2015; Parenteau-G et al., 2014; Palmer et al., 2017). These studies have commented that the FMS is a reliable tool for assessing movement patterns in healthy young, active individuals. The inline lunge and rotary stability were two component tests that had the poorest reliability in several studies (Parenteau-G et al., 2014; Teyhen et al., 2012; Gulgin and Hoogenboom, 2014; Shultz et al., 2011; Frohm et al., 2012). The press up, shoulder mobility and ASLR were three tests that consistently had excellent reliability (Table 4). The results from this review are similar to the three meta-analyses, which reported excellent to substantial reliability for the total score (intra-class correlation coefficient (ICC) range = 0.81-0.86) (Moran et al., 2016; Cuchna et al., 2016; Bonazza et al., 2017).

When reporting reliability, the majority of studies used either weighted or non-weighted Kappa statistics to report the reliability of the individual components of the FMS and ICC when examining the reliability of the total FMS score (Sim and Wright, 2005). Weighted Kappa statistics examine the likelihood of agreement between raters beyond that which is likely due to chance (Sim and Wright, 2005). There is excellent agreement between raters when Kappa scores are 80% and higher. Kappa scores of 60-79.9% represent substantial agreement and 40-59.9% equates to moderate agreement. Finally, Kappa scores below 40% represent fair to poor agreement (Sim and Wright, 2005). With regards using ICC, values between 0.75 and 1 represent good reliability, values between .50 and .74 equate to moderate reliability and values below .50 are deemed to have poor reliability (Portney and Watkins, 2008).
With the exception of Schultz et al. (2013) all studies reported good to moderate overall score reliability for the FMS (Frohm et al., 2012; Schneiders et al., 2011; Gribble et al., 2013; Gulgin and Hoogenboom, 2014; Leeder et al., 2016; Minick et al., 2010; Onate et al., 2012; Smith et al., 2013; Teyhen et al., 2012; Waldron et al., 2015; Parenteau-G et al., 2014; Palmer et al., 2017). However, due to the narrow scoring system of zero to three, it may be that the high levels of reliability reported are due to this narrow scoring system and random chance rather than consistent agreement between raters for all components of the FMS (Kraus et al., 2014).

For example, two raters may give the same participant a score of 14 out of 21. The reliability in this incidence would be reported at 100% agreement. However, the first rater may have given the participant a score of one for the squat, two for the hurdle and three for the inline lunge. The second rater may have given the same participant a score of two for the squat, one for the hurdle and three for the inline lunge or two for the squat, two for the hurdle and two for the inline lunge. In each case, despite the different raters scoring each individual test differently, the overall test scores would be reported at 100% agreement. Providing only the reliability of the final score is a limited assessment of FMS reliability and therefore, the results of studies that only report the reliability of the final score of the FMS should be viewed with caution.

The reliability of the individual component tests provides a more comprehensive method of assessing the actual reliability of the FMS. Several studies examined the inter- and intra-rater reliability of the seven individual component tests of the FMS (Frohm et al., 2012; Gulgin and Hoogenboom, 2014; Minick et al., 2010; Onate et al., 2012; Shultz et al., 2013; Teyhen et al., 2012; Schneiders et al., 2011). Two studies reported the reliability of left, right and total score given for each component test, making up 17 scores where reliability was assessed (Schneiders et al., 2011; Minick et al., 2010). The other studies only stated the reliability of the seven total scores for each component test (Gulgin and Hoogenboom, 2014; Onate et al., 2012; Teyhen et al., 2012; Parenteau-G et al., 2014). As was discussed with the total score of the FMS, analysing
the reliability of only the final scores for each component test may lead to an overestimation of reliability, as the total score is determined by the lower score between left and right. For example, if one rater marked the right hurdle step a one and scored the left hurdle step a two, the final score reported would be one. If a second rater scored both the left and right sides a score of one, then the final score would also be a one. Only recording the final score would result in 100% agreement being reported between the two raters when this is clearly not the case. However, in this review, it is interesting that the two studies that examined left, right and final component scores separately reported higher reliability for the FMS than the studies that just reported the final component scores (Schneiders et al., 2011; Minick et al., 2010). The analysis in this review indicates that there is a relationship between the reliability of the individual FMS component tests and the number of criteria required to score the test reliably (Table 4). The tests with set markers to determine the score (i.e. shoulder mobility and active straight leg raise) or tests with only one element to examine (push up) had the strongest reliability. The limited number of variables to be assessed in these three tests likely accounts for the high reliability recorded in all the studies. Conversely, those tests with the poorest reliability (inline lunge, rotary stability) also have the greatest number of criteria to be assessed, thus making them inherently more difficult to grade (Table 4). Furthermore, the rotary stability and inline lunge tests also have much larger variation in participants achieving the same score (Figure 3). An unwillingness to grade two participants with clearly differing abilities the same may be a potential reason for the reduced reliability with these two tests.
Example of two participants who score a two but have very differing lunging abilities. A reluctance to score these two athletes the same may be one potential reason for a reduced reliability with this test compared to the other tests.

With regard to improving inter-rater reliability specifically, it may be appropriate to follow a protocol similar to that outlined by Schneiders et al. (2011) who recorded excellent or substantial inter-rater reliability for all seventeen components assessed. The authors of this study commented that the two raters involved undertook the same training and were well accustomed to each other’s style of marking before marking separately. Future reliability studies should examine whether a protocol where raters clearly identified scoring criteria for each component test, in particular the lunge and rotary stability, and marked participants together before marking separately would lead to improved reliability for both final score and component scores. Setting out clearly stated, definitive guidelines at the outset may help increase reliability between raters (Gulgin and Hoogenboom, 2014).
<table>
<thead>
<tr>
<th>Author</th>
<th>Participants</th>
<th>Method</th>
<th>Results</th>
<th>QAREL score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frohm et al. (2010)</td>
<td>26 elite male soccer players</td>
<td>Real time analysis</td>
<td>Intra-rater reliability (ICC) and ME of final score for 8 raters and independent t-test for inter-rater.</td>
<td>No sig difference between raters scores. Intra-rater ICC range: 0.87-0.74 ME: 2.0-4.2</td>
</tr>
<tr>
<td>Schneiders et al. (2011)</td>
<td>209 healthy active participants (108 female and 101 male)</td>
<td>Real time analysis</td>
<td>Inter-rater reliability of final score and component tests/ ICC and unweighted Kappa statistics</td>
<td>ICC: 0.97 Kappa: 1-0.73 85%</td>
</tr>
<tr>
<td>Study</td>
<td>Sample Size</td>
<td>Design</td>
<td>Rater Training</td>
<td>Rater Credibility</td>
</tr>
<tr>
<td>------------------------</td>
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</tr>
<tr>
<td>Teyhen et al. (2012)</td>
<td>64 military recruits (53 male and 11 female)</td>
<td>Real time analysis</td>
<td>2 sessions 48 hour apart</td>
<td>Experience of FMS</td>
</tr>
<tr>
<td>Onate et al. (2012)</td>
<td>19 physically active participants (12 male, 7 female)</td>
<td>Real time analysis</td>
<td>2 sessions (1 week apart)</td>
<td>Rater 1: Experienced Rater and novice rater</td>
</tr>
<tr>
<td>Smith et al. (2013)</td>
<td>19 participants (10 male and 9 female)</td>
<td>Real time analysis</td>
<td>2 days of testing (1 week apart)</td>
<td>Four raters: 1. FMS certified (experience not stated) 2. Non certified PT student with 100 FMS tests completed</td>
</tr>
<tr>
<td>Study</td>
<td>Number of Participants</td>
<td>Video Analysis</td>
<td>Raters</td>
<td>Inter-rater reliability</td>
</tr>
<tr>
<td>-----------------------</td>
<td>------------------------</td>
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</tr>
<tr>
<td>Minick et al. (2010)</td>
<td>40 healthy college students (23 female; 17 male)</td>
<td>Video analysis</td>
<td>4 raters: 2 expert and 2 novice</td>
<td>Level of training, certification, or years of experience not stated for any rater.</td>
</tr>
<tr>
<td>Gribble et al. (2013)</td>
<td>3 university students (2 males and 1 female)</td>
<td>Video analysis</td>
<td>38 raters recruited (17 men and 21 female).</td>
<td>Athletic therapy student (ATS): 16</td>
</tr>
</tbody>
</table>
Certified Athletic trainer (AT):
15
Athletic trainers with at least
six months FMS experience
ATS and AT had no FMS
experience
Training: Provided with
scoring script from Cook et al.
(2010).
Not stated whether ATExp
were certified

<table>
<thead>
<tr>
<th>Gulgin and Hoogenboom (2014)</th>
<th>20 collegiate students (10 male and 10 female).</th>
<th>Video Analysis (no slow motion allowed)</th>
<th>3 novice certified FMS raters</th>
<th>Inter-rater reliability of component tests and total score/ Fisher’s Exact test</th>
<th>ICC inter-rater: 0.88</th>
<th>No sig. diff</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Video Analysis</td>
<td>1 expert rater with 3 years FMs experience</td>
<td>Standard instructions</td>
<td>One way ANOVA Percentage Agreement</td>
<td>between novice and expert</td>
<td>71%</td>
</tr>
</tbody>
</table>
from Cook et al. (2010).

4 raters then independently watched videos.

<table>
<thead>
<tr>
<th>Study</th>
<th>Participants</th>
<th>Methodology</th>
<th>Raters</th>
<th>Reliability Measures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parenteau-G et al. (2014)</td>
<td>28 male ice hockey players</td>
<td>Real time analysis and Video analysis (6 weeks apart)</td>
<td>3 final year physiotherapist students and 1 physiotherapist</td>
<td>Inter- and Intra-rater reliability of total score/ ICC Kappa Range: 0.65-0.98</td>
</tr>
<tr>
<td>Schultz et al. (2013)</td>
<td>39 varsity athletes (21 female and 18 male)</td>
<td>Real time and video analysis</td>
<td>6 raters (1 student, 1 PT, 2 ATs, 2 strength coaches)</td>
<td>Inter-rater reliability of total score and individual component tests. ICC Inter-rater ICC: 66%</td>
</tr>
<tr>
<td>Study</td>
<td>Gender</td>
<td>Age Range</td>
<td>Analysis Type</td>
<td>Experience</td>
</tr>
<tr>
<td>---------------</td>
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</tr>
<tr>
<td>Waldron et al. (2015)</td>
<td>13 male, 19 rugby players</td>
<td>Real time analysis</td>
<td>Description of raters not stated</td>
<td>Varying levels of experience (&lt;1 month to 3-4 yrs)</td>
</tr>
<tr>
<td>Leeder et al. (2016)</td>
<td>3 male, 2 Female Elite Squash Players</td>
<td>Video Analysis</td>
<td>20 Physiotherapists (&gt;4 years experience)</td>
<td>No experience with FMS</td>
</tr>
<tr>
<td>Palmer et al. (2017)</td>
<td>40 male university students</td>
<td>Video Analysis</td>
<td>6 Hospital based physiotherapists</td>
<td></td>
</tr>
</tbody>
</table>

SA=Statistical Analysis; ICC= Intra-class coefficient; SEM= Standard Error of Measure; MD=Mean Difference; Kw= Weighted Kappa
2.3.2.1 Variables influencing FMS reliability

When assessing the reliability of the FMS there are a number of issues that may account for the variability between studies. The main issues examined in the literature would be level of experience, population examined and scoring method (real-time vs. videotaped) (Frohm et al., 2012; Schneiders et al., 2011; Gribble et al., 2013; Gulgin and Hoogenboom, 2014; Leeder et al., 2016; Minick et al., 2010; Onate et al., 2012; Smith et al., 2013; Teyhen et al., 2012; Waldron et al., 2015; Parenteau-G et al., 2014).

There are conflicting results about the role that experience plays in improving the reliability of the FMS. The highest inter- and intra-rater reliability results involve raters who have conducted a large number of FMS tests (Schneiders et al., 2011; Gribble et al., 2013). Gribble et al. (2013) reported that athletic therapy (AT) students had poor intra-rater reliability (ICC=.372; 95% CI= -0.798 to 0.78) whereas certified AT students with at least six months of FMS experience had good reliability (ICC=.946; 95%CI=0.68 to .99). A study by Teyhen et al. (2012) involving eight novice testers recorded good inter-rater (ICC=.76) and intra-rater reliability (ICC=.74). The authors of this study commented that this demonstrated that the FMS was a reliable tool even with novice raters but that novices’ reliability scores were lower than studies that involved experienced examiners (Minick et al., 2010; Onate et al., 2012; Schneiders et al., 2011). However, the results of the aforementioned studies conflict with other studies, which have reported that novice and experienced raters have comparable reliability (Gulgin and Hoogenboom, 2014; Minick et al., 2010). A study by Gulgin and Hoogenboom (2014) reported no significant difference between scores given by one expert rater and three novice raters. Schultz et al. (2013) found that raters with two years’ experience with the FMS had poor reliability (ICC = 0.177, 95% CI=-0.15 to 0.46) whereas those with less than one year experience had fair intra-rater reliability (ICC= 0.44, 95% CI=0.12 to 0.6).
There are several reasons for the lack of consensus in the literature about the role of experience. The majority of studies examining the differences in reliability between novice and experienced raters have defined experience by the number of years that the raters have been using the FMS (Gribble et al., 2013; Gulgin and Hoogenboom, 2014; Minick et al., 2010; Onate et al., 2012; Shultz et al., 2013; Teyhen et al., 2012). However, classifying experience or expertise in relation to the number of years that have passed since the rater first performed the FMS is a somewhat limited viewpoint (Shultz et al., 2013; Frohm et al., 2012). Schultz et al. (2013) discusses that a more appropriate measure of experience/expertise may be the number of tests conducted and the level of training and feedback received. For example, in a study by Frohm et al. (2012) a rater with five years experience using the FMS had completed nearly three times as many tests as those raters with seven years experience (800 tests vs. 300 tests respectively). This study also outlined that a rater with four years experience had twenty five percent more tests completed than the raters with seven years experience (Frohm et al., 2012). Therefore, the difference in the number of tests completed by the novices and experts in each study may account for the discrepancy in results reported between these two groups.

Other factors, such as training and certification may also play an important role regarding reliability. Some of the FMS reliability studies used experienced raters who were also certified in the FMS (Gulgin and Hoogenboom, 2014; Parenteau-G et al., 2014), whereas in other studies (Shultz et al., 2013) the experienced FMS raters were not certified. Similarly, in the study by Minick et al. (2010) the novices were presumably instructed by the authors of the study, some of whom were the founders of the FMS. It is conceivable to imagine that their training may have been more comprehensive than that attained by novices in other studies, thus allowing greater reliability in their scoring compared to novices or even those with experience in other studies (Shultz et al., 2013; Teyhen et al., 2012). Given the limited criteria provided to classify raters as experienced or as having expertise in the majority of studies in this review it is difficult
to compare studies accurately. Therefore, to get a more comprehensive view, future studies should examine the effect of (1) the number of teaching hours (2) the number of screens conducted and (3) FMS certification on reliability of the FMS.

Another aspect of reliability is the raters’ background and professional experience (Gribble et al., 2013; Smith et al., 2013). As previously mentioned, Gribble et al. (2013) reported that AT students with no experience had poor intra-rater reliability scoring of the FMS (ICC=.372; 95% CI=-0.798 to 0.78). However, in the same study, those with no FMS experience but who were certified ATs had moderate reliability (ICC=.75; 95%CI= 0.68 to .99). These results are similar to a study conducted by Smith et al. (2013), who found that a rater with a PhD in biomechanics and no experience with the FMS had greater reliability than someone certified in the FMS. This result highlights that perhaps the skills acquired from a rater's profession and past experience may enhance intra-rater reliability more than having experience alone with the FMS. It may be that those with experience in professions that analyse movement have ‘their eyes trained in’. This may allow them to analyse mechanical faults in movement more effectively than those who have only learned the set up and scoring criteria of the FMS. These issues should be addressed in order to fully discern the role that experience in a rater’s profession may have on reliability with the FMS.

The second main element concerning reliability is real-time scoring vs. video scoring. Studies utilising real-time scoring have commented that it is more practical and representative of current practice than video scoring (Frohm et al., 2012; Schneiders et al., 2011; Smith et al., 2013; Teyhen et al., 2012). Furthermore, real-time analysis allows the rater to get a 3D perspective of the participants’ movement, thus potentially allowing more accurate scoring (Teyhen et al., 2012; Schneiders et al., 2011). Studies utilising video scoring have argued that it allows smoother administration of the tests (Gribble et al., 2013; Gulgin and Hoogenboom, 2014; Minick et al., 2010; Onate et al., 2012; Parenteau-G et al., 2014). In addition, video
allows a rater to play the test numerous times until they are satisfied with the score given. In particular, with software that allows the video to be slowed down it may provide clarity that real-time analysis does not allow (Parenteau-G et al., 2014).

In examining the results reported in both the real-time and video scoring studies, there does not appear to be a trend favouring one approach over the other (Table 4). Both methods have been reported to have good reliability with both expert and novice groups (Minick et al., 2010; Teyhen et al., 2012; Parenteau-G et al., 2014; Schneiders et al., 2011). A recent study (Shultz et al., 2013) examining the differences in reliability between real-time and video scoring would concur with this observation. Schultz et al. (2013) reported excellent reliability (ICC=.92, 95%CI=.85 to 0.95) when one rater assessed 39 participants in real-time and then scored the participants' tests by video one week later.

One of the most important findings for use of the FMS is that there is good to moderate test-retest reliability (Teyhen et al., 2012). This indicates that studies reporting changes in scores following an intervention are due to appreciable changes in movement quality rather than participants having random movement variation from test to test. However, Teyhen et al. (2012) reported that with novice testers the minimal detectable change is 2.1 on the 21 point scale. This poses a problem for those who score highly as their scores may be too high pre-intervention to have a detectable change post intervention. Therefore, this review points to the need for a control group with all intervention based studies for comparison. Furthermore, the use of the 100 point system, developed by Butler et al. (2012) may give a more accurate or sensitive indication of the changes that have occurred following the intervention (Butler et al., 2012).

The findings of this review indicate that the majority of studies recommended the FMS as a reliable screening tool. However, due to both the discrepancy in results reported between
studies and the different methods utilised, this review recommends that future studies using the FMS need to conduct and report in full, a reliability study to ensure that the study raters have both acceptable inter- and intra-rater reliability. When conducting reliability studies, the literature advocates using a protocol similar to Schneiders et al. (2011), where raters undertake similar training and score participants together first before scoring separately to enhance the likelihood of good reliability between raters. Future reliability studies should examine how training, the number of screens conducted and slow motion video analysis may influence the reliability of the FMS.

### 2.3.3 FMS and injury risk

The FMS was originally designed to identify gross movement limitations in movement patterns (Cook et al., 2010, Cook et al., 2006a). Several authors have examined whether examining these gross limitations in movement predispose athletes to increased chance of injury (Table 5). There have been several peer-reviewed papers, abstracts and anecdotal evidence regarding the role of the FMS as an injury prediction tool. For the purposes of this review, only peer-reviewed studies were included. Following a comprehensive search and analysis of five databases (MEDline, Cinhal, Web of Science, Sports Discus, Science Direct) 28 studies were discovered related to the FMS and injury risk. The quality of the studies ranged from six to 10 out of 11 using a version of the Strengthening of Reporting of Observational Studies in Epidemiology (STROBE) that was modified for musculoskeletal injuries rather than examining systemic disease (Von Elm et al., 2008). Common weaknesses in study quality included failure to provide adequate details of testing sessions, lack of information regarding rater characteristics, and a lack of information about how the injury was recorded. An overview of these studies is presented in Table 5.
The cohorts examined with the FMS have been young, active individuals either involved with sport or employed in a physically active profession (e.g. military, fire-fighting, coast guards) (Table 5). Seventeen of these studies have reported that those with low FMS scores below a specified cut point had a significantly greater chance of injury than those with high FMS scores (Table 5)(Kiesel et al., 2007; Peate et al., 2007; Chorba et al., 2010; Lehr et al., 2013; Dossa et al., 2014; Kiesel et al., 2014; Shojaedin et al., 2014; O’Connor et al., 2011; Knapik et al., 2015; Dorrell et al., 2018; Bushman et al., 2016; Hammes et al. 2016; Garrison et al., 2015; Hotta et al., 2015; McGill et al., 2015; Kodesh et al., 2015; Armstrong et al., 2018). All studies used a ROC curve analysis to determine a cut-off score with the greatest sensitivity and specificity to categorise participants into two groups; "at risk of injury" and "not at risk of injury". With the exception of Dorrell et al. (2018), Peate et al. (2007), Shojaedin et al. (2013), Knapik et al. (2015) and Armstrong et al. (2018) who used a cut-off score of 15, 16, 17, 17 and 11.5 respectively, all other studies utilised a score of 14 and below to determine the difference between "at risk of injury" scores and "not at risk of injury" scores (Table 5). Twelve studies reported that FMS scores were unable to predict injury in a various cohorts (Lima et al., 2015; Warren et al., 2015; Azzam et al., 2015; Kodesh et al., 2015; Schroeder et al., 2016, Mokha et al., 2016; McGill et al., 2012; Bardenett et al., 2015; Rusling et al., 2015; Newton et al., 2018; Schroder et al., 2016; Zalai et al., 2015), although Mokha et al. (2016) did report that individuals who scored a 1 in any of the seven FMS screens were at a greater risk of injury regardless of their final score (Table 5). In addition to the contrasting results, there were several limitations with regards the FMS as an injury prediction tool, the main limitation being the low sensitivity reported in the majority of the studies (Table 5). A more detailed breakdown of the FMS injury studies and the associated limitations will be discussed in the preceding paragraphs.
### Table 5- Characteristics of studies exploring FMS and injury risk

<table>
<thead>
<tr>
<th>Author (Year)</th>
<th>Study design/ Follow up period</th>
<th>Number and description of participants (Mean)</th>
<th>FMS scores</th>
<th>Description of injury</th>
<th>FMS Cut off Score</th>
<th>Results</th>
<th>Quality Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kiesel et al. (2007)</td>
<td>Retrospective study design/ 17 weeks</td>
<td>46 male professional Football Players. Age: NR; Height: NR; Mass: NR</td>
<td>All participants: 16.9; Injured: 14.3; Non-injured: 17.4</td>
<td>TL of ≥ 3 weeks</td>
<td>14</td>
<td>Relative Risk: 4.2; Odds Ratio: 11.67; Sensitivity: 54%; Specificity: 91%</td>
<td>6/11</td>
</tr>
<tr>
<td>Chorba et al. (2010)</td>
<td>Cross sectional design/ 20 weeks</td>
<td>38 female student-athletes NCAA Division 2. Age: 19 yrs Height: NR; Mass: NR</td>
<td>All participants: 14.3</td>
<td>Any MSK injury</td>
<td>14</td>
<td>Relative Risk: 4.2; Odds Ratio: 3.9; Sensitivity: 58%; Specificity: 74%</td>
<td>10/11</td>
</tr>
<tr>
<td>O'Connor et al. (2011)</td>
<td>Prospective Cohort Study/ 10 weeks</td>
<td>874 Male military recruits Age: NR; Height: NR; Mass: NR</td>
<td>All participants: 16.6</td>
<td>Physical damage to body due to physical training MA</td>
<td><code>NA</code></td>
<td>Relative Risk: NR; Odds Ratio: NS; Sensitivity: NR; Specificity: NR</td>
<td>10/11</td>
</tr>
<tr>
<td>McGill et al. (2012)</td>
<td>Prospective Injury study/ 40 weeks</td>
<td>14 male elite basketballers Age: 20.4yrs Height: 1.97m</td>
<td>NR</td>
<td>Back injury leading to missed game</td>
<td><code>NA</code></td>
<td>Relative Risk: NR; Odds Ratio: NS; Sensitivity: NR; Specificity: NR</td>
<td>9/11</td>
</tr>
<tr>
<td>Study</td>
<td>Design</td>
<td>Participants</td>
<td>Risk Factors</td>
<td>Outcomes</td>
<td>References</td>
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<tr>
<td>Butler et al. (2013)</td>
<td>Prospective Cohort Study/16 weeks</td>
<td>108 trainee firefighters Age: NR Height: NR Mass: NR</td>
<td>TL of ≥ 3 days</td>
<td>Relative Risk: NR Odds Ratio: 8.3 Sensitivity: 84% Specificity: 30%</td>
<td>7/11</td>
<td></td>
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</tr>
<tr>
<td>Lehr et al. (2013)</td>
<td>Prospective Cohort Study/28 weeks</td>
<td>273 healthy collegiate athletes from a variety of sports 118 Males; Age: 19.4 yrs Height: 1.84m Mass: 89.1 kg 65 Females Age: 19.0 yrs Height: 1.63m Mass: 65.1kg</td>
<td>Non-contact lower extremity injury MA and TL of ≥ 1 day.</td>
<td>Relative Risk: NR Odds Ratio: 3.40 Sensitivity: NR Specificity: NR</td>
<td>9/11</td>
<td></td>
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<tr>
<td>Lima et al. (2013)</td>
<td>Prospective cohort study/17 weeks</td>
<td>Trainee Coast Guards 770 male Age: 18.1 yrs Height: 1.79m Mass: 76.8kg 286 female Age: 17.9 yrs Height: 1.65m Mass: 62.6kg</td>
<td>MSK or dermatological injury requiring MA.</td>
<td>Relative Risk: NR Odds Ratio: 1.2 (NS) Sensitivity:55% Specificity: 49%</td>
<td>9/11</td>
<td></td>
<td></td>
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<tr>
<td>Study Authors</td>
<td>Study Design</td>
<td>Participants</td>
<td>Duration</td>
<td>Relative Risk</td>
<td>Odds Ratio</td>
<td>Sensitivity</td>
<td>Specificity</td>
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<tr>
<td>Shojaedin et al. (2014)</td>
<td>Prospective cross-sectional design/ 26 weeks</td>
<td>100 university athletes (50 male, 50 female) Age: 22.56 yrs Height: 1.72.6m Mass: 69.44kg</td>
<td>All participants: 16 TL of ≥ 2 sessions.</td>
<td>17</td>
<td>NR</td>
<td>4.7</td>
<td>64%</td>
</tr>
<tr>
<td>Wiese et al. (2014)</td>
<td>Prospective Injury Study/ 16 weeks</td>
<td>144 male collegiate American football players; Age: 18.9 yrs Height: 187.1 Mass: 100kg</td>
<td>Injured 14.1 Non-injured: 16.1</td>
<td>Identical to Garrison 2015.</td>
<td>RR: 1.15</td>
<td>OR: 1.42</td>
<td>NR</td>
</tr>
<tr>
<td>Dossa et al. (2014)</td>
<td>Prospective Cohort Study/ 32 weeks</td>
<td>20 Male junior hockey players Age: NR Height: NR Mass: NR</td>
<td>All participants: 14.7 Injured: 15.0 Non-injured: 14.4</td>
<td>Any injury requiring MA</td>
<td>Relative Risk: 1.67</td>
<td>Odds Ratio: NR</td>
<td>Sensitivity: 50%</td>
</tr>
<tr>
<td>Kiesel et al. (2014)</td>
<td>Prospective Injury Study/ 7 weeks</td>
<td>238 professional American football players Age: NR; Height: NR; Mass: NR</td>
<td>All participants: 16.9</td>
<td>TL of ≥ 1 day</td>
<td>Relative Risk: 1.80</td>
<td>Odds Ratio: NR</td>
<td>Sensitivity: 50%</td>
</tr>
<tr>
<td>Rusling et al. (2015)</td>
<td>Prospective Injury Study/ 8.5 months</td>
<td>135 male soccer players. Age: 13.6 yrs Height: 1.78m Weight: 55.3kg</td>
<td>All participants: 12.1 Physical complaint excluding contact or injury</td>
<td>14</td>
<td>Relative Risk: NR</td>
<td>Odds Ratio: 1.25 (NS)</td>
<td>Sensitivity: NR</td>
</tr>
<tr>
<td>Study</td>
<td>Injury Study Duration</td>
<td>Participants</td>
<td>Age (yrs)</td>
<td>Height (m)</td>
<td>Mass (kg)</td>
<td>Injured</td>
<td>Non-injured</td>
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<tr>
<td>McGill et al. (2015)</td>
<td>Prospective Injury Study/ 5 years</td>
<td>53 Elite police males.</td>
<td>38.5</td>
<td>1.86</td>
<td>78</td>
<td>NR</td>
<td>Back injury excluding contact</td>
</tr>
<tr>
<td>Warren et al. (2015)</td>
<td>Prospective Injury Study/ 24 weeks</td>
<td>195 Division 1 US Varsity athletes (18-24)</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
<td>All participants: 14.2</td>
<td>Non contact MSK injury requiring MA.</td>
</tr>
<tr>
<td>Hotta et al. (2015)</td>
<td>Prospective Injury Study/ 52 weeks</td>
<td>84 male runners.</td>
<td>20</td>
<td>171.6</td>
<td>57.5</td>
<td>Injured: 13.3</td>
<td>Non-injured: 14.4</td>
</tr>
<tr>
<td>Kodesh et al. (2015)</td>
<td>Prospective Injury Study/ 13 weeks</td>
<td>158 female soldiers</td>
<td>19</td>
<td>1.64</td>
<td>56</td>
<td>NR</td>
<td>TL of ≥ 2 days</td>
</tr>
<tr>
<td>Study</td>
<td>Study Design</td>
<td>Participants</td>
<td>Injury Definition</td>
<td>Relative Risk</td>
<td>Odds Ratio</td>
<td>Sensitivity (%)</td>
<td>Specificity (%)</td>
</tr>
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<tr>
<td>Azzam et al. (2015)</td>
<td>Prospective injury study / 60 weeks</td>
<td>34 male basketballers</td>
<td>TL injury ≥ 7 days</td>
<td>14</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
</tr>
<tr>
<td>Zalai et al. (2015)</td>
<td>Prospective Injury study / 26 weeks</td>
<td>20 male soccer players</td>
<td>TL injury of ≥ 1 day requiring M.A</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
</tr>
<tr>
<td>Mokha et al. (2016)</td>
<td>Prospective cohort study / 10 week training</td>
<td>84 Division 2 collegiate athletes. 20 males: Age: 20 yrs Height: 1.77m Mass: 73.5kg 64 Females: Age: 19.1 yrs Height: 1.69m Mass: 64.8kg</td>
<td>Identical definition to Garrison et al. (2015)</td>
<td>Relative Risk: 0.68 Odds Ratio: 0.54 Sensitivity: 26.3% Specificity: 58.7%</td>
<td></td>
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</tr>
<tr>
<td>Bushman et al. (2016)</td>
<td>Prospective cohort study / 6 months</td>
<td>2476 military recruits. Age: NR Height: NR Mass: NR</td>
<td>Any injury requiring MA and TL of 1 day or more</td>
<td>Relative Risk: 1.60 Odds Ratio: 2.00 Sensitivity: 28% Specificity: 81%</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Study</td>
<td>Type</td>
<td>Duration</td>
<td>Subjects</td>
<td>Age (yrs)</td>
<td>Height (m)</td>
<td>Mass (kg)</td>
<td>Injured (%)</td>
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<tr>
<td>Schroder et al. (2016)</td>
<td>Prospective Injury Study/10 weeks</td>
<td>96 soccer players</td>
<td>23.7</td>
<td>1.82</td>
<td>79.9</td>
<td>14.1</td>
<td>15.7</td>
</tr>
<tr>
<td>Hammes et al. (2016)</td>
<td>Prospective study/32 weeks</td>
<td>238 male soccer players</td>
<td>44</td>
<td>NR</td>
<td>NR</td>
<td>11.7</td>
<td>12.2</td>
</tr>
<tr>
<td>Bond et al. (2017)</td>
<td>Prospective Injury Study/23 weeks</td>
<td>119 male and female basketballers</td>
<td>19</td>
<td>1.92</td>
<td>85.0</td>
<td>NR</td>
<td>NR</td>
</tr>
<tr>
<td>Duke et al. (2017)</td>
<td>Prospective Injury Study/50 weeks</td>
<td>76 Rugby players</td>
<td>21.6</td>
<td>NR</td>
<td>NR</td>
<td>15.04</td>
<td>15.55</td>
</tr>
<tr>
<td>Newton et al. (2017)</td>
<td>Prospective Injury Study/24 weeks</td>
<td>84 male academy soccer players</td>
<td>14.5</td>
<td>1.83</td>
<td>60.1</td>
<td>NR</td>
<td>NR</td>
</tr>
<tr>
<td>Dorrell et al. (2018)</td>
<td>Prospective Injury Study/22 weeks</td>
<td>Variety of sports 176 male and 81 female</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
<td>14.99</td>
<td>15.3</td>
</tr>
<tr>
<td>Study</td>
<td>Prospective Injury Study/12 weeks</td>
<td>Intervarsity athletes.</td>
<td>Age: 20.1 yrs</td>
<td>Height: 1.81m</td>
<td>Mass: 80kg</td>
<td>Sensitivity: 63%</td>
<td></td>
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<tr>
<td></td>
<td>45 Female rugby players</td>
<td>Age: 20.39 yrs</td>
<td>Height: 1.66m</td>
<td>Mass: 73.98kg</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>55 Varsity Male Rugby players</td>
<td>Age: 21.05 yrs</td>
<td>Height: 1.88m</td>
<td>Mass: 86.60kg</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Armstrong et al. (2018)</td>
<td>NR</td>
<td>TL of one match or training session</td>
<td>11.5</td>
<td>RR: NS</td>
<td>OR: NR</td>
<td>Specificity: 90%</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Sensitivity: 89%</td>
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</table>

OR= Odds Ratio; RR: Relative Risk; NR=Not Recorded; NS=Not significant; TL=Time-loss; MA=Medical attention
Kiesel et al. (2007) published the first study that retrospectively examined the relationship between FMS scores and injury risk. A professional American Football team was assessed using the FMS and a retrospective analysis was performed at the end of the year to determine if there was a relationship between FMS scores and injury risk. Analysis of a receiver-operated characteristic (ROC) curve revealed that those with an FMS score of 14 and below had the highest sensitivity and specificity at determining an increased chance of injury (Kiesel et al., 2007). Using this cut off of ≤14, Kiesel et al. (2007) reported that those below this cut point were significantly more at risk of injury with an odds ratio of 11.67. This study had a high specificity score of 91% (Kiesel et al., 2007). However, the sensitivity of the results was moderate at 54%. This indicates that serious injury could not be discounted for those above 14.

The findings of Kiesel et al. (2007) are supported by other studies (Chorba et al., 2010; Dossa et al., 2014; Kiesel et al., 2007; Kiesel et al., 2014; Lehr et al., 2013; Shojaedin et al., 2014) however, a limitation in several of these studies is the small number of participants examined (20-48 participants) (Chorba et al., 2010; Dossa et al., 2014; Kiesel et al., 2007; Kiesel et al., 2014; Lehr et al., 2013; Shojaedin et al., 2014). In this regard, the studies by O’Connor et al. (2011) and Bushman et al. (2016) are highly informative as they demonstrate similar findings with a large cohort of military participants. O’Connor et al. (2011) examined the relationship between injury risk and FMS scores in 874 marine officer candidates. Candidates were either participating in a short training cycle of six weeks or a longer training cycle of ten weeks. Each candidate was screened prior to beginning training. Participants enrolled in both the short and long training cycles were statistically more at risk of injury with an FMS score of 14 or below (O’Connor et al., 2011). The risk ratio for all recruits in this study with scores of ≤14 was 2.0 (CI=1.3 -3.1) indicating that they were two times more likely to sustain injury than those with scores greater than 14. Bushman et al. (2016) examined a cohort of 2476 military recruits and reported that those recruits with scores of 14 or less, were 1.84 and 1.64 times more likely to
sustain an injury (overuse or otherwise) compared to their high scoring counterparts. However, as with other FMS injury studies, the sensitivity of these two studies was low (.45 and .36) indicating that good FMS scores do not necessarily equate to reduced injury risk (Hopkins et al., 2009; Hopkins, 2008). This limitation will be discussed more in a later paragraph in this section.

Twenty eight studies were included in this review of FMS scores and their association with injury. Twelve of the prospective injury studies reported no significant difference in injury risk between high and low scoring FMS groups (Lima et al., 2015; Warren et al., 2015; Azzam et al., 2015; Kodesh et al., 2015; Schroeder et al., 2016, Mokha et al., 2016; McGill et al., 2012; Bardenett et al., 2015; Rusling et al., 2015; Newton et al., 2018; Schroder et al., 2016; Zalai et al., 2015). These studies examined varied populations (Table 5) and highlighted that total score was unable to predict injury risk (Mokha et al., 2016; Schroeder et al., 2016; Azzam et al., 2015; Warren et al. 2015; Kodesh et al., 2015; Lima et al., 2015; Duke et al., 2017). However, the study by Mokha et al. (2016) reported that having a score of one in an individual FMS test was a significant predictor of injury. Schroeder et al. (2016) reported that neither final score nor any individual test was able to predict injury, however the study by Schroeder et al. (2016) was an observational study conducted across a number of soccer teams. Therefore, confounding factors, such as different training loads, nutritional regimes, training methods etc. could have impacted on the injury rates reported, making it more difficult to examine the true association of injury to FMS scores (Hopkins et al., 2009).

The mixed results reported in the individual studies is also echoed in three meta-analyses that have examined injury association with FMS scores (Dorrell et al., 2015; Bonazza et al., 2017; Moran et al. 2017). The largest of these meta-analyses reported a moderate to weak association between FMS scores and injury in military populations but FMS scores had a weak association with all other sporting populations and active professions (Moran et al., 2017). Dorrell et al.
(2015) evaluating seven FMS injury studies reported a weak association between FMS scores and injury risk with a pooled sensitivity score of .24. However, Bonazza et al. (2017) examining nine studies reported a significantly higher likelihood of injury in those who scored poorly on the FMS compared to those who scored highly. The results of the meta-analyses may differ due to the studies included and their interpretation of injury statistics. When examining odds ratio independently, the FMS appears to be a good predictor of injury risk (Table 5). However, when sensitivity and relative risk are examined, the association between injury and FMS scores becomes more inconclusive.

The majority of studies included in this review have reported low sensitivity of the odds ratio (Table 5). The sensitivity ranged from .24 to .64 (Table 5), with the two ‘gold standard’ studies by O’Connor et al. (2011) and Bushman et al. (2016) having low sensitivity scores of .45 and .36 respectively. This is concerning as a sensitivity score above .50 is desirable (Hopkins et al., 2009). A low sensitivity score indicates that there may be athletes with scores above the cut-off who are still susceptible to injury (Hopkins et al., 2009). The low sensitivity of the FMS may be a reason that the FMS does not detect differences between those who have sustained serious previous injury and those who have not (Chorba et al., 2010), despite several studies demonstrating that previous injury is a key predicting factor for future injury (Boling et al., 2009; Paterno et al., 2014; Paterno et al., 2010).

Another limitation with previous studies involving FMS scores and injury risk is that the definition of injury differs considerably across studies (Table 5). Some injuries were only recorded if they were non-contact lower limb injuries (Lehr et al., 2013; Shojaedin et al., 2014) while other studies recorded any injury, contact or non-contact (Kiesel et al., 2007; O’Connor et al., 2011; Bushman et al., 2016) (Table 5). Furthermore, the time that an athlete had to be absent for an injury to be recorded ranged from one day of missed practice (Shojaedin et al., 2014; Lehr et al., 2013;) to four weeks (Hotta et al., 2015). These differences in injury
definitions could impact on the results therefore. For example, one would have to question what impact an athlete’s movement capability would have on these athletes receiving a direct blow in competition that results in an injury. Therefore, the discrepancies in the recording of injuries, the low power and low sensitivity in the majority of studies make it difficult to categorically state that FMS scores are predictive of injury for large, diverse groups.

A final limitation of the FMS may be the use of a cut-off score (generally ≤14) to predict injury. As already mentioned, twelve studies have reported that there was no relationship between injury and a FMS cut-off score (Mokha et al., 2016; Schroder et al., 2016; Warren et al., 2015; Azzam et al., 2015; Kodesh et al., 2015; Lima et al., 2015; Duke et al., 2017; Newton et al., 2017). Two studies examining the internal consistency of the FMS have reported that the FMS has poor internal validity (Li et al., 2014; Kazman et al., 2014). This finding indicates that the seven FMS tests do not measure the same variables. Therefore, both studies concluded that, statistically, it is inappropriate to add the scores of the seven tests together and use a total score, which is performed to get a cut-off score. With debate about whether total score can be used to predict injury, it is apparent that well-controlled, large prospective studies are required to clarify the position on whether the FMS scores can predict injury.

2.3.4 FMS and Dynamic Field-based screens

From the preceding section it is apparent there are conflicting results regarding FMS as an injury prediction tool (Table 5). Bishop et al. (2015) argued that the FMS is limited in this capacity due to the absence of a more dynamic test (Bishop et al., 2015). Several injuries occur in sport during phases of rapid deceleration, in actions such as landing, cutting or sprinting (Bishop et al. 2015). During these actions, a large degree of dynamic stability (the ability to prevent aberrant motion at speed) and eccentric strength are required (Bishop et al., 2015). The fact that the FMS does not stress movement patterns at the speed replicated in sport may limit its effectiveness in identifying some key predisposing factors for injury (Bishop et al., 2015).
In order to address this limitation, there have been a number of dynamic field-based tests developed (Myer et al., 2008; Padua et al., 2009; Ford et al., 2006; Myer et al., 2015). These tests have been developed in an effort to identify the key kinematic variables associated with injury as derived through the 'gold standard' 3D movement analysis. In section 2.1.3, the rationale for not using the TJA and other movement screens was discussed. The proceeding section will now discuss the rationale for including the LESS as the dynamic field-based movement screen to use in this research programme as well as outlining key research topics related to the LESS that require further investigation.

2.3.5 Landing Error Scoring System (LESS)

With regards reliability and validity, the LESS test is the most examined field-based dynamic screening tool (Padua et al., 2009; Smith et al., 2012; Onate et al., 2010; Padua et al., 2011; Padua et al., 2015). The LESS assesses an individual’s landing technique based on a set of 17 criteria that are easily observable to the human eye (Padua et al., 2009). The task involves a participant jumping forward off a 0.3 m box, landing on a designated spot that is a distance half their height away from the front of the box and then immediately jumping vertically as high as they can (Figure 4)(Padua et al., 2009). The scoring criteria (Table 7) for the LESS have been derived from previous research that identified specific movements that may contribute to increased risk of injury, in particular ACL injury (Padua et al., 2009). The 17 criteria examine lower extremity and trunk motion in three planes from initial ground contact through until the participant jumps again vertically and can be subdivided into three main categories. The first category scores the jump-landing technique in relation to trunk and lower extremity position at the time of initial ground contact. The second category scores any faults associated with the feet between contact with the ground and the time of maximum knee flexion. A third category scores trunk and lower extremity movements between initial ground contact and the time of maximum knee flexion. The final two scoring criteria ask the examiner
to judge the amount of overall sagittal plane movement at the hips and knee from initial ground
contact to maximum knee flexion angle and to provide an overall impression of jump
technique.
The developers of the LESS scoring system have undertaken several robust trials to prove the tool’s reliability, its association with drop jump tasks assessed by 3D kinematics and its ability to prospectively predict those with high risk of ACL injury in a large military cohort (Goerger et al., 2014; Padua et al., 2009; Onate et al., 2010). Further studies have examined the ability of the LESS to prospectively predict those at greater chance of knee injury (Padua et al., 2015; Smith et al., 2012) and its ability to detect movement deficits in those who have previously sustained ACL injury (Bell et al., 2014; Markbreiter et al., 2015).

Inter- and intra-rater reliability have been examined by the developers of the LESS (Padua et al., 2009). Fifty participants (25 male and 25 female) were chosen and a single rater graded participants over two sessions. Using ICC and standard error of measure, the authors reported that the LESS had good to excellent inter- and intra-rater reliability (ICC’s = .84 and .91 respectively).
A potential limitation of this reliability study is that it involved those who developed the LESS and the raters underwent significant training before assessing the participants (Padua et al., 2009). Therefore, reliability reported may not accurately reflect the reliability of the LESS when used by practitioners using the standardised scoring sheets and instructions. Onate et al. (2010) addressed this issue by examining the inter-rater reliability between a rater who had developed the LESS and a novice rater with no experience of the LESS (Onate et al., 2010). This study reported excellent inter-rater reliability for total score of the LESS. This is very encouraging as the novice rater was a certified athletic therapist and had only received one hour of formal training on the LESS. While the results of these studies indicate that the LESS is a reliable test some limitations exist with these reliability studies (Onate et al., 2010; Padua et al., 2009). From a methodological standpoint, both studies used two raters and scored the raters only over two sessions. This is a small pool of raters and may lead to bias in the results reported (Lucas et al., 2010). Furthermore, both reliability studies have involved raters involved in the development of the LESS and so may not accurately represent the reliability of the LESS when used with raters only using the standardised scoring sheet. Finally, the reliability of individual scoring criteria of the LESS has yet to be examined. Two raters could score the individual scoring criteria differently yet arrive at the same final score. This difference in scoring would be masked by only examining the reliability of the final score. Therefore, more comprehensive reliability studies examining the final score and the individual scoring criteria with raters using only the standardised instructions and scoring are required to accurately assess the reliability of the LESS.

The validity of the LESS has been examined in several ways. The concurrent validity of the LESS was initially assessed by comparing LESS scores to lower extremity kinematic variables using 3D marker based technology (Padua et al., 2009). With a large cohort of military recruits, this study divided the participants into four groups, excellent (<4), good (>4 to ≤5), moderate
(≥5 to ≤6) and poor (≥6). Using one way analysis of variance for each of the kinematic and kinetic variables (with group as the between participant factor) this study reported those participants with poor LESS scores (≥6) had significantly worse transverse, frontal and sagittal plane mechanics than those with excellent LESS scores. Specifically, those who performed poorly in the LESS (≥6) displayed decreased knee and hip flexion angle; increased knee and hip extension moment, increased anterior tibial shear force and increased knee valgus and hip adduction angle and moment. In the transverse plane, poor landing technique was associated with increased internal knee and hip internal rotation moment. Furthermore, several kinematic and kinetic variables (peak knee flexion angle and displacement, peak hip flexion angle and displacement, peak vertical ground-reaction force, peak knee valgus angle, and peak) were significantly different across each of the four groups. The 3D kinematic measures associated with poor LESS scores are the same variables that have been utilised to prospectively and retrospectively identify those at increased risk of injury, in particular ACL injury (Hewett et al., 2013, Hewett et al., 2010; McLean et al., 2005; Paterno et al., 2014). Therefore, the authors concluded that the LESS has good concurrent validity compared to gold standard methods of assessing 3D kinematics during a drop jump task.

Padua et al. (2009) reported that females were more likely to score in the poor LESS group compared to males (Padua et al., 2009). The results of Padua et al. (2009) were supported by Beutler et al. (2009) who analysed this cohort further and reported that LESS scores were significantly higher in females than males (5.34 ± 1.51 vs. 4.65 ± 1.69) indicating worse jump-landing mechanics (less hip and knee flexion, greater hip and knee adduction) (Beutler et al., 2009). Several 3D kinematic studies have demonstrated that females display significantly worse mechanics during high risk cutting or landing tasks, which have been prospectively and retrospectively linked with increased chance of injury (Boling et al., 2009; Hewett et al., 2010; Myer et al., 2007; Myer et al., 2011a; Renström et al., 2008; Powers, 2010). Therefore, the
ability of LESS scores to identify differences between males and females increases the strength of its relationship to 3D analysis, which also identifies differences between males and females (Hewett et al., 2010; Myer et al., 2011a).

Studies involving the LESS have in the main reported a strong relationship with more established, ‘gold standard’ 3D mechanical markers (Onate et al., 2010; Padua et al., 2009; Beutler et al., 2009). However, the association between LESS scores and injury is less conclusive (Smith et al., 2012; Padua et al., 2015). One large prospective study involving 5047 high school basketballers over a 3 year period reported no relationship between LESS scores and ACL injury risk (Smith et al., 2012). The results of the study by Smith et al. (2012) directly conflict with another large scale study involving 829 soccer players (348 males, 481 females) (Padua et al., 2015). The results of the study by Padua et al. (2015) reported that over a season, seven athletes sustained ACL injuries. These seven had significantly worse LESS scores than the uninjured population in this study (Padua et al., 2015). A ROC analysis indicated that a cut-off LESS score of 5 could predict injury with 86% sensitivity and 64% specificity.

Difference in the sports examined (basketball vs. soccer), such as surface, number of landings per game and size of the pitch/court could account for the discrepancy between the two studies. Furthermore, ACL injury is relatively uncommon and therefore, despite the large numbers in both studies the limited numbers of ACL injuries in the cohorts potentially makes it difficult to analyse ACL injury risk. In both studies only 0.8 % of participants examined sustained an ACL injury. Future studies may be better served to examine the association of total injuries sustained in a cohort to LESS scores.

Despite the research conducted to date there are several limitations with the LESS that require investigation. In addition to the conflicting results regarding LESS and ACL injury risk, there have been no studies examining injury association in an adult population. Furthermore, there have been no studies examining the association of LESS scores to overall injury risk.
Therefore, there is no research examining the association between LESS scores and lower limb injuries in general. This research is required in order to examine the full value of the LESS as an injury prediction tool.

The majority of published research regarding the LESS has been conducted by the developers of the tool and involves the JUMP-ACL military study (Beutler et al., 2009; Onate et al., 2010; Padua et al., 2011; Padua et al., 2009). This may be subject to bias and therefore research is required to ensure similar results are reported by those without such intimate knowledge of the screen. In addition, to the research conducted by the founders of the LESS, there have been limited studies examining whether the LESS correlates to 3D mechanics in other population groups (Bishop et al., 2015). Finally, there is limited research examining how LESS scores correlate to other common but less dynamic field-based screens, such as the FMS and how the association of injury to both screens in the same cohort. Investigating the relationship between LESS scores, FMS scores and overall injury risk would provide greater clarity regarding the ability of the LESS as an injury prediction tool. Therefore, this research programme will include the LESS as a screening tool to examine its relationship to FMS scores, 3D mechanics and its association to overall injury risk.

2.3.6 FMS and 3D movement analysis

A topic that lacks empirical evidence at present is the mechanisms as to why a relationship may exist between FMS scores and injury risk. Currently, any potential reasons for a correlation between FMS scores and injury risk is speculative in nature (Kraus et al., 2014). A common, plausible explanation provided by studies examining FMS scores and injury risk is that the mechanics involved undertaking the FMS are related to the mechanics involved in more dynamic sporting actions (Lisman et al., 2013; Kiesel et al., 2007). Studies utilising three dimensional (3D) analysis have reported that faulty mechanics during complex actions, such as landing, jumping and cutting predispose athletes to both chronic and acute injury (Hewett et
al., 2010; Powers, 2010; Goerger et al., 2014; Renström et al., 2008). Therefore, if poor scores in the FMS were related to poor mechanics in these actions it could provide a rationale for the correlation commonly reported between FMS scores and increased injury risk.

Only one study by Frost et al. (2015) has examined the relationship between FMS scores and 3D kinematics of the knee and lumbar spine during five of the seven FMS tests (squat, hurdle, inline lunge, rotary stability and press up). The results revealed that on average fire-fighters with scores above 14 (high scoring group) displayed less frontal plane knee valgus and spine motion during the seven FMS screens, in comparison to their mass- and height-matched low-scoring counterparts. Frontal plane knee and excessive spinal motion are factors that predispose individuals to increased chance of injury (Ford et al., 2006; Hewett et al., 2010; McLean et al., 2005; Myer et al., 2008; McGill and Cholewicki, 2001). Therefore, the study by Frost et al. (2015) indicated that there may be some merit in the proposed assumption that those with poor FMS scores display faulty mechanics similar to those that predispose athletes to injury (Frost et al., 2015). However, two notes of caution are advised with these findings. First, the variability in results was quite large. Some individuals in the low scoring group had less spine and frontal plane knee motion than individuals in the high scoring group (Frost et al., 2015). Second, the study by Frost et al. (2015) does not provide insight into whether those who perform well on the FMS will perform dynamic tasks with less spinal motion or knee valgus but rather only reports that those who score highly on the FMS tests have less aberrant knee and spinal motion during the seven tests.

To date, there have been no studies conducted examining whether those with poor FMS scores have differing lower limb kinematics at the hip or knee during dynamic actions compared to those with good FMS scores. Answering this question may provide a potential mechanism as
to why 17 peer reviewed papers have reported a relationship between FMS scores and injury risk (Table 5).

2.3.7 Conclusion

Evaluating the previously mentioned movement screens using the ARMSS model, it becomes apparent that most of these screens have not been examined robustly to date. Several of the movement screens previously discussed have only been examined through descriptive research outlining how the screens may help address injury risk or sporting performance (McKeown et al., 2014; Parsonage et al., 2014; Myer et al., 2008) (Bishop, 2008). The screens require more robust examination of reliability and preferably, by individuals not involved in developing the movement screens (Table 1).

In comparison to these other screens, the reliability and efficacy of the Functional Movement Screen and the Landing Error Scoring System have been more extensively examined within the scientific literature. The FMS is the most widely used movement screen in sporting and active professional settings (McCall et al., 2015; Teyhen et al., 2014). McCall et al. (2015) surveying elite soccer in Europe, America and Oceania reported that 77% of teams in the top divisions use the FMS to assess movement. The LESS has been utilised with military and sporting populations as a novel screening tool (Padua et al., 2009; Smith et al., 2012). Therefore, due to the practical use and more substantive research, the FMS and LESS were determined as the most appropriate movement screens to use in this programme of research. While the FMS and LESS have been most extensively examined there are still areas that need to be addressed, namely examining the relationship of the scores of the FMS and LESS in the same cohort, their relationship to a 3D kinematic drop jump and finally their association with injury.
2.4 Laboratory 3D motion analysis of kinematic data during dynamic actions

2.4.1 Justification for examining 3D motion analysis of kinematic data during dynamic actions

A key question that must be answered when undertaking any research programme is whether or not the research is worthwhile? This section examines the retrospective and prospective studies related to injury rates in those with significantly different 3D kinematic data during dynamic actions and also examines whether these differing mechanics can be altered and improved with training. Exploring the research on this clarifies the relevance of examining potential correlations that may exist between field-based screens and 3D kinematics of more complex sporting actions. This review also highlights the key kinematic data that would be practically useful to examine and help inform methods and practices in future research studies.

2.4.2 Association of injury with 3D kinematic data of dynamic actions

Studies utilising 3D kinematic data have predominantly focused on its potential to identify extrinsic risk factors for both acute and chronic lower limb injury, particularly at the knee (Boling et al., 2009; Goerger et al., 2014; Hewett et al., 2010; Myer et al., 2007; Padua et al., 2009; Renström et al., 2008; Weiss and Whatman, 2015). The array of knee injuries that have been investigated include; Anterior Cruciate Ligament (ACL) tears, patellofemoral pain syndrome (PFPS), iliotibial band friction syndrome (ITBFS) and osteoarthritis of the knee (Boling et al., 2009; Goerger et al., 2014; Hewett et al., 2010; Renström et al., 2008; Weiss and Whatman, 2015; Ferber et al., 2010; Souza and Powers, 2009; Powers, 2010; Foch and Milner, 2013; Noehren et al., 2014). ACL tears have been the most extensively examined injury site using 3D kinematics during dynamic tasks (der Worp et al., 2015; Hewett et al., 2005; Zazulak et al., 2007; Hewett et al., 2010, McLean et al., 2005, Myer et al., 2008). A large number of prospective and retrospective studies have identified key kinematic differences between those predisposed to ACL injury during landing, cutting and running (Krosshaug et al., 2007; Olsen
et al., 2004; Hewett et al., 2005; Goerger et al., 2014; Myer et al., 2011b; Renström et al., 2008; Weiss and Whatman, 2015). Furthermore, the aberrant kinematics and kinetics during dynamic tasks associated with knee injuries have also been associated with other lower limb injuries such as chronic ankle instability, femoracetabular impingement of the hip and tibial stress fractures during landing, cutting and running (Ferber et al., 2010; Hewett et al., 2005; Souza and Powers, 2009; Powers, 2010; Pohl et al., 2008; Milner et al., 2007; Milner et al., 2006; Delahunt et al., 2006).

While the pathology of all these injuries differ considerably, the kinematic variables that predispose individuals to these injuries are similar. Excessive frontal plane motion at the knee and trunk, increased hip and knee adduction, increased hip and knee internal rotation angles and decreased hip and knee flexion during dynamic tasks such as landing, cutting and running are the key kinematic variables examined in the prospective and retrospective studies associated with injury (Ferber et al., 2010; Hewett et al., 2005; Souza and Powers, 2009; Powers, 2010; Pohl et al., 2008; Milner et al., 2007; Milner et al., 2006; Delahunt et al., 2006). Therefore, it is apparent from the research above that for FMS and LESS scores to be useful field-based movement screens they should be able to identify the 3D kinematic variables associated with injury during dynamic tasks.

In relation to injury, there are two main groups that have demonstrated an increased chance of injury when active; those who have sustained previous injury and females (Ford et al., 2006; Ford et al., 2005; Hewett et al., 2010; Paterno et al., 2014; Paterno et al., 2010). Various studies have demonstrated that the 3D kinematic data significantly associated with injury during dynamic tasks are more prevalent and more pronounced in both of these cohorts (Arendt et al., 1999, Goerger et al., 2014, Hewett et al., 2013, McLean et al., 2005). This further validates the use of 3D analysis as the 'gold standard' in movement assessment and provides further rationale for comparing results of 3D analysis to field-based screening protocols.
Paterno et al. (2010) prospectively examined 56 athletes following reconstruction of their ACL who were cleared for sports participation. In a one year follow up, thirteen athletes had sustained re-injury of the ACL (Paterno et al., 2010). Those that were re-injured displayed the biomechanical deficits mentioned in the previous section (Paterno et al., 2010). These deficits were able to predict the chance of injury with excellent sensitivity (92%) and specificity (88%) (Paterno et al., 2010). Furthermore, several studies have discussed that this increased chance of re-injury may not be the result of the initial injury and subsequent surgery, but may be due to the athlete’s pre-injury movement patterns (Hewett et al., 2005; Hewett et al., 2012; Paterno et al., 2014; Paterno et al., 2010; McLean et al., 2005). This further strengthens the importance of examining these modifiable risk factors from injury rehabilitation and prevention standpoints (Hewett et al., 2005; Hewett et al., 2012; Paterno et al., 2014; Paterno et al., 2010; McLean et al., 2005).

Further support for the use of lower limb kinematic data to identify those at risk of injury, in particular knee injury, is that females display significantly poorer lower limb kinematics (decreased hip flexion, increased knee valgus and internal rotation) than their male counterparts during dynamic athletic actions (Agel et al., 2005; Beutler et al., 2009; Ford et al., 2003; Hewett et al., 2005; Sigward and Powers, 2006; Zazulak et al., 2005; Foch and Milner, 2013; Salci et al., 2004). In relation to knee injuries, in particular ACL tears, females are four to six times more likely to sustain injury when participating in landing and cutting sports compared to their male counterparts (Agel et al., 2005; Arendt et al., 1999). Furthermore, ACL re-injury is four times more likely to occur in female athletes than male athletes who have sustained a previous ACL injury (Paterno et al., 2014). While the reasons for these differences in injury rates is multi-factorial (hormone differences, anatomical differences, genetics etc.) many authors have reported that females display significantly worse kinematics (decreased hip flexion, increased knee valgus and internal rotation) associated with injury during landing and cutting tasks.
compared to their male counterparts (Nagano et al., 2007; Pollard et al., 2007; Sigward and Powers, 2006; Wikstrom et al., 2006; Zazulak et al., 2005). Therefore, the fact that 3D analysis can identify differences in the mechanics of males and females that correlate to increased chance of injury further justifies the use of 3D analysis as a ‘gold standard’ assessment tool (Hewett et al., 2013; Hewett et al., 2010; Hewett et al., 2012; McLean et al., 2005; Myer et al., 2015).

2.4.3 3D kinematic variables associated with injury

From a biomechanical standpoint, the kinematic variables that predispose individuals to injury are nearly identical to the mechanism of injury associated with acute ligament injuries, such as ACL and lateral ankle ligament injuries (Delahunt et al., 2006; Doherty et al., 2014; Goerger et al., 2014; Hewett et al., 2010; Paterno et al., 2014; Renström et al., 2008). With ACL injuries for example, during the stance phase of landing or cutting actions there is excessive lateral shifting of the pelvis over the landing foot (Hewett et al., 2010). This causes the ground reaction force vector to pass laterally to the knee joint (Figure 5). This lateral shift is coupled with a valgus collapse at the knee joint and increased hip adduction (Hewett et al., 2010; Sigward and Powers, 2006; Powers, 2010). The poor mechanics at the knee joint result in the knee being outside the base of support at the point of contact during the landing action (Padua et al., 2009; Hewett et al., 2010). As the knee is outside the base of support, it is essentially unstable and therefore there will be less ability to control movement of the knee (Hewett et al., 2010). Sigward and Powers (2006) outline that this valgus collapse at the knee places too much stress on ligaments, such as the ACL and therefore may predispose athletes to a rupture of the ACL (Sigward and Powers, 2006) (Figure 5).
Figure 5- 3D mechanics associated with lower limb injury

The figures highlight the key kinematic variables during a cutting action that can predispose athletes to injury, in particular ACL injury. Figure taken from Hewett et al., 2005, pg 499

This predictive model of assessing risk of ACL tears has been supported by a number of studies that have performed video analysis of actual ACL tears in athletes (Alentorn-Geli et al., 2009;
Krosshaug et al., 2007; Olsen et al., 2004). Using questionnaires and video analysis of recorded ACL tears in various sports, the aforementioned studies reported that those who sustain non-contact ACL injury were in a forced valgus position at the knee, the knee was in near extension and there was excessive internal knee rotation (Olsen et al., 2004; Krosshaug et al., 2007). This is a nearly identical position to the position undertaken by at-risk, healthy individuals during landing and cutting tasks (Agel et al., 2005; Alentorn-Geli et al., 2009; Arendt et al., 1999; Cochrane et al., 2007; Goerger et al., 2014; Hewett et al., 2013; Hewett et al., 2005; Hewett et al., 2012; McLean et al., 2005; Paterno et al., 2010; Sugimoto et al., 2015). Furthermore, in vivo studies using MRI fluoroscopy have supported this finding by reporting an elongation of the ACL ligament in individuals who had increased knee valgus and internal rotation during dynamic tasks (Utturkar et al., 2013). An increased stretch on this ligament coupled with rapid loading of the ligament due to increased knee adduction moment highlights why these kinematic variables are associated with increased chance of ACL injury (Sutton and Bullock, 2013; Krosshaug et al., 2007).

These altered mechanics associated with acute ligament tears also predispose athletes to chronic injuries due to the excessive stress and overload on particular joints or parts of the body. Retrospective studies examining running mechanics in athletes who have sustained ITBFS have reported that the injury group had 3.7 degrees more internal knee rotation angle and 3.6 degrees more knee adduction (Ferber et al., 2010; Louw and Deary, 2013; Noehren et al., 2014). Increased hip adduction angle has also been associated with ITBFS because of the increased strain this causes at the attachment of the band, especially when combined with increased internal rotation (Foch and Milner, 2013; Louw and Deary, 2013). Excessive rotation and adduction at the hip and knee have been proposed to alter the positioning of the patella and head of the femur, which may account for the increased likelihood of PFPS or FAI respectively.
in individuals who perform dynamic tasks with the altered kinematics and kinetics highlighted previously (Powers, 2010; Leunig et al., 2009).

While there is compelling evidence in examining the kinematics of dynamic actions to help prevent injury some caution should be advised. In particular, research studies examining ankle and hip injuries through examination of kinematic data are retrospective in design (Delahunt et al., 2006; Doherty et al., 2014; Hamstra-Wright et al., 2015; Leunig et al., 2009; Souza and Powers, 2009). A cause-effect relationship cannot be determined from retrospective studies so it is unclear whether these factors are predisposing factors for the injuries mentioned above or a consequence of the injuries (Hopkins et al., 2009).

Despite some limitations with the research discussed in this section it is apparent that 3D analysis of dynamic actions provides insightful information relating to injury risk in sport (Delahunt et al., 2006; Ferber et al., 2010; Hewett et al., 2005; Sigward and Powers, 2006). 3D analysis of lower limb mechanics during cutting and landing actions has demonstrated in prospective and retrospective epidemiological studies to highlight risk factors associated with injury, in particular ACL injuries (Hewett et al., 2012; McLean et al., 2005; Paterno et al., 2010; Sugimoto et al., 2015). Numerous studies utilising 3D motion analysis have also outlined mechanical differences between males and females during landing tasks (Agel et al., 2005; Alentorn-Geli et al., 2009; Arendt et al., 1999; Cochrane et al., 2007; Goerger et al., 2014; Hewett et al., 2013; Hewett et al., 2005; Hewett et al., 2012; McLean et al., 2005; Paterno et al., 2010; Sugimoto et al., 2015). This information helps validate the use of 3D analysis, in particular the variables of (1) increased knee and hip adduction (valgus) (2) increased hip and knee internal rotation (3) decreased hip and knee flexion (4) increased motion of the trunk and (5) increased GRF during the stance phase of actions such as a jump, land or cut.
2.5 Conclusion

From the subsequent literature review it is apparent that examining movement quality has merit in identifying and reducing potential risk factors associated with sport and training. Currently, laboratory 3D motion analysis of kinematic data during dynamic tasks is the 'gold standard' movement assessment technique due to its ability to identify aberrant kinematics that are associated with injury. Furthermore, motion analysis of 3D kinematic data during dynamic tasks are able to identify specific populations predisposed to increased chance of injury, such as females and those who have sustained previous injury. However, examining 3D kinematic data during dynamic tasks is expensive, time consuming and not practically available to the majority of sporting populations. Therefore, field-based screening protocols need to be examined as possible alternatives.

The FMS is the most popular field-based movement screen. This chapter has identified several important questions that need to be addressed regarding the FMS. First, research is required regarding the relationship of the FMS to dynamic actions, such as landing. Proponents of the FMS have stated those who perform poorly in the FMS most likely perform poorly during more dynamic actions (Kiesel et al., 2007; Lisman et al., 2013) yet to date, this has not been examined. Therefore, research is required to determine whether poor performance in the FMS is related to poor performance in dynamic actions as measured by the gold standard 3D kinematic data during a dynamic drop jump and by a dynamic field-based screen, the LESS. Second, as highlighted by the systematic review by Moran et al. (2017), further clarity is required related to the ability of the FMS and the LESS to detect those at increased risk of injury. There have been no prospective studies examining whether the FMS has a greater association with injury than more dynamic field-based tests, such as the LESS in an active population or whether a combination of both provides more accurate detection of individuals at increased risk of injury. Answering these questions will provide novel insights and help
clarify several aspects relating to the FMS and LESS that are currently lacking in the empirical evidence.
Chapter 3

Study 1: Establishing Reliability of The Functional Movement Screen and Landing Error Scoring System

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3.0 Abstract

**Background:** The purpose of this chapter was to investigate the inter- and intra-rater reliability of the 100 point and 21 point scoring systems of the FMS and the inter- and intra-rater reliability of the final score and the individual scoring criteria of the LESS.

**Methods:** This chapter comprised of two studies. The first study examined the inter- and intra-rater reliability of the 21 and 100 point scoring systems of the FMS with the author of this thesis and another experienced rater who was also certified in the FMS. The second study involved grading the inter- and intra-reliability of the LESS with the author of this thesis and another experienced rater using the standardised scoring sheet. Both studies involved the two raters scoring thirty participants and the author of this thesis scoring the videos again six weeks later for the intra-rater component of both studies.

Both studies used ICC statistics to analyse the inter- and intra-rater reliability of the final scores and kappa statistics to examine the inter- and intra-rater reliability of the seven FMS tests and the individual scoring criteria of the LESS.

**Results:** The ICC inter- and intra-rater reliability of the total FMS (21 point and 100 point) scores and total LESS score were excellent (ICC range= 0.95-0.98). The inter- and intra-rater reliability of the seven FMS subtests with the 21 and 100 point scoring systems and the individual scoring criteria of the LESS had between moderate and perfect agreement using kappa statistics.

**Conclusions:** The results highlight that the 21 point and 100 point scoring systems of the FMS have acceptable reliability with experienced, certified raters. The final score and individual scoring criteria of the LESS also has acceptable reliability with experienced raters using the standardised scoring sheet.
3.1 Introduction

As outlined in chapter one, there are several key topics related to the FMS and LESS that require examination. Investigating the relationship between the FMS and LESS, their association with injury and 3D kinematics will provide practitioners with greater clarity regarding the use of these popular screens. However, before any validation assessments are undertaken, it is essential that reliability be established for both screens (Lucas et al., 2010).

The FMS is originally scored with a 21 point scoring system (Cook et al., 2010). Originally each of the seven FMS sub-tests are scored out of three with a score of zero indicating the participant experienced pain in one of the screens or had pain in one of the clearing tests (Cook et al., 2006a; Cook et al., 2006b). A score of one is given if the participant cannot complete a screen or if they have compensations when performing an easier, modified version of the original screen (Cook et al., 2006a). A participant scores a two if they can perform the original screen but have some compensations in the movement or if they can perform an easier, modified version perfectly without fault (Cook et al., 2010). Finally, a three is awarded if the participant can perform the screen perfectly without compensation (Cook et al., 2006a). As there are seven tests, the maximum score available is 21 and the lowest possible score for an athlete not reporting pain is seven (Cook et al., 2006a; Cook et al., 2006b).

The majority of studies examining the original 21 point scoring system have reported that it has good to excellent levels of inter- and intra-rater reliability (Anstee et al., 2003; Gribble et al., 2013; Gulgin and Hoogenboom, 2014; Leeder et al., 2016; Minick et al., 2010; Onate et al., 2012; Smith et al., 2013; Teyhen et al., 2012; Waldron et al., 2015). The authors of these studies have proposed that the slow nature of the tests and simple scoring criteria are the reasons for the good reliability reported. However, despite the good reliability reported, these reliability studies have still suggested that future studies using the FMS first undertake a reliability study.
due to discrepancies in the findings of FMS reliability studies using different raters (Anstee et al., 2003; Gribble et al., 2013; Gulgin and Hoogenboom, 2014; Leeder et al., 2016; Minick et al., 2010; Onate et al., 2012; Smith et al., 2013; Teyhen et al., 2012; Waldron et al., 2015).

Despite the good to excellent reliability of the 21 point FMS there are potential limitations of such a simple scoring system of movement (Frost et al., 2012). Two studies reporting no significant differences in FMS scores following an intervention suggested that a potential reason for the lack improvement maybe due to the 21 point scoring system lacking the sensitivity to detect worthwhile changes in movement quality (Frost et al., 2012; Waldron et al., 2015). For example, a score of two is given to an athlete who has one slight fault during the movement test (i.e. slight knee valgus during the lunge). A score of two is also given to a participant who has numerous, severe faults during the movement test, provided they can complete the action (i.e. severe knee valgus, movement at the trunk, front heel lifting, dowel not staying in contact throughout the movement in the lunge). It is conceivable that an athlete could significantly improve their movement quality with no change in FMS score using the original scoring system (Frost et al., 2012). To address this potential limitation, a 100 point scoring scheme was devised for the FMS (Butler et al., 2012; Hickey et al., 2010).

The developers of this 100 point scoring scheme have reported excellent inter-rater reliability for the individual component tests and the sum score (ICC range for component scores = .91 to 1.00 and ICC for total score =.99) (Butler et al., 2012; Hickey et al., 2010). However, intra-rater reliability has yet to be examined. Furthermore, there may be an inherent bias from the developers in relation to the reliability reported (Gratton and Jones, 2010). Certainly, the reliability reported by the developers of the 100 point scale is higher than the reliability of any study examining reliability of the 21 point scale (Anstee et al., 2003; Frohm et al., 2012; Gribble et al., 2013; Gulgin and Hoogenboom, 2014; Leeder et al., 2016; Minick et al., 2010; Onate et al., 2012; Shultz et al., 2013; Smith et al., 2013; Teyhen et al., 2012; Waldron et al., 2015).
Therefore, it is apparent that further investigation into the inter- and intra-rater reliability of the 100 point scoring system is required.

In contrast to the FMS, there have been a limited number of studies examining the reliability of the LESS. Three studies have examined the reliability of the LESS, with all three reporting good intra- and inter-rater reliability (Onate et al., 2010; Padua et al., 2011; Padua et al., 2009). Despite the positive reliability reported, there were several limitations with these three studies. All three studies involved raters who were founders of the LESS, therefore, it is unclear whether the reliability reported reflects that which would be observed with practitioners without such specialised and intimate knowledge of the screen only using the standardised set of instructions. Furthermore, the three reliability studies examined the final LESS score and did not examine the reliability of the individual scoring criteria. Examining the final score of the LESS may over-estimate the reliability of the tool as it fails to account for two raters scoring the individual criteria differently but still totalling the same final score (Lucas et al., 2010). It is apparent that examining the individual scoring criteria in addition to the total score of the LESS with practitioners who were not involved in developing the screening protocol is required to provide a more accurate representation of the reliability of the LESS.

The first element of this study aims to compare the inter- and intra-rater reliability of the 21 point and 100 point FMS scoring systems. The second element of this study aims to examine the reliability of the final score and individual criteria of the LESS when scored by two experienced practitioners using only the standardised instructions and scoring sheet. Addressing these aims will provide a more comprehensive understanding of the reliability of the FMS and LESS.
3.2 Methods

3.2.1 Participants

For FMS reliability, thirty participants (age = 22.45 ± 4.4 years; body mass = 76.84 ± 7.9 kg; height = 1.79 ± 7.4 m) were randomly chosen from a pool of 98 participants part of a larger study. Their videos were re-scored six weeks later by the second rater and again by the first rater. Participants were numbered in a random order 1-98 and the rater chose 30 numbers at random. The participants were all involved in a variety of inter-varsity sports (Gaelic games; soccer; boxing/mixed martial arts; Olympic weightlifting and track and field).

For the reliability of the LESS, the LESS videos of 30 participants (age = 21.8 ± 3.9 years; height = 1.75 ± 0.46 m; mass = 75.5 ± 6.6 kg) part of a larger study detailed in chapter 5 were randomly chosen and were scored by two raters. The videos were re-scored six weeks later by the first rater.

3.2.2 Procedures

The FMS tests were assessed by the author of this thesis and a certified FMS instructor. Both raters have screened over 1000 people and are both certified to use the FMS (Table 6). With regards the LESS, the author and a certified strength and conditioning specialist with an MSc in Strength and Conditioning scored the LESS tests. Both raters had experience (Table 6) using the standardised scoring instructions with the LESS.
Table 6- FMS reliability studies: Rater characteristics

<table>
<thead>
<tr>
<th>Years qualified in profession (Years)</th>
<th>No of FMS screens</th>
<th>No. of LESS screens</th>
<th>Years screening</th>
<th>Highest formal education</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rater 1 (Author)</td>
<td>8</td>
<td>1500</td>
<td>500</td>
<td>8</td>
</tr>
<tr>
<td>FMS Rater 2</td>
<td>14</td>
<td>&gt;2000</td>
<td>N.A</td>
<td>10</td>
</tr>
<tr>
<td>LESS Rater 2</td>
<td>5</td>
<td>N.A</td>
<td>&gt;100</td>
<td>5</td>
</tr>
</tbody>
</table>

N.A= Not applicable

3.2.3 Functional Movement Screening

The FMS involves seven tests (overhead squat, inline lunge, hurdle, rotary stability, press up, active straight leg raise (ASLR), shoulder mobility (Shld Mob) that examine three different levels of movement difficulty (Cook et al., 2006b; Cook et al., 2010). In addition to the seven tests, there are three pain clearing tests for possible back or shoulder pain (Cook et al., 2010). The FMS tests have been described previously (Cook et al., 2006a; Kiesel et al., 2007), are illustrated in Figure 2 and described in full in Appendix 3b.

3.2.4 Landing Error Scoring System

The LESS is a screening assessment that scores an individual’s landing technique based on a set of 17 criteria that are easily observable to the human eye (Padua et al., 2009). The task involves a participant jumping forward from a 0.3 m box, landing on a designated spot that is a distance equal to half their height away from the front of the box and then immediately jumping vertically as high as they can (Padua et al., 2009) (Figure 4).
The scoring criteria for the LESS have been derived from previous research that have identified specific movements that may contribute to increased risk of injury, in particular ACL injury (Padua et al., 2009). The 17 criteria (Table 6) examine lower extremity and trunk motion in the frontal and sagittal planes from initial ground contact until the participant jumps again vertically and can be subdivided into three main categories. The first category scores the jump-landing technique in relation to trunk and lower extremity position at the time of initial ground contact. The second category scores any faults associated with the feet between the point of contact with the ground and the time of maximum knee flexion. A third category scores trunk and lower extremity movements between the point of initial ground contact and the time of maximum knee flexion. The final two scoring criteria require the examiner to judge the amount of overall sagittal plane movement at the hips and knee from initial ground contact to maximum knee flexion angle and to provide an overall impression of jump technique (Table 7).
**Table 7 - Scoring of the LESS**

<table>
<thead>
<tr>
<th>1. Knee flexion @ initial contact &gt; 30 degrees</th>
<th>10. Stance width @ Initial Contact &gt; Shoulder width</th>
</tr>
</thead>
<tbody>
<tr>
<td>___ Yes (0)</td>
<td>___ Yes (1)</td>
</tr>
<tr>
<td>___ No (1)</td>
<td>___ No (0)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>2. Knee Valgus @ Initial Contact: Knee over midfoot</th>
<th>11. Initial Foot Contact: Symmetric</th>
</tr>
</thead>
<tbody>
<tr>
<td>___ Yes (0)</td>
<td>___ Yes (0)</td>
</tr>
<tr>
<td>___ No (1)</td>
<td>___ No (1)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>3. Hip Flexion @ Initial Contact: Hips are flexed</th>
<th>12. Knee flexion Displacement: &gt;45 degrees</th>
</tr>
</thead>
<tbody>
<tr>
<td>___ Yes (0)</td>
<td>___ Yes (0)</td>
</tr>
<tr>
<td>___ No (1)</td>
<td>___ No (1)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>4. Trunk Flexion @ Initial Contact: Trunk is flexed</th>
<th>13. Knee Valgus Displacement ≥Great toe</th>
</tr>
</thead>
<tbody>
<tr>
<td>___ Yes (0)</td>
<td>___ Yes (1)</td>
</tr>
<tr>
<td>___ No (1)</td>
<td>___ No (0)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>5. Lateral Trunk Flexion @ Initial Contact: Trunk is vertical</th>
<th>14. Hip Flexion Displacement: Hips flex more than @ initial contact</th>
</tr>
</thead>
<tbody>
<tr>
<td>___ Yes (0)</td>
<td>___ Yes (0)</td>
</tr>
<tr>
<td>___ No (1)</td>
<td>___ No (1)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>6. Ankle Plantar Flexion @ Initial Contact: Toe to heel</th>
<th>15. Trunk Flexion Displacement: Trunk Flexion more than @ initial contact</th>
</tr>
</thead>
<tbody>
<tr>
<td>___ Yes (0)</td>
<td>___ Yes (0)</td>
</tr>
<tr>
<td>___ No (1)</td>
<td>___ No (1)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>7. Foot Position @ Initial Contact: Toes &gt;30 ER</th>
<th>16. Joint Displacement (Sagittal Plane)</th>
</tr>
</thead>
<tbody>
<tr>
<td>___ Yes (1)</td>
<td>___ Soft (0)</td>
</tr>
<tr>
<td>___ No (0)</td>
<td>___ Average (1)</td>
</tr>
<tr>
<td></td>
<td>___ Stiff (2)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>8. Foot Position @ Initial Contact &gt; 0 of IR</th>
<th>17. Overall Impression</th>
</tr>
</thead>
<tbody>
<tr>
<td>___ Yes (1)</td>
<td>___ Excellent (0)</td>
</tr>
<tr>
<td>___ No (0)</td>
<td>___ Average (1)</td>
</tr>
<tr>
<td></td>
<td>___ Poor (2)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>9. Stance Width @ Initial Contact &lt; Shoulder width</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>___ Yes (1)</td>
<td></td>
</tr>
<tr>
<td>___ No (0)</td>
<td></td>
</tr>
</tbody>
</table>

IR=Internal Rotation; ER=External Rotation

**3.2.5 Data collection and scoring the FMS and LESS**

The FMS and LESS tests were recorded using a Sony HDD handycam, with a frame rate of 30 frames per second (DCR-SR62 hard disk drive camera, Tokyo, Japan). Frontal and sagittal view recordings were obtained for all tests with the exception of the ASLR and shoulder mobility where only one view was necessary. Camera positioning was consistent with that of
Butler et al. (2012) with the camera positioned so that participants could be fully observed during each of the seven FMS tests and the LESS test. FMS and LESS videos were analysed using 2D video software (Dartfish Prosuite 5.5, Fribourg, Switzerland). The raters were allowed to view the videos as many times as possible and as slow a speed required.

3.2.6 Statistical Analysis

SPSS Version 22 (SPSS Inc., Chicago, IL, USA) was used for all statistical analysis performed. For the FMS and LESS, inter- and intra-rater reliability of the test scores were analysed using Intra-Class Coefficients (ICC) with 95% Confidence Intervals (CI). Kappa statistics with 95% CI were conducted for the individual scoring criteria of the LESS and the seven component tests of the FMS. Kappa statistics were chosen due to the analysis being stronger than calculating percentage agreement between raters (Sim and Wright, 2005). Kappa statistics take the chance of random agreement into account (Sim and Wright, 2005). Using criteria described by Sim and Wright (2005), reliability was classified as follows: Excellent agreement between raters when Kappa scores were 80% and higher. Kappa scores of 60-79.9% represent substantial agreement and scores of 40-59.9% equate to moderate agreement. Finally, Kappa scores below 40% represent fair to poor agreement (Sim and Wright, 2005). With regards using ICC, values between 0.75 and 1 represent good reliability, values between .50 and .74 equate to moderate reliability and values below .50 are deemed to have poor reliability (Portney and Watkins, 2008).

3.3 Results

For the FMS, the inter- and intra-rater ICC values for the total scores were 0.97 (0.95-0.98) and 0.98 (0.97-0.99) for the 100 point and 0.98 (0.96-.99) and 0.99 (0.96-0.99) for the 21 point scoring system, indicating that both scoring systems had almost perfect inter- and intra-rater reliability. All the component tests using both scoring systems had between perfect and
substantial agreement for inter- and intra-rater reliability (Tables 8 and 9). With regards intra-rater reliability, the 100 point scale had seven measures that were perfect or almost perfect (Shld Mob, ASLR, squat, right rotary stability) and five measures had substantial agreement (lunge, left rotary stability, hurdle) (Table 8). Regards inter-rater reliability, the 100 point scale had 10 of the tests that were either perfect or near-perfect agreement and two (Right Lunge and Hurdle) with substantial agreement (Table 9). Every measure using the 21 point scale had perfect or almost perfect inter- and intra-rater agreement with the exception of the rotary stability test, which had substantial agreement (Tables 8 and 9).

Inter- and intra-rater ICC values for total LESS scores were 0.95 (95% CI= 0.90-0.97; p>.001) and 0.96 (95% CI= 0.93-0.98; p>.001) respectively, indicating that total LESS score had almost perfect inter- and intra-rater reliability. Table 10 illustrates the inter- and intra-rater reliability results of the individual scoring criteria for the LESS. For inter-rater reliability seven measures had moderate reliability, one measure had substantial, three had excellent reliability and four had perfect agreement (Table 10). Regards intra-rater reliability, two measures had moderate reliability, four substantial, three excellent and five measures had perfect reliability (Sim and Wright, 2005)(Table 10).
<table>
<thead>
<tr>
<th>Name of Test</th>
<th>Intra-rater</th>
<th>Inter-rater</th>
<th>Level of agreement</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Kappa Statistics (95% C.I)</td>
<td>Kappa Statistics (95% C.I)</td>
<td>Intra-rater/Inter-rater</td>
</tr>
<tr>
<td>Overhead Squat*</td>
<td>.948 (.829-1)</td>
<td>.948 (.829-1)</td>
<td>Almost Perfect</td>
</tr>
<tr>
<td>Lunge R*</td>
<td>.784 (.597-.951)</td>
<td>.786 (.588-.954)</td>
<td>Substantial</td>
</tr>
<tr>
<td>Lunge L*</td>
<td>.62 (.40-.791)</td>
<td>.916 (.784-1)</td>
<td>Substantial/Almost Perfect</td>
</tr>
<tr>
<td>Hurdle R*</td>
<td>.756 (.537-.94)</td>
<td>.756 (.537-.94)</td>
<td>Substantial</td>
</tr>
<tr>
<td>Hurdle L*</td>
<td>.80 (.59-.94)</td>
<td>.845 (.66-1)</td>
<td>Substantial</td>
</tr>
<tr>
<td>RotStabR*</td>
<td>.87 (.44-1)</td>
<td>.87 (.44-1)</td>
<td>Almost perfect</td>
</tr>
<tr>
<td>RotStabL*</td>
<td>.83 (.46-1)</td>
<td>.83 (.46-1)</td>
<td>Substantial/Almost Perfect</td>
</tr>
<tr>
<td>Pressup*</td>
<td>.85 (.61-1)</td>
<td>.85 (.60-1)</td>
<td>Almost perfect</td>
</tr>
<tr>
<td>ASLRR*</td>
<td>1 (1-1)</td>
<td>1 (1-1)</td>
<td>Perfect</td>
</tr>
<tr>
<td>ASLRL*</td>
<td>1 (1-1)</td>
<td>1 (1-1)</td>
<td>Perfect</td>
</tr>
<tr>
<td>Shld Mob R*</td>
<td>1 (1-1)</td>
<td>1 (1-1)</td>
<td>Perfect</td>
</tr>
<tr>
<td>Shld Mob L*</td>
<td>1 (1-1)</td>
<td>1 (1-1)</td>
<td>Perfect</td>
</tr>
</tbody>
</table>

*= p<.001
Table 9- Intra-rater and Inter-rater reliability of the 21 point FMS scoring system

<table>
<thead>
<tr>
<th>Name of Test</th>
<th>Intra-rater</th>
<th>Inter-rater</th>
<th>Level of agreement</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Kappa Statistics (95% C.I)</td>
<td>Kappa Statistics (95% C.I)</td>
<td>Intra-rater/Inter-rater</td>
</tr>
<tr>
<td>Overhead Squat*</td>
<td>.941 (.799-1)</td>
<td>.948 (.829-1)</td>
<td>Almost Perfect</td>
</tr>
<tr>
<td>Lunge R*</td>
<td>1 (1-1)</td>
<td>.784 (.597-.951)</td>
<td>Perfect/ Substantial</td>
</tr>
<tr>
<td>Lunge L*</td>
<td>.842 (.615-1)</td>
<td>.62 (.40-.791)</td>
<td>Substantial</td>
</tr>
<tr>
<td>Hurdle R*</td>
<td>.815 (.74-1)</td>
<td>.756 (.537-.94)</td>
<td>Substantial</td>
</tr>
<tr>
<td>Hurdle L*</td>
<td>.814 (62-1.0)</td>
<td>.8 (.59-.94)</td>
<td>Substantial</td>
</tr>
<tr>
<td>RotStabR*</td>
<td>.87 (.44-1)</td>
<td>.87 (.44-1)</td>
<td>Almost perfect</td>
</tr>
<tr>
<td>RotStabL*</td>
<td>.63 (.42-1)</td>
<td>.63 (.42-1)</td>
<td>Substantial</td>
</tr>
<tr>
<td>Pressup*</td>
<td>.85 (.61-1)</td>
<td>.85 (.61-1)</td>
<td>Almost perfect</td>
</tr>
<tr>
<td>ASLRR*</td>
<td>1 (1-1)</td>
<td>1 (1-1)</td>
<td>Perfect</td>
</tr>
<tr>
<td>ASLRL*</td>
<td>1 (1-1)</td>
<td>1 (1-1)</td>
<td>Perfect</td>
</tr>
<tr>
<td>Shld R*</td>
<td>1 (1-1)</td>
<td>1 (1-1)</td>
<td>Perfect</td>
</tr>
<tr>
<td>ShldL*</td>
<td>1 (1-1)</td>
<td>1 (1-1)</td>
<td>Perfect</td>
</tr>
</tbody>
</table>

*= p<.001
Table 10- Inter- and intra-rater Kappa statistics of LESS scoring criteria

<table>
<thead>
<tr>
<th>Knee flexion @ IC</th>
<th>Hip Flexion @IC</th>
<th>Trunk flexion @IC</th>
<th>Heel Add to Knee flexion @IC</th>
<th>Add Hip Flexion</th>
<th>Add Trunk Flexion</th>
<th>Joint Displacement valgus @ IC</th>
<th>Knee Valgus @ IC</th>
<th>Stance Side Flexion</th>
<th>Foot Width Placement</th>
<th>Asymmetric foot contact</th>
<th>Max Overall</th>
<th>Overall Impression</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inter-rater</td>
<td>0.41*</td>
<td>1.0*</td>
<td>0.61*</td>
<td>1.0*</td>
<td>0.51*</td>
<td>0.53*</td>
<td>0.47*</td>
<td>0.46*</td>
<td>0.86*</td>
<td>0.49*</td>
<td>1.00*</td>
<td>0.84*</td>
</tr>
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<td></td>
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<td></td>
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<td>1.00*</td>
</tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.93*</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.55*</td>
</tr>
<tr>
<td>Intra-rater</td>
<td>0.63*</td>
<td>1.0*</td>
<td>0.60*</td>
<td>1.0*</td>
<td>0.47*</td>
<td>0.60*</td>
<td>0.55*</td>
<td>0.64*</td>
<td>0.86*</td>
<td>0.49*</td>
<td>1.00*</td>
<td>1.00*</td>
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<td></td>
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<td>1.00*</td>
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<td>0.87*</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.89*</td>
</tr>
</tbody>
</table>

* = significant to >.05; Add = Additional; IC = Initial contact
3.4 Discussion

The main findings of this study were that the FMS (21 point and 100 point) and the LESS screening protocols had acceptable inter- and intra-rater reliability. Both screens had excellent inter- and intra-rater ICC values of over .90 for the final scores, indicating that final scores of both screens are very reliable. The ICC scores reported in this study are comparable to other reliability studies involving the FMS and LESS tests (Padua et al., 2009, Padua et al., 2011, Gulgin and Hoogenboom, 2014; Waldron et al., 2015; Hickey et al., 2010; Minicik et al., 2010; Butler et al., 2012). These results highlight that the FMS (21 and 100 point scoring) and the LESS have acceptable levels of reliability with experienced raters.

While the reliability of the FMS and LESS composite scores were excellent this is only a limited assessment of reliability (Sim and Wright, 2008). Two raters could score two component tests differently but when the components are added up arrive at the same score (Kraus et al., 2014). Therefore, there is a chance that the high levels of reliability reported relating to the total scores may be due to random chance rather than consistent agreement between raters for all components of the FMS and LESS (Kraus et al., 2014). In this regards, the reliability of the individual component tests of the FMS and the scoring criteria of the LESS is more important to examine.

All seven individual FMS tests had either substantial or perfect inter- and intra-rater reliability. The tests with set markers to determine the score (i.e. shoulder mobility and active straight leg raise) or tests with only one element to examine (push up) had the highest reliability. The limited number of variables to be assessed in these three tests likely accounts for the high reliability recorded. Conversely, the lunge and rotary stability test had slightly poorer reliability. This would be similar to the findings of previous FMS reliability studies (Hickey et al., 2010; Minicik et al., 2010; Butler et al., 2012). A possible explanation is that these tests have the greatest number of criteria to be assessed, thus making them inherently more difficult
to grade. Furthermore, with regards the original scoring system, the rotary stability and inline lunge tests have much larger variation in participants achieving the same score. A rater may not wish (consciously or subconsciously) to grade two participants with clearly differing abilities the same. This may be a potential reason for the reduced reliability with these two tests.

Given the narrow scoring system of the original FMS (21 points) compared to much greater variation of scores in the 100 point system, it was somewhat surprising how similar the reliability of both scoring systems were to each other. The original scoring system is divided into very basic criteria (Cook et al, 2006). For the majority of tests, a score of one is given if the participant cannot complete the test and a score of three is given if the participant can perform the test perfectly. A participant scores a two if they can complete the test but have at least one fault or if they have many faults provided they complete the test. With the 100 point scoring system, each individual scoring criteria are graded. Therefore, it is possible that two raters scoring a lunge test would score a participant a two with the original scoring system (perfect agreement) and could score the same participant a 2/10 and an 8/10 on the 100 point scoring system. Given this possibility of much more varied scores on the 100 point scoring system, it was surprising that the 100 point scores had very comparable reliability to the 21 point scoring system. This indicates that the criteria to score the FMS are very reliable and that experienced, certified practitioners can be confident in using either the 21 or 100 point scoring system for the FMS.

This was the first study to examine reliability of the total score of the LESS with raters who were not founders of the tool. The similar reliability reported in this study is encouraging for practitioners who use the LESS and only have the standardised instructions to guide them. The results of this study indicate that they will have acceptable reliability using the standardised scoring criteria instructions.
All individual scoring criteria of the LESS had between perfect and moderate reliability. Unsurprisingly, the scoring criteria where subjective, clinical judgment was required, such as overall impression and overall joint displacement had the worst reliability (Table 10). There are no set criteria to determine a soft vs. an average landing but it is determined by the clinical judgement of the rater (Padua et al., 2009). Therefore, two raters subjectively disagreeing on the softness of the landing may account for these criteria having the lowest reliability. In contrast, the scoring criteria, with set yes or no objective markers had perfect or almost perfect reliability. Using video analysis it is easy to observe whether a participant keeps their feet shoulder width apart during the jump. Therefore, it is unsurprising that reliability was high with these objective scoring criteria (Table 10). Even with the more subjective criteria, inter- and intra-rater reliability of the total score and individual scoring criteria of the LESS was moderate to perfect.

There were two main limitations of this chapter that should be addressed. First, two raters is the minimum number of raters required for an inter-rater reliability study (Lucas et al., 2013). Increasing the number of raters would strengthen the quality of this study (Lucas et al., 2013). The use of only two raters in this chapter was due to an inability to recruit additional raters with high levels of experience with the FMS and LESS. However, where possible future research should use multiple raters when assessing reliability of the FMS and LESS. Secondly, the study would have been further strengthened by examining the reliability of total number of participants in the larger study and not randomly selecting 30 participants. Lucas et al. (2013) outlines that numbers above 25 are generally sufficient for reliability studies however, the additional participants would have increased the power of the study.

3.5 Conclusion

The results of this study demonstrate that the 21 point and 100 point FMS scoring systems and the LESS are reliable screening tools. This was the first study to examine the intra-rater
reliability of the 100 point scoring system. It was also the first study to compare the reliability of the 21 point scoring system to the 100 point scoring system. The results indicate that experienced practitioners can be confident using either scoring system.

With regards the LESS, this was the first study to demonstrate that the LESS is a reliable screen with practitioners who have only used the standardised scoring criteria. The results highlight that practitioners can be confident using the LESS. The results of this study help to provide a much more comprehensive assessment of the reliability of the FMS (21 point and 100 point scoring systems) and LESS, than had been previously reported in the literature.
Chapter 4

Study 2: To Examine the Relationship Between the Functional Movement Screen and The Landing Error Scoring System in an Active, Male Collegiate Population.

4.0 Abstract

**Background:** There has been an increasing focus on movement screening as the principal aspect of pre-participation testing. Two of the most common movement screening tools are the FMS and the LESS. Several studies have examined the reliability and validity of these tools but so far there have been no studies comparing the results of these two screening tools against each other. Therefore, the purpose of this study was to determine the relationship between FMS scores and LESS scores.

**Methods:** Ninety-eight collegiate athletes actively participating in sport (Gaelic games, soccer, athletics, boxing/mixed martial arts, Olympic weight lifting) participated in the study and performed the FMS and LESS screens. The 21 point and 100 point scoring systems were used to score the FMS. Spearman's correlation coefficients were used to determine the relationship between the FMS and LESS.

**Results:** The results showed a significant moderate correlation between FMS and LESS scores (rho 100 and 21 point = -.528; -.487; p< .001). In addition, r² values of .26 and .23 indicate a poor shared variance between the two screens.

**Conclusions:** The results indicate that performing well in one of the screens does not necessarily equate to performing well in the other. This has practical implications as it highlights that both screens may assess different movement patterns and should not be used as a substitute for each other.
4.1 Introduction

As outlined in the introduction, movement screening has become a main element of pre-participation testing with the FMS becoming one of the most popular and well-researched screening tools with sporting, fire-fighting and military populations (McCall et al., 2015; Cook et al., 2006a). Several studies have reported that participants with low FMS scores have a significantly greater chance of injury than their high scoring counterparts (Chorba et al., 2010; Dorrel et al., 2015; Kiesel et al., 2007; Shojaedin et al., 2014). However, the sensitivity in some of these studies is quite low (O’Connor et al., 2011; Kraus et al., 2014; Kiesel et al., 2007). A meta-analysis examining the relationship between FMS scores and injury risk in seven peer-reviewed studies reported a very low sensitivity score of .24 (Dorrel et al., 2015). Low sensitivity indicates that the FMS might class individuals as “low risk” who have in fact a high susceptibility to injury (Dorrel et al., 2015). These results were supported by a larger, more recent meta-analysis involving 24 studies, which indicated a limited ability of the FMS to predict injury given limitations with sensitivity (Moran et al., 2017).

A potential reason that the FMS might ‘miss’ people who are still susceptible to injury during sport or activity may be that it does not include a dynamic test that requires high levels of eccentric strength and dynamic control in order to score highly (Dorrel et al., 2015; Myer et al., 2011; Padua et al., 2009). The mechanisms associated with many injuries, particularly acute knee injuries, are generally associated with poor mechanics that occur at speed during accelerating, decelerating, changing direction or landing from a jump (Pollard et al., 2010; Powers, 2010; Hewett et al., 2010). These actions require a large degree of eccentric strength and dynamic control to ensure correct performance. Since the FMS does not test these elements, this may limit its effectiveness in identifying participants who are predisposed to injury (Dorrel et al., 2015).
To address the potential limitations in current screening protocols, such as the FMS, dynamic field-based screens involving jumping and landing have been advocated (Myer et al., 2011; Padua et al., 2009). As mentioned in previous chapters the LESS is one of the most popular of these dynamic screens (Padua et al., 2009).

The FMS and LESS both aim to assess the underlying movement patterns required to reduce the risk of injury associated with sport and activity (Padua et al., 2009; Cook et al., 2006a). The fact that these two screens essentially have the same purpose may lead practitioners to choose one or the other in order to be more efficient with pre-participation testing. However, to the authors' knowledge, no study has examined the relationship between FMS and LESS scores, making it unclear whether these two screens provide the same information. Therefore, the aim of this study was to examine the relationship between the FMS (using both 21 and 100 point scoring systems) and LESS scores. Investigating this relationship will provide practitioners with insight into whether both tests provide similar information or if these tests are measuring different components that should be considered separately.

4.2 Methods

4.2.1 Participants

Ninety-eight male college strength and conditioning students (age= 21 ±3 years; body mass= 77.27 ±10.4 kg; height=1.77 ±6.85 m) involved in a variety of collegiate level sports (Gaelic games (43); soccer (26); boxing/mixed martial arts (7), Olympic weight lifting (10) and track and field (12)) participated in this study. Participants were engaged in sport on average, 3.5 times per week (range 2-6 sessions/week).

The University of Limerick Research Ethics Committee approved all procedures undertaken in this study. Participants were recruited via convenience sampling of a third level institute through posters and emails to sports teams explaining the nature of the study in full (Appendix
5). All participants received appropriate explanation of the study, including the benefits and risks of participating. Informed written consent was obtained before testing commenced. All participants were required to be 18 years or older, participating at least twice per week in either organised sports training or competition for over a year, with no medical condition that would compromise participation in the study. Similar to criteria set out by Chorba et al. (2010), participants were excluded from the study if they had sustained an injury that prohibited them from training or competition in the previous 30 days or had recent surgery that limited athletic participation. This was undertaken to limit the influence that a recent injury may have on screening scores (Chorba et al., 2010; Lockie et al., 2015).

4.2.2 Procedure

Participants completed one testing session that involved recording key anthropometric data, such as height and mass and undertaking the seven FMS tests and the LESS test in a random order. Body mass was measured using a digital scales (Utopia Digital Technologies, Wisconsin, USA). Height was recorded barefoot using a portable stadiometer (Ecomed Trading, Seven Hills, Australia). All assessments were conducted in a strength and conditioning gym. Participants were asked to refrain from intensive exercises and abstain from alcohol, caffeine or any other stimulant that may influence their performance in the 24 hours prior to testing. All participants had undertaken the FMS and LESS previously and so a learning session was not required (Frost et al., 2015b). Participants were given both verbal instructions as described by Cook et al. (2010) for the FMS and Padua et al. (2009) for the LESS and visual demonstrations of the actions. All testing was conducted by the author of this thesis.

The FMS and LESS tests were recorded and scored exactly as is outlined in chapter three of this thesis.
4.2.3 Statistical analysis

SPSS Version 22 (SPSS Inc., Chicago, IL, USA) was used for all statistical analysis performed. Data were analysed using descriptive statistics. LESS scores were reported as mean ± SD as well as 95% confidence intervals and FMS scores as median (range). The FMS (21 and 100 point) and LESS scores were correlated against each other using a Spearman’s correlation coefficient and alpha was set to α ≤ 0.001. Spearman's correlations were used to examine the relationship between the individual FMS tests and the LESS scores (Hauke & Kossowski, 2011). The correlation coefficient strength using Spearman's correlations was interpreted as described by Hopkins where a rho value between 0 to .3 was small, .31 to .49 moderate, .5 to .69 as large, .7 to .89 very large and .9 to 1 considered near perfect for predicting relationships (Hopkins et al., 2009; Hopkins, 2008). Finally, scatter plots were created to illustrate the relationship between FMS scores and LESS scores.

4.3 Results

The median 21 point and 100 point FMS scores were 15 (range = 11-19), and 63.5 (range = 32-91) respectively. The FMS median scores are similar to the mean scores reported in similar active male populations (Lockie et al., 2015b; Kiesel et al., 2007; O’Connor et al., 2011). The median score was reported rather than the mean due to FMS data being ordinal in nature (Hopkins, 2008). The mean LESS score (7.3 ± 3.3) was approximately 2 points higher than that reported in a large military study (4.93 ± 1.67) utilising the LESS test indicating the healthy male college population in this study had worse landing technique than the participants in that military study (Padua et al., 2009).

Tables 1, 12 and 13 display the correlations between the LESS and the total FMS scores and between the LESS scores and the individual FMS component tests respectively. There was a significant, moderate inverse relationship between FMS and LESS scores in this male population (rho 100 and 21 point = -.528; -.487; p< .001). Since lower scores in the LESS and
higher scores in the FMS represent good performance, the results highlight that there is a moderate correlation between performing well in the FMS and the LESS tests. The $r^2$ value of .26 and .23 between the FMS (100 and 21 scores respectively) and LESS indicates a low shared variance between the two tests as illustrated by the scatter plot (Figure 6) (Hopkins et al., 2009). For the individual component tests, there were significant moderate correlations with the lunge and squat tests with the 100 point score, with non-significant correlations between the LESS scores and the other five FMS tests (Table 12). Only the squat test had a significant moderate correlation to LESS scores using the original 21 point scoring system (Table 13).
Table 11- Correlation between FMS scores and LESS scores

<table>
<thead>
<tr>
<th></th>
<th>LESS</th>
<th>FMS (100)</th>
<th>FMS (21)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spearman's rho</td>
<td>LESS</td>
<td>1.00</td>
<td>-0.53 (-0.36--0.66)**</td>
</tr>
<tr>
<td></td>
<td>FMS(100)</td>
<td>-0.53 (-0.36--0.66)**</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td>FMS(21)</td>
<td>-0.49 (-0.32--0.63)**</td>
<td>0.88(0.8-0.92)**</td>
</tr>
</tbody>
</table>

**Correlation is significant at the 0.001 level (2-tailed).**

Table 12- Spearman’s correlation between LESS and individual FMS tests (100 point score)

<table>
<thead>
<tr>
<th>100 point</th>
<th>Squat</th>
<th>LungeR</th>
<th>LungeL</th>
<th>HurdleR</th>
<th>HurdleL</th>
<th>RotStR</th>
<th>RotStL</th>
<th>Press up</th>
<th>ASLRR</th>
<th>ASLRL</th>
<th>Shld R</th>
<th>ShldL</th>
</tr>
</thead>
<tbody>
<tr>
<td>FMS</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LESS</td>
<td>-0.36**</td>
<td>-0.39**</td>
<td>-0.39**</td>
<td>-0.08</td>
<td>-0.08</td>
<td>-0.11</td>
<td>-0.24*</td>
<td>-0.23*</td>
<td>-0.25*</td>
<td>-0.28**</td>
<td>-0.19</td>
<td>-0.09</td>
</tr>
</tbody>
</table>

* Correlation is significant at .05 level; **Correlation is significant at the 0.001 level
Table 13- Spearman's Correlation between LESS and individual FMS tests (21 point score)

<table>
<thead>
<tr>
<th>21 point FMS</th>
<th>Squat</th>
<th>Lunge</th>
<th>Hurdle</th>
<th>RotSt</th>
<th>Press up</th>
<th>ASLR</th>
<th>Shld</th>
</tr>
</thead>
<tbody>
<tr>
<td>LESS</td>
<td>-0.33**</td>
<td>-0.2*</td>
<td>-0.19</td>
<td>-0.24**</td>
<td>-0.28**</td>
<td>-0.28**</td>
<td>-0.18</td>
</tr>
</tbody>
</table>

(RotSt=Rotary Stability; ASLR= Active Straight Leg Raise; Shld= Shoulder mobility) **= significant to p<.001 *=significant to p<.05
4.4 Discussion

The results of this study demonstrate a moderate correlation between the FMS and LESS screens. Regarding individual FMS tests, the lunge and squat had significant moderate correlations with the LESS test while the other FMS tests had either non-significant to the LESS scores. In addition, the shared variance between the LESS and FMS scores was quite low (FMS 100 point and 21 point $r^2 = .26$ and .23). These results indicate that good performance in one of the screens does not necessarily equate to good performance in the other. This has practical significance as it highlights that the FMS and LESS assess different movement patterns and should not be used as a substitute for one another. It also indicates that improving the scores in one test will not necessarily result in improvements in the other.

The composite 21 point FMS score for this study (15.34 ± 1.79) was similar to other studies involving active sporting males (15.09 ± 2.18 (Lockie et al., 2015b), 16.9 ± 3.0 (Kiesel et al., 2007), and 15.7 ± 1.9 (Schneiders et al., 2011), suggesting that this sample had movement...
patterns typical of other healthy, male cohorts. The mean LESS score (7.37 ± 3.3) was higher than that reported in other studies (4.93 ± 1.67) indicating that the sample in this study had poorer landing mechanics than previously reported in active populations (Beutler et al., 2009; Padua et al., 2009). This was unexpected since cohorts examined in previous studies using LESS have included both male and female participants (Beutler et al., 2009, Padua et al., 2009).

It has been noted that active females generally have significantly worse landing mechanics than their male counterparts (Ford et al., 2005; Nagano et al., 2007; Zazulak et al., 2005), therefore, the fact that the mean of a large group of males would be slightly worse than large groups including both males and females is somewhat unexpected. The differences may be due to the participants in this study being collegiate athletes whereas Padua et al. (2009) examined LESS scores in a military population.

Before discussing reasons for the disparity between the LESS and FMS it may be pertinent to discuss the potential contributing factors for the moderate correlation reported between the LESS scores, the FMS composite score, squat and lunge tests. One potential reason maybe the similarities in mechanics and muscle recruitment between the tests (Caterisano et al., 2002; Distefano et al., 2009). The squat, lunge and LESS tests involve triple extension and flexion of the ankle, knee and hip joints (Cook et al., 2006a; Padua et al., 2009). Good performance in all three tests is categorised by the absence of transverse and frontal plane motion at the hip, knee and trunk (Padua et al., 2009; Cook et al., 2006a; O’Connor et al., 2011). Caterisano et al. (2002) reported that good squat performance involved significantly greater activation of the gluteus maximus than poor squat performance (Caterisano et al., 2002). Some authors have commented that posterior chain development and correct, sequenced muscle activation are essential in developing better jump technique and performance (Hewett et al., 2010; Myer et al., 2011a), thus perhaps those who exhibit coordination limitations and poor activation of the posterior chain muscles in simple squatting and lunging actions also display faults in more
dynamic jump-landing actions (Kiesel et al., 2011; Lisman et al., 2013a). The lack of similarity between the other FMS screens and jump-landing tasks could be a potential reason for the non-significant correlations reported for these other component tests.

As mentioned previously in this discussion the results of this study indicate that good performance in the FMS tests does not necessarily equate to good performance in the LESS (Tables 10, 11 and 12). There are several potential reasons for the low shared variance between the FMS and LESS one of which is the slow, controlled nature of the FMS tests compared to the dynamic nature of the LESS jump test. The FMS does not involve any screen performed at speed (Cook et al., 2006a). Dynamic jump-landing tests, such as the LESS, are performed at a much greater speed and as such involve much greater dynamic control to be performed correctly (Padua et al., 2009). Furthermore, none of the FMS tests involve rapid decelerations that require high levels of eccentric control to be performed correctly (Hewett et al., 2010). The LESS test involves a rapid deceleration when landing from a 0.3m box before accelerating back into a jumping action (Padua et al., 2009). In order to manage the rapid deceleration a large degree of eccentric strength is required (Padua et al., 2009). Poor shock absorption and greater ground reaction force, which are associated with poor eccentric strength, have been linked with poor landing technique and a subsequent greater risk of injury (Noehren et al., 2014; Willson and Davis, 2009; Hewett et al., 2010). Therefore, due to the relatively controlled nature of the individual FMS tests, poor eccentric strength may not be a limiting factor in performing the FMS, thus limiting the ability of the FMS to predict performance in dynamic landing tasks where good eccentric control is of paramount importance (Hewett et al., 2010; Myer et al., 2011b).

4.4.1 Practical implications of research

This study highlights that the FMS and LESS provide different information to each other indicating that performing well on the FMS does not necessarily equate to performing well on
the LESS. From the results of this study it cannot be determined which screen has greater association with injury or if a combination of both provides the best results. Therefore, this study recommends that practitioners use both screens to capture the full range of information with respect to movement ability.

4.5 Conclusion

The results of this study indicate that the two screens do not assess the same movement patterns. Practically, the findings of this study indicate that the FMS, and its component tests, have limited capacity to identify performance in dynamic jump-landing tests in healthy, college males. Therefore, strength and conditioning specialists and health-care providers should not consider these screens to be interchangeable or assessing the same capacities. From the results it cannot be established which screen (FMS or LESS) more accurately identifies the poor mechanics in sport associated with increased chance of injury. Future studies are required to examine both screens against potentially 'gold standard' 3D assessments. It is also recommended that both screens should be used in prospective injury studies to examine whether one screen is more effective at predicting injury risk or if a combination of both identifies injury risk most effectively in active cohorts.
Chapter 5

Study 3: An examination of the relationship between the FMS, LESS and 3D kinematic data during a drop jump task.

- Accepted by Journal of Strength & Conditioning Research 09-05-2019
5.0 Abstract

**Background:** The results from chapter 4 highlight that the FMS and LESS do not measure the same movement variables and should not be used as a substitute for one another. These results cast doubt on previous assumptions that FMS scores provide insights into the dynamic actions undertaken in sport. To clarify the relationship between FMS scores and dynamic actions it is important to examine FMS scores to the ‘gold standard’ assessment of dynamic actions 3D kinematic data. The purpose of this study was to examine the relationship between the LESS and FMS and their association with lower limb 3D kinematics during a drop jump.

**Methods:** Fifty-two male collegiate athletes undertook the LESS, FMS and a drop jump task where the 3D lower limb kinematic variables were assessed. Based on previous injury research, cut-off scores for the LESS (>6) and FMS (≤14) were derived and a series of independent t-tests were undertaken against several 3D lower limb kinematic variables (hip flexion and adduction, knee flexion, valgus and rotation) at initial contact and maximal displacement.

**Results:** Participants with poor LESS scores displayed significantly worse lower limb kinematics compared to their counterparts with good LESS scores. The FMS scores were able to differentiate the group for maximal knee valgus and hip flexion displacement but not for any other hip or knee kinematics or any variable at initial contact. Furthermore, there were only small to moderate effect sizes for maximal displacement knee kinematics between the FMS groups (0.3-0.72) in comparison to large effect sizes between the LESS groups (1.99-2.76).

**Conclusion:** The results indicate that the LESS is a valid tool for identifying potentially high-risk movement patterns during a drop jump. The FMS is limited in its ability to identify participants with poor kinematics during a drop jump. The clinical relevance of these findings is important as they confirm limitations in the ability of the FMS to distinguish between groups for landing biomechanics.
5.1 Introduction

Despite the FMS and LESS differing greatly in the movements assessed and the speed at which these movements are performed, proponents of both screens have hypothesised that good performance in their respective screen relates to participants undertaking dynamic actions with good mechanics (Kiesel et al., 2007; Padua et al., 2009). Kiesel et al. (2007) stated that the FMS tests 'are thought to provide the foundation for more complex athletic movements to be performed efficiently'. Padua et al. (2009) outlined that the LESS was developed to be a viable alternative to 3D analysis of dynamic actions. It is apparent from these statements that there is an assumed link between performance on these screens and the performance of complex athletic actions, such as double leg landing. However, the results of chapter 4 highlight that the FMS and LESS do not provide similar information to each other. The two screens providing different information to each other casts doubt on the possibility that they would both have a strong relationship to dynamic actions undertaken in sport.

Identification of aberrant movement patterns during dynamic actions undertaken in sport with three dimensional (3D) kinematic analysis has long been established as the 'gold standard' in movement analysis (Ford et al., 2005; Hewett et al., 2010; Hewett et al., 2005). The International Olympic Committee has advocated the use of 3D analysis of a drop jump as a gold standard screening assessment in the prevention of ACL injury (Renström et al., 2008). Several prospective and retrospective studies have reported a significant association between 3D kinematic data of dynamic tasks and injury in the lower limb, particularly acute and chronic knee injury (Alentorn-Geli et al., 2009; Ferber et al., 2010; Hewett et al., 2005; Powers, 2010). Comprehensive reviews of the literature examining 3D kinematic data during drop jump landings have highlighted that decreased hip flexion with increased hip adduction, knee valgus and knee internal rotation were significantly associated with lower limb injuries (Hewett et al., 2010; Powers, 2010; Paterno et al., 2010). Conversely, those with larger hip flexion, less hip
adduction, less knee valgus and knee rotation during a drop jump were less likely to sustain injury or re-injury (Delahunt et al., 2015; Hewett et al., 2010; Paterno et al., 2010). Furthermore, neuromuscular training interventions that improved the 3D kinematic landing mechanics outlined above resulted in a significant reduction in injury rates (Myer et al., 2007; Myer et al., 2011a). The preceding research highlights the rationale for why 3D kinematic assessment of a drop jump is considered the ‘gold standard’ assessment of dynamic actions. Therefore, investigating the relationship of the FMS and LESS to a 3D kinematic drop jump will provide clarity on the accuracy of the assumption that good performance in the FMS and the LESS is associated with good mechanics during dynamic tasks (Kiesel et al., 2007; Padua et al., 2009).

With such little empirical evidence available, it is apparent that research is required to establish the association between 3D analysis of a drop jump and the scores of the LESS and FMS. The aim of this study therefore, is to examine the relationship between FMS scores, LESS scores and drop jump 3D kinematic data, namely; hip flexion and adduction, knee flexion, valgus and rotation at initial contact and maximal displacement during the stance phase of the landing section of the drop jump. Examining this relationship will provide coaches, clinicians and participants involved in sport with more detailed information and clarity regarding the value of the FMS and LESS as pre-participation tests. The results will also clarify whether the FMS can be used as a standalone pre-participation screen or whether a more dynamic screen, such as the LESS should be used as an adjunct in order to get a more comprehensive assessment of dynamic movement.

5.2 Methods

5.2.1 Participants

Fifty-two male college-based strength and conditioning students (age= 21 ± 3 years; body mass= 76.17 ± 9.7 kg; height=1.78 ± 5.75 m) actively participating and training in a variety of
sports [Gaelic games (23); soccer (10); boxing/mixed martial arts (4), Olympic weight lifting (7), track and field (8)] at a collegiate level, voluntarily participated in this study. All participants were at least 18 years old and the inclusion and exclusion criteria were identical to that outlined in chapter three and four (Chorba et al., 2010; Lockie et al., 2015).

5.2.2 Procedures

The University of Limerick Ethics review board approved this study in advance of the study commencing. Testing was conducted over two days separated by 48 hours. The first day of testing consisted of the participants either performing; (1) the LESS and FMS or (2) a drop jump assessed using 3D motion analysis. The order of testing was randomly assigned for all participants. Anthropometric data, health questionnaires and pertinent medical history was also recorded on the first day of testing for all participants. The second day required the participants to complete the tests that they did not perform on their first day of testing (LESS / FMS or 3D motion analysis of drop jump). As with all studies in this programme of research, the author of this thesis conducted all FMS and LESS tests in this study.

Conducting and scoring of the FMS and LESS was identical to the description provided in chapters three and chapter four of this thesis.

5.2.3 3D motion analysis of the drop jump

For the drop jump, all participants were given a demonstration of the task and completed 2-5 trials until they were comfortable with the task. The drop jump involved stepping off a 0.3 m box on to a force plate and then jumping up and touching a target suspended over-head. The target was suspended at each participant’s previously recorded maximum drop jump height. Maximum drop jump height was established by recording the maximal jump height of each participant off a 0.3 m box using a Vertec height measure (Gill Athletics Ltd., Illinois, USA) prior to beginning the study. Previous research has outlined that reaching for an overhead target
can help replicate 'competition-like' conditions in the laboratory setting more than the original drop jump due to the external focus during the task (Ford et al., 2003).

A total of 45 reflective markers were placed on each participant. These markers included four rigid four-marker cluster sets placed on both thigh and shank and a trio marker set on the pelvis, heel and forefoot to help define the segments. Kinematic data were recorded during the landing phase of the drop jump task using eight Eagle and four Hawk infrared Motion Analysis Cameras sampling at 500 Hz. Kinematic data were recorded simultaneously using Cortex Software (Motion Analysis Capture, v6.0, Santa Rose, CA, USA). A static pose with all markers was performed to establish the joint centres, body segment coordinate systems and segment lengths after which eight of the medial markers were removed to prevent obstruction of movement during testing.

5.2.4 Data reduction for 3D analysis

The raw marker co-ordinates and ground reaction force data were transferred from the Cortex 6 software (Motion Analysis Corporation, Santa Rosa, CA, USA) to Visual 3D (C-Motion, Rockville, MD, USA). Visual 3D models of the thigh, tibia and foot segments were constructed as cones and the pelvis as a cylinder. The local co-ordinate system and joint centres of these segments were defined from a static trial of each participant.

From previous literature, several retrospective and prospective studies have reported variables that have been strongly associated with injury (Renström et al., 2008; Hewett et al., 2010; Paterno et al., 2010). These high-risk lower limb biomechanics include decreased hip and knee flexion, increased knee valgus, knee internal rotation and hip adduction during the landing phase of a drop jump (Hewett et al., 2010). Therefore, these variables were chosen for analysis in this study.
An embedded right-handed Cartesian coordinate system was defined for the tibia, thigh, and pelvis segments to describe the 3-dimensional position and orientation of these segments. Euler angles were used to calculate the knee joint angle between the tibia and thigh, and the hip joint angle between the thigh and pelvis in an order of rotations of (1) flexion-extension about the y-axis, (2) varus-valgus knee or adduction-abduction hip about the x-axis, and (3) internal-external rotation about the z-axis.

All kinematic data were filtered using a low-pass Butterworth filter with a cut-off frequency of 12 Hz, similar to other trials using a drop jump (Padua et al., 2009; Hewett et al., 2005). 3D peak knee and hip joint angles were determined at initial contact and during the stance phase of the jump-landing task. The stance phase was defined as the period between initial ground contact with the force plate until take-off for the rebound jump (Padua et al., 2009). Initial ground contact was the instant when vertical ground-reaction force exceeded 10 N as the participant landed on the force plate from the 0.3 m high platform (Padua et al., 2009). Take-off was identified as the instant when vertical ground-reaction force dropped below 10 N after initial contact (Padua et al., 2009).

5.2.5 Data Analysis
SPSS Version 24 (SPSS Inc., Chicago, IL, USA) was used for all statistical analysis. Data were analysed using descriptive statistics. LESS scores were reported as mean ±SD with 95% confidence intervals and FMS scores as median (minimum-maximum). The FMS and LESS scores were correlated separately against the key 3D kinematic variables of interest (hip and knee flexion, knee valgus, internal rotation at the knee & hip adduction) using Spearman's correlations. The correlation coefficient strength (rho) was interpreted as described by Hopkins et al. (2009) where a rho value between 0 to .3 was small, .31 to .49 moderate, .5 to .69 as large, .7 to .89 very large and .9 to 1 considered near perfect for predicting relationships (Hopkins et al., 2009). Differences between all 3D kinematic variables for acceptable and poor scoring
FMS and LESS groups were also illustrated using boxplots (Tableau inc, Washington, USA) in Figures 8, 9 and 10.

As highlighted in the introduction, movement screening is utilised to identify gross limitations in movement patterns (Cook et al., 2006). For the FMS and LESS, several studies have reported an association with injury at specific cut-off scores that highlight gross differences between acceptable and poor scores (Padua et al., 2015; Kiesel et al., 2007; Lisman et al., 2013). Therefore, in addition to examining the correlation between FMS scores, LESS scores and 3D kinematic variables, this study also conducted a series of independent t-tests against the key kinematic variables identified and acceptable and poor FMS and LESS groups. For the FMS, two groups were derived, a score of ≤14 and >14 group and a group containing individuals who scored a 1 on any individual test. For the LESS scores, the group was divided into poor (≥6) and acceptable (≤5) as derived from previous injury research of chapter 5 and previous injury research using the LESS (Padua et al., 2015).

5.3 Results

The overall mean scores for LESS was 7.42 ± 3.9 and median score for the FMS was 14 (11-19). The mean LESS score in the poor group was 9.54 ±2.2 and in the acceptable group was 2.2 ±2.1. In the FMS, the ≤14 group median score was 13 and the >14 score was 16. The key kinematic variables in all three planes at initial contact and for maximal displacement are outlined in Tables 17 and 18. Spearman's correlation data is presented in Table 19.

With the exception of knee flexion, there were significant differences between the LESS groups (acceptable vs. poor scores) for all key kinematic variables at the initial contact and the maximum angles achieved during the stance phase of the drop jump. There were no significant differences between FMS groups at initial contact for any kinematic variable but there were significant differences between the group for maximum knee valgus and hip flexion with no
significant differences for the other variables (Table 17) (Figure 8, 9 and 10). The poor scoring LESS and FMS groups had greater knee valgus and decreased hip flexion compared to the acceptable scoring groups (Tables 17 and 18) (Figure 8, 9 and 10). Those who scored a 1 on the overhead squat had significantly different hip flexion angles during the drop jump. There were no other significant differences between those with scores of 1 on any FMS sub-tests for any of the kinematic variables assessed.
Table 14- Lower limb kinematics at initial contact for LESS and FMS score

<table>
<thead>
<tr>
<th>Joint angle (°)</th>
<th>Acceptable LESS (15)</th>
<th>At risk LESS (≥6) (37)</th>
<th>&gt;14 FMS (31)</th>
<th>≤ 14 FMS (21)</th>
<th>P-Value</th>
<th>Cohen-d Effect Size</th>
<th>P-Value</th>
<th>Cohen-d Effect Size</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean ±SD</td>
<td>95% C.I</td>
<td>Mean ±SD</td>
<td>95% C.I</td>
<td>P-Value</td>
<td>Effect Size</td>
<td>Mean ±SD</td>
<td>95% C.I</td>
</tr>
<tr>
<td>Hip Flexion (°)</td>
<td>28 ±6</td>
<td>24-31</td>
<td>20 ±8</td>
<td>17-22</td>
<td>.007</td>
<td>0.64</td>
<td>24 ±8</td>
<td>21-27</td>
</tr>
<tr>
<td>Hip Adduction(°)</td>
<td>2 ±8</td>
<td>-2-6</td>
<td>-4±7</td>
<td>-6--2</td>
<td>.001</td>
<td>0.83</td>
<td>-2 ±8</td>
<td>-5-0</td>
</tr>
<tr>
<td>Knee Flexion(°)</td>
<td>23 ±9</td>
<td>27-18</td>
<td>17±10</td>
<td>21-14</td>
<td>.085</td>
<td>0.55</td>
<td>19 ±9</td>
<td>23-16</td>
</tr>
<tr>
<td>Knee Valgus(°)</td>
<td>4 ±3</td>
<td>2-6</td>
<td>-2±6</td>
<td>-5--1</td>
<td>.001</td>
<td>1.43</td>
<td>0 ± 6</td>
<td>-2-2</td>
</tr>
<tr>
<td>Knee Rotation(°)</td>
<td>2±3</td>
<td>1-4</td>
<td>-4±5</td>
<td>-6--2</td>
<td>.001</td>
<td>1.59</td>
<td>-1±5</td>
<td>-4-1</td>
</tr>
</tbody>
</table>
Table 15- Lower limb kinematics during the stance phase for LESS and FMS scores

<table>
<thead>
<tr>
<th>Joint angle (°)</th>
<th>Acceptable LESS (15)</th>
<th>At risk LESS (≥6) (37)</th>
<th>&gt;14 FMS (31)</th>
<th>≤14 FMS (21)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean ±SD</td>
<td>Mean ±SD</td>
<td>Mean ±SD</td>
<td>Mean ±SD</td>
</tr>
<tr>
<td></td>
<td>95% C.I</td>
<td>95% C.I</td>
<td>95% C.I</td>
<td>95% C.I</td>
</tr>
<tr>
<td></td>
<td>P-Value Cohen-d Effect Size</td>
<td>P-Value Cohen-d Effect Size</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hip Flexion (°)</td>
<td>54 ±17</td>
<td>46-63</td>
<td>42 ±13</td>
<td>38-46</td>
</tr>
<tr>
<td></td>
<td>.007</td>
<td>0.81</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hip Adduction(°)</td>
<td>2 ±11</td>
<td>-3.9</td>
<td>-4 ±8</td>
<td>-7--1</td>
</tr>
<tr>
<td></td>
<td>.018</td>
<td>0.7</td>
<td>-2 ±9</td>
<td>-5 -1</td>
</tr>
<tr>
<td>Knee Flexion(°)</td>
<td>64 ±33</td>
<td>45-77</td>
<td>48 ±44</td>
<td>32-61</td>
</tr>
<tr>
<td></td>
<td>.227</td>
<td>0.39</td>
<td>52 ±47</td>
<td>36-68</td>
</tr>
<tr>
<td>Knee Valgus(°)</td>
<td>5 ±7</td>
<td>-1.9</td>
<td>-9 ±7</td>
<td>-10-6</td>
</tr>
<tr>
<td></td>
<td>.001</td>
<td>1.99</td>
<td>-2 ±10</td>
<td>-6 -1</td>
</tr>
<tr>
<td>Knee Rotation(°)</td>
<td>5 ±5</td>
<td>3-7</td>
<td>-14 ±8</td>
<td>-17-12</td>
</tr>
<tr>
<td></td>
<td>.001</td>
<td>2.96</td>
<td>-7 ±13</td>
<td>-12-2</td>
</tr>
</tbody>
</table>

Effect Size calculated using Cohen’s d.
Table 19- Correlations between LESS, FMS and Kinematic Variables.

<table>
<thead>
<tr>
<th></th>
<th>Initial Contact</th>
<th>Maximum Displacement</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Hip Flex</td>
<td>Hip Add</td>
</tr>
<tr>
<td>LESS</td>
<td>-.5''</td>
<td>-.28'</td>
</tr>
<tr>
<td>FMS</td>
<td>.25'</td>
<td>-.09</td>
</tr>
</tbody>
</table>

*=Significant to .05; **=significant to .001
Figure 7- Hip flexion and knee flexion at initial contact and maximal displacement
Figure 8- Hip Adduction, knee valgus and knee rotation angles at initial contact (IC)
Figure 9- Hip Adduction, knee valgus and knee rotation angles at maximal displacement during stance phase
5.4 Discussion

The results demonstrated that good LESS scores were associated with larger hip flexion, less knee valgus and knee internal rotation than their poor scoring counterparts at initial contact and maximal displacement. All of these variables have been strongly associated with injury in previous research (Hewett et al., 2005; Ferber et al., 2010; Powers, 2010). In contrast, FMS scores were only able to differentiate maximal displacement angles for knee valgus and hip flexion. Furthermore, there was an approximate 14° degree mean difference and a 19° degree mean difference in knee valgus and knee rotation respectively between the acceptable and poor LESS groups, whereas this difference was only four and six degrees respectively between good and poor FMS scores for these variables. These differences in mean angles constituted a large effect size for all the biomechanical variables at the knee for the LESS test and only small to moderate effect sizes for these variables for the FMS.

There are two possible reasons why the acceptable LESS group would display significantly more hip flexion and less hip adduction, knee valgus and internal rotation. Firstly, the LESS is a modified drop jump making it nearly identical to a traditional drop jump (Padua et al., 2009). Secondly, the scoring criteria of the LESS provides qualitative visual assessment of positional data making it fundamentally based on joint kinematics (Padua et al., 2009). Therefore, due to the near identical action performed and the same criteria used to determine good and poor performance, the results confirm the validity of the qualitative estimates of the LESS test. The results of this study support the results of previous studies indicating that the LESS test has a strong association with hip flexion, knee valgus and knee rotation during a drop jump as assessed by 3D kinematic analysis (Padua et al., 2009).

The limited ability of the FMS to differentiate between knee valgus, knee internal rotation and hip adduction is not surprising given the lack of a dynamic test and the varied nature of the
seven FMS tests (Cook et al., 2006). Only three of the seven FMS tests (squat, lunge and hurdle) assess similar joint angles and scoring criteria of the drop jump whereas the other FMS tests are more simple assessments of core stability and upper and lower body mobility. Furthermore, the squat, lunge and hurdle are performed at a much slower speed than the drop jump (Cook et al., 2006). Therefore, the differences in the type of tests examined and the speed at which the tests are conducted may account for the limited ability of the FMS to differentiate 3D jump landing mechanics.

5.4.1 Practical implications of research

The clinical relevance and practical implications of these findings are important as they confirm limitations in the ability of the FMS to distinguish between groups for landing biomechanics in the transverse plane and for all kinematic variables at initial contact. The findings cast doubt on assumptions from previous research related to the FMS, which speculated that poor FMS performance would have a strong association with lower limb mechanics during more dynamic actions (Lisman et al., 2013; Kiesel et al., 2007). Therefore, this study recommends that practitioners should not use the FMS independently when assessing movement but also use a dynamic screen such as the LESS in order to get greater insights into the dynamic landing ability of their clients.

The results from this study also provide a potential rationale for the low sensitivity reported with FMS scores in several FMS injury studies (Moran et al., 2017; Lisman et al., 2013; Bushman et al., 2016). Several studies have reported low sensitivity with FMS scores (Moran et al., 2017; Lisman et al., 2013; Bushman et al., 2016), indicating that scoring highly on the FMS does not necessarily equate to a reduced likelihood of injury (Hopkins, 2008). The findings of this study support the assumption that the sensitivity of the FMS may be poor due
to FMS scores not identifying those with aberrant movements, such as knee valgus and rotation during dynamic actions integral in training and sport.

**5.5 Conclusion**

The results of this study highlight that there were significant differences in hip flexion, hip adduction, knee valgus and knee rotation between acceptable and poor LESS groups at initial contact and maximal displacement. Apart from maximal hip flexion and knee valgus, there were non-significant differences for all kinematic variables between acceptable and poor FMS groups. These results highlight a limited ability of FMS scores to identify mechanics associated with increased chance of injury during a drop jump compared to LESS scores. The limited relationship of FMS scores to 3D kinematics of a drop jump highlights a potential reason for the low sensitivity reported with FMS scores in several studies. The practical implications for practitioners from this study is that is highlights limitation in using the FMS as a standalone pre-participation movement screen due to its inability to distinguish those with good mechanics during a drop jump at initial contact and at maximal displacement. This programme of research recommends that practitioners using the FMS also use a more dynamic test, such as the LESS to get a more comprehensive assessment of dynamic movement.
Chapter 6

**Study 4:** An examination of the ability of the Functional Movement Screen and Landing Error Scoring System to predict injury in Military recruits.

- *Journal of Science and Medicine in Sport, 2018: 21(6); 569-573.*
6.0 Abstract

**Background:** The purpose of this study was to investigate the association of injury with the FMS and LESS in the same cohort.

**Methods:** One hundred and thirty-two entry-level male soldiers (18-25 years) were tested using the FMS and LESS. The participants underwent an intensive 16-week training program with injury data recorded daily. Chi-squared statistics were used to examine associations between injury risk and (1) poor LESS scores, (2) any score of 1 on the FMS and (3) composite FMS score of ≤14.

**Results:** A composite FMS score of ≤ 14 was not a significant predictor of injury. LESS scores of > 5 and having a score of 1 on any FMS test were significantly associated with injury. LESS scores had greater relative risk, sensitivity and specificity (2.2 (95% CI= 1.48-3.34); 73% and 87% respectively) compared to scores of 1 on the FMS (relative risk = 1.32 (95% CI= 1.0-1.7); sensitivity =50% and specificity = 76%).

**Conclusions:** There was no association between composite FMS score and injury but LESS scores and scores of 1 in the FMS test were significantly associated with injury in varying degrees. LESS scores had a better association with injury than both any scores of 1 on the FMS and a combination of LESS scores and scores of 1 on the FMS. Furthermore, the LESS provides comparable information related to injury risk as other well-established markers associated with injury such as age, muscular strength and previous injury.
6.1 Introduction

Musculoskeletal (MSK) injuries are among the leading causes of morbidity in sport and military settings (O’Connor et al., 2011; Teyhen et al., 2014; Cohen et al., 2010). The impact of MSK injury ranges from limiting training to complete withdrawal from military service and sports participation (Cohen et al., 2010; Teyhen et al., 2014). As outlined in previous chapters, movement screens, such as the FMS and LESS were developed to address the negative and costly consequences associated with MSK injury (Teyhen et al., 2014; McCall et al., 2015).

While the reliability of the FMS has been established (Kraus et al., 2014), there are conflicting reports about its association with injury (Kraus et al., 2014; Bushman et al., 2016; Moran et al., 2016). Several studies have reported that a composite score of ≤14 is associated with an increased risk of injury (Moran et al., 2017; Kiesel et al., 2007; Kraus et al., 2014; Shojaedin et al., 2014) however, more recent studies have reported no relationship between the composite FMS score and injury risk (Mokha et al., 2016; Warren et al., 2015; Rusling et al., 2015). Secondly, some of the studies reporting a relationship between composite FMS score and injury risk have reported low sensitivity, indicating that the FMS may not detect individuals who are still at risk of injury (Kiesel et al., 2007; O’Connor et al., 2011; Shojaedin et al., 2014).

Given the potential limitations of FMS as an injury prediction tool, practitioners have started to include more dynamic screens, such as the LESS in their pre-participation screening (Padua et al., 2009). The more dynamic nature of the LESS compared to the FMS may mimic more closely the dynamic nature of sport and activity, thus providing more insight into injury risk (Padua et al., 2009). The results of chapter 5 confirm limitations in the ability of the FMS to identify those who will poorly during a dynamic drop jump assessed with 3D kinematics. However, despite the rationale for the use of the LESS as an injury prediction tool, there are limited and conflicting results concerning the ability of the LESS to directly predict injury (Padua et al., 2015; Smith et al., 2012). Two studies have reported conflicting results related to
the association of LESS scores with ACL injury with Padua et al. (2015) reporting that LESS scores are associated with increased risk of ACL injury whereas Smith et al. (2012) reported no such relationship. Furthermore, no study to date has examined the association of LESS scores to overall injury risk. There is an apparent lack of research examining the use of the LESS as an injury prediction tool. Additionally, there is a lack of any prospective or retrospective injury studies examining the association of the FMS and LESS in the same cohort. The results from chapter four highlighted that the FMS and LESS have low shared variance, indicating that performing well in one screen does not necessarily equate to performing well in the other. Both screens were designed to identify those who move poorly and are predisposed to injury. However, it is unclear whether those who perform poorly in the LESS or those who perform poorly with the FMS would have a greater association with injury in the same cohort. Therefore, the aim of this study was to examine whether the FMS, LESS or a combination of both could predict injury in a group of military recruits undertaking a well-controlled, 16-week military training program.

6.2 Methods

6.2.1 Participants

One hundred and thirty two male entry-level military recruits (age = 22.4 ±4.2 years; height = 1.77 ±0.35 m; mass = 74.5 ±5.8 kg) voluntarily participated in this study. Participants were recruited from a convenience sample undergoing introductory fitness training in the Irish Army. All participants were provided an information sheet about the study, informed that participation was voluntary and that refusing to participate would in no way influence their training (Appendix 5). Participants were excluded from the study if they had a current injury, medical condition or recent surgery that would compromise their ability to perform the tests or participate in the 16-week military training program.
The University of Limerick Research Ethics Committee and Institutional Review Boards of the National Defence Forces approved all the procedures undertaken in this project. All participants were fully briefed about the study and provided written informed consent before testing.

6.2.2 Procedures

The procedures related to preparation of participants, the testing and scoring of the FMS and LESS were identical to the procedures described in Chapters three and four and are therefore not repeated here.

6.2.3 Training intervention and recording of injury data

The training environment was well controlled. Participants remained on base for the 16 week period with similar schedule (meal and sleep times) and training loads. Furthermore, participants were not involved in any other activity or sport during the 16 week period. However, it must be noted that while meals were similar, how much participants chose to eat or additional eating (snacks etc.) were individual and therefore, there was most likely discrepancies between participants. Similarly, the quality and quantity of sleep for each participant was not recorded and so likely varied also.

There were 599.25 overall training hours with 85 formal physical training hours comprising of resistance training, aerobic exercise (primarily running), battle runs (with military gear), swimming and organized recreational training. Other training comprised of orientation, weapons training, drills, guard duties, first responder courses, unarmed combat courses and tactical training.

Injury data were collected daily during the 16 week training program at the medical facility in the military base. Medical care providers trained in physiotherapy, independent of the study, assessed participants for MSK injury and recorded injuries manually using a specialised form.
For this study, injury was defined similar to Fuller et al. (2006) and O’Connor et al. (2011) as physical damage to the body which was secondary to physical training and required medical care one or more times during the study period and resulted in at least one day of missed training.

6.2.4 Statistical Analysis

All data were analysed using SPSS Statistical Software (SPSS Version 22, SPSS Inc., Chicago, IL, USA). Descriptive statistics were analysed for LESS and FMS results. LESS scores were reported as mean ±SD as well as 95% confidence intervals and FMS scores as median (minimum-maximum). To examine the relationship between potential risk factors and injury, discrete and continuous variables were converted into dichotomous variables (Mokha et al., 2016). For the FMS, a ‘yes’ was assigned for any individual with a score of 1 in the FMS and ‘no’ for the participants who did not have a score of 1. The composite score of 14 was also dichotomised using 14 as a cut point (>14 vs. <14). Using a cut-off score of >5, as determined by a receiver operating characteristics (ROC) curve analysis, LESS scores were dichotomised into acceptable and poor (Padua et al., 2015). Chi squared ($\chi^2$) statistics were used to examine any potential associations between (1) injury risk and poor LESS scores; (2) injury risk and a score of 1 on the FMS and (3) injury risk and a composite FMS score of ≤14. Injury was the dependent variable for each analysis. Finally, ROC curves were utilised to determine the optimal cut-point for both composite LESS and FMS scores in predicting MSK injury.

6.3 Results

The median FMS score was 15 (range=11-20) and the mean LESS score was 4.76 (± 2.71). 28 injuries were sustained during the 16-week training program. A summary of all injuries sustained and the severity of each injury is presented in Table 14.
Table 17- Details of injuries sustained during the 16 week military training

<table>
<thead>
<tr>
<th>Factors</th>
<th>Classification</th>
<th>Frequency</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injury Location</td>
<td>Knee</td>
<td>13</td>
<td>46%</td>
</tr>
<tr>
<td></td>
<td>Lower Limb muscle tear</td>
<td>5</td>
<td>18%</td>
</tr>
<tr>
<td></td>
<td>Ankle</td>
<td>4</td>
<td>14%</td>
</tr>
<tr>
<td></td>
<td>Back</td>
<td>4</td>
<td>14%</td>
</tr>
<tr>
<td></td>
<td>Shoulder</td>
<td>2</td>
<td>8%</td>
</tr>
<tr>
<td>Type of injury</td>
<td>Muscle tear</td>
<td>9</td>
<td>32%</td>
</tr>
<tr>
<td></td>
<td>Muscle Spasm</td>
<td>7</td>
<td>25%</td>
</tr>
<tr>
<td></td>
<td>Ligament</td>
<td>3</td>
<td>11%</td>
</tr>
<tr>
<td></td>
<td>Tendon</td>
<td>9</td>
<td>32%</td>
</tr>
<tr>
<td>Onset</td>
<td>Immediate</td>
<td>21</td>
<td>75%</td>
</tr>
<tr>
<td></td>
<td>Delayed</td>
<td>7</td>
<td>25%</td>
</tr>
<tr>
<td>Causative Factors</td>
<td>Non Contact</td>
<td>27</td>
<td>96%</td>
</tr>
<tr>
<td></td>
<td>Contact</td>
<td>1</td>
<td>4%</td>
</tr>
<tr>
<td>Severity</td>
<td>Mild (1-7 days)</td>
<td>16</td>
<td>57%</td>
</tr>
<tr>
<td></td>
<td>Moderate (7-21 days)</td>
<td>9</td>
<td>33%</td>
</tr>
<tr>
<td></td>
<td>Severe (Surgery or discharge)</td>
<td>3</td>
<td>10%</td>
</tr>
<tr>
<td>Mechanism</td>
<td>Acute</td>
<td>13</td>
<td>44%</td>
</tr>
<tr>
<td></td>
<td>Chronic</td>
<td>15</td>
<td>56%</td>
</tr>
</tbody>
</table>

The main findings were that total FMS scores of ≤14 were not associated with an increased chance of injury ($\chi^2 = .40; p = .52$). However, scores of 1 in the FMS and poor LESS scores were associated with a significant likelihood of injury ($\chi^2 = 7.14; p < .01; \chi^2 = 17.64; p <.01$). Using the contingency values outlined in Table 15, sensitivity and specificity were calculated at 73% and 87% respectively for LESS scores with a relative risk of 2.2 (95% CI = 1.48 to
3.34). For scores of 1 on the FMS, the sensitivity and specificity were 50% and 76% respectively with a relative risk of 1.32 (95% CI= 1.0 to 1.7, Table 15). Classifying participants with poor LESS scores and a score of 1 on the FMS did not increase the predictability of injury (Table 15).

Finally, the ROC curve analysis results for the FMS and LESS composite scores are shown in Figure 7. The ROC curves for FMS scores were not significant (area under the curve = .433) but the LESS had a significant ROC curve (area under the curve = .761) with a maximised specificity cut-point score of 5.5 and sensitivity and specificity values of 73% and 75% respectively (Figure 8).
Table 18- FMS and LESS scores and Injury statistics associated with military training.

<table>
<thead>
<tr>
<th></th>
<th>Injury (Total)</th>
<th>Chi Squared</th>
<th>Odds Ratio (95% CI)</th>
<th>Relative Risk (95% CI)</th>
<th>Sensitivity</th>
<th>Specificity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scores of 1 on FMS</td>
<td>14 (39)</td>
<td>7.14</td>
<td>3.16 (1.32-7.5)</td>
<td>1.32 (1.0-1.7)</td>
<td>50%</td>
<td>76%</td>
</tr>
<tr>
<td>No Scores of 1 on FMS</td>
<td>14 (93)</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Poor LESS</td>
<td>14 (34)</td>
<td>38.75</td>
<td>16.07 (5.94-43.45)</td>
<td>2.2 (1.48-3.34)</td>
<td>73%</td>
<td>87%</td>
</tr>
<tr>
<td>Acceptable LESS</td>
<td>9 (98)</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Poor LESS and Score of 1</td>
<td>11 (19)</td>
<td>17.87</td>
<td>7.76 (2.7-22.11)</td>
<td>2.01 (1.18-3.4)</td>
<td>57%</td>
<td>85%</td>
</tr>
<tr>
<td>Scores of ≤14</td>
<td>10 (42)</td>
<td>NS</td>
<td>1.25 (0.52-3.0)</td>
<td>1.05 (0.86-1.2)</td>
<td>23%</td>
<td>77%</td>
</tr>
</tbody>
</table>

CI=Confidence intervals; NS=Not Significant; NA=Not Applicable
Table 19- Location and Severity of Injury in relation to FMS and LESS scores

<table>
<thead>
<tr>
<th>Variable</th>
<th>No Injury (Total participants)</th>
<th>Location of Injury</th>
<th>Severity of Injury</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Ankle (TI)</td>
<td>Knee (TI)</td>
</tr>
<tr>
<td>FMS</td>
<td>24 (39)</td>
<td>0 (4)</td>
<td>9 (13)</td>
</tr>
<tr>
<td>Poor</td>
<td>14 (34)</td>
<td>3 (4)</td>
<td>10 (13)</td>
</tr>
<tr>
<td>LESS (&gt;5)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Poor</td>
<td>8 (19)</td>
<td>0 (4)</td>
<td>7 (13)</td>
</tr>
</tbody>
</table>

TI= Total Injury number
Figure 10- ROC Curves for LESS and FMS scores.
6.4 Discussion

The main findings of this study were that composite FMS score was not significantly associated with injury but a poor LESS score (\(> 5\)) and having a score of 1 on any FMS test were associated with injury in a military cohort undergoing an intensive, 16 week military training program (Table 15). Poor LESS scores had a much greater association with injury than either scores of 1 on any FMS test or scores of 1 and LESS scores combined (Table 15). Furthermore, the specificity and sensitivity figures for the LESS test were also high compared to other established markers associated with injury such as age, previous injury and aberrant movement patterns (Hägglund et al., 2013), indicating that the LESS provides similar information to other well established markers associated with injury.

Due to the relatively small number of injuries, it was considered inappropriate to perform statistical analysis examining the relationship between the LESS, FMS and the severity and location of injury (Table 16) (Hopkins et al., 2009). However, as outlined in Table 16, the LESS had the greatest association with lower limb injuries. Of the 34 participants who scored poorly on the LESS, 10 (29%) sustained an injury to the knee, three sustained an ankle injury and four had lower limb injuries. In contrast, only 3% of the 98 participants with acceptable LESS scores (\(\leq 5\)) sustained a knee injury and there was only one ankle and lower limb injury in this group. Furthermore, poor LESS scores identified all three (100%) of the severe injuries (injury serious enough to jeopardise completion of training program), 56% (five out of nine) of the moderate injuries (injury requiring at least seven days rest and substantial medical treatment) and 12 out of 16 (75%) of the mild injuries (injury resolving within 7 days and little medical intervention required) sustained in this cohort. In contrast, any score of one on the FMS or combining FMS and LESS scores did not have as strong an association with injury, in particular, scores of one on the FMS were only associated with only one of the three severe injuries and three of the nine moderate injuries sustained in this cohort (Table 16).
The finding that composite FMS score or scores of ≥14 were not associated with injury contradicts previous research in sports (Kiesel et al., 2007; Shojaedin et al., 2014) and military settings (O’Connor et al., 2011). However, this finding is supported by three recent studies that have reported no relationship between composite score and injury risk (Bushman et al., 2016; Mokha et al., 2016; Rusling et al., 2015). There are several reasons for the lack of association between composite FMS score and injury risk. First, the creators of the FMS have stated that composite FMS score was never intended as a means of predicting injury, but rather it was intended to identify severe limitations (i.e. scores of one) in certain movement patterns (Cook et al., 2006b). This theoretical framework is supported by two studies that have undertaken factorial analyses of the seven FMS test components and reported poor internal consistency between the tests (Kazman et al., 2014; Li et al., 2014). This indicates that the seven individual tests measure different variables, making it statistically inappropriate to add the scores of these tests together (Kazman et al., 2014).

While composite FMS scores were not associated with injury, individuals with a score of one on the FMS tests were 1.3 times more likely to sustain injury than those without a score of one (relative risk = 1.32; 95% CI= 1.0-1.7). The rationale for scores of one on the FMS being associated with injury is clear. The FMS was designed to assess basic movement patterns required for training and daily living (Kiesel et al., 2007; Cook et al., 2006a) and scores of one indicate that an individual cannot complete or has severe limitations in one of these basic patterns (Cook et al., 2006a). The results of this study support this underlying premise that severe limitations in one or more of these basic patterns predispose individuals to injury during intensive training (Table 15). Caution is required when interpreting these results however, as a sensitivity score of only 50% needs consideration. The relatively poor sensitivity in this study supports previous research highlighting that the FMS is much better at including individuals with potential injury risk than excluding those who may have less chance of injury (Dorrel et al., 2015; O’Connor et al., 2011).
In contrast to composite FMS score, poor LESS scores of >5 were associated with over a two-fold increased likelihood of injury. In addition, good sensitivity (73%) and excellent specificity (87%) related to the LESS score indicate that the LESS is a good screening tool to identify both those who have increased and decreased risk of injury when undergoing military training. To our knowledge, this is the first study to examine the relationship between overall injury risk and LESS scores. Unsurprisingly, given it was originally designed to detect ACL risk, poor LESS scores had a strong association with knee injuries. In addition, LESS scores also had a strong relationship with total lower limb injuries sustained. Seventeen of the 22 (77%) lower limb injuries sustained in the entire cohort were with participants with poor LESS scores (>5). In contrast, from our results, there does not appear to be a strong association between either upper limb or back injuries and poor LESS scores (Table 16).

The results of this study clearly indicated that the LESS had a greater association with injury than the FMS and had a very strong association with lower limb injuries. The reason for this greater association may be due to the more dynamic nature of the LESS test (Padua et al., 2009). In chapter four a possible explanation for the poor shared variance between the LESS and FMS was that the LESS requires much more eccentric strength and dynamic control to ensure satisfactory performance (Bishop et al., 2015). Several studies have argued that the low sensitivity associated with the FMS arises because it does not challenge the eccentric strength and dynamic control required during intensive training or competition (Bishop et al., 2015; Bushman et al., 2016; Dorrel et al., 2015). Individuals who lack these forms of strength and control may place their joints and muscles in compromised positions that are linked with the mechanisms of acute and chronic injuries (Delahunt et al., 2006; Hewett et al., 2010). Therefore, the increased eccentric strength and dynamic control required of the LESS may explain why this test has a better association with injury than the FMS (Table 15).
Additionally, the results of chapter five highlighted that LESS scores have a greater association to the 3D kinematic variables associated with injury compared to FMS scores. Several studies utilizing similar 3D kinematic and kinetic procedures have reported relationships between these faults and various other lower limb injuries such as ankle ligament sprains, chronic knee injuries and hip impingement (Delahunt et al., 2006; Ferber et al., 2010). Therefore, the fact that the LESS scores had a strong association with 3D kinematics compared to the FMS may underlie its superiority as an injury prediction tool compared to the FMS.

6.4.1 Practical implications of research

This study highlights that practitioners should not use a composite FMS score as an injury prediction tool but rather use scores of 1 to guide who has greater susceptibility to injury. Second, coaches and health care practitioners should not use the FMS as an independent assessment of movement due to the low sensitivity associated with the FMS. Instead when using the FMS practitioners should also use the LESS to examine more dynamic movements and combat the sensitivity issues associated with the FMS.

6.5 Conclusion

The results of this study do not advocate the use of composite FMS score as an injury prediction tool but did find that LESS scores and scores of one on an FMS test were significantly associated with injury. The LESS screen had a better association with injury than both scores of 1 on the FMS and a combination of LESS scores and scores of one on the FMS. Furthermore, the LESS provides comparable information related to injury risk as other well-established markers associated with injury (i.e. age, muscular strength, previous injury) (Hägglund et al., 2013; Hewett et al., 2010). The results of this study provide clarity to the relationship of injury with both the FMS and LESS in the same cohort. For practitioners, the results highlight limitations in using the FMS as an independent measure of movement. This programme of
research recommends using the LESS in addition with the FMS in order to address limitations with the sensitivity of the FMS.
Chapter 7

Discussion
7.0 Introduction

The relevant discussion for each study has been included in the individual study chapters and therefore, this chapter does not revisit these considerations. This general discussion instead examines how the key overall findings of the thesis link together and how the findings contribute new knowledge to the literature. This chapter then provides practical recommendations based on the findings in this thesis and addresses the key method-related issues associated with this programme of research before concluding with the limitations of each study and providing recommendations for future research.

7.1 Contributions to knowledge

The aim of this programme of research was to examine the relationship between the FMS, LESS and their association with injury and 3D lower limb kinematics during a drop jump. A large proportion of the findings of this programme of research were previously unknown or had been speculative in nature, thus the results of this research contributes novel insight into the role of two of the most common field-based screens currently used in the practical setting. These novel insights relate to the reliability of the FMS and LESS, the relationship of the FMS and LESS to each other, their association with injury and finally the relationship between FMS and LESS scores and 3D kinematic variables during a dynamic drop jump. All of these novel insights are described below.

7.1.1 Reliability of FMS and LESS

Chapter three provided several novel insights into the reliability of the FMS and LESS that were previously not examined in the literature. The reliability of the LESS had never been examined by anyone not involved in the development of the screen (Padua et al., 2009; Onate et al., 2010). Furthermore, there was a lack of empirical evidence examining the reliability of the individual scoring criteria of the LESS. Examining the final score of the LESS with raters who founded the screen may lead to an inherent bias to over-estimate the reliability of the LESS.
The reliability reported in previous LESS reliability studies therefore may not accurately represent the reliability of the typical practitioner who scores the LESS (Padua et al., 2009; Onate et al., 2010). In addition, reporting only the reliability of the final score does not account for scoring individual criteria differently but arriving at the same final score by chance. The results of chapter three, which reported moderate to excellent inter- and intra-rater reliability for the total score and the individual scoring criteria of the LESS, was an important finding as it established credibility in the reliability of the LESS for raters who only use the standardised instructions and scoring sheets. This provides a more accurate estimation of reliability compared to the previous LESS reliability studies involving the founders of the screen.

The reliability of the 21 point FMS scoring system had been established in previous research (Kraus et al., 2014; Bonazza et al., 2016). However, only the inter-rater reliability of the 100 point scoring system had been examined and only with the creators of the 100 point scoring system (Butler et al., 2012). The results from this programme of research demonstrated that the 21 point and 100 point FMS scoring systems had moderate to excellent reliability for the seven sub-tests and for total score. These results indicate that practitioners should be confident using either scoring system.

The acceptable levels of reliability reported in this programme of research for the FMS and LESS concur with previous research reporting moderate to excellent reliability for both screens (Cuchna et al., 2016; Moran et al., 2016; Padua et al., 2009). However, by establishing the reliability of the final score and the components of the FMS (21 point and 100 point) and the individual components of the LESS with raters using the standardised instructions, this programme of research provides greater clarity regarding the reliability of these screens that was previously unknown.

Finally, as outlined in the literature review of this thesis, it is important that researchers using the FMS and LESS establish their reliability with the screens before beginning any research
trials. The results of chapter three demonstrate that the FMS and LESS scores reported would have been similar each time the participants were assessed and that the results provided would have been similar to other experienced testers in the field (Lucas et al., 2013, Gribble et al., 2013).

7.1.2 Relationship between FMS and dynamic actions

There were several assumptions from previous research related to the FMS that were not supported by this research. One main finding of this programme of research was that scoring highly on FMS tests was not strongly associated with mechanics displayed during a drop jump as measured by the LESS test and by 3D kinematics during a drop jump. The FMS had only a moderation correlation and a low shared variance with LESS scores (rho 100 and 21 point FMS scores = -.528; -.487; r²= .26 and .23). Furthermore, scoring highly on the FMS had weak to moderate or non-significant associations with 3D kinematics, such as decreased hip adduction, knee valgus and decreased knee internal rotation during a drop jump. Participants who perform a drop jump with the kinematic variables outlined in the preceding sentence are significantly less likely to sustain acute or chronic lower limb injury compared to those who perform a drop jump with increased knee valgus, knee internal rotation and hip adduction (Hewett et al., 2010; Powers, 2010; McLean et al., 2005). These results indicate that performing well on the FMS does not necessarily equate to displaying better mechanics in dynamic tasks as measured by the LESS and a 3D drop jump. This has practical implications as it highlights that the FMS provides limited information about dynamic movements and thus limits its potential as an independent screening tool. This finding contradicts assumptions from previous research that suggested FMS scores may provide an insight into mechanics displayed on dynamic tasks (Kiesel et al., 2007; Lisman et al., 2013).
7.1.3 Association of LESS and FMS scores to injury.

Movement screening research to date has examined the ability of screens, such as the LESS and FMS to predict injury independently. While this type of research is useful as it informs practitioners whether movement screening is generally worthwhile, it does not help determine which screen is most effective. Prior to the study outlined in chapter five there had been a lack of empirical evidence comparing the association of injury with the LESS and FMS in the same cohort. Without this research it is impossible to know whether a dynamic screen, such as the LESS or a more varied but more controlled screen, such as the FMS provides more information relating to injury risk.

The results of chapter five demonstrated that the LESS screen had a greater association with injury compared to both scores of 1 on the FMS and a combination of LESS scores and scores of 1 on the FMS. Total FMS score was not associated with injury. Furthermore, the sensitivity score of 50% with scores of 1 on the FMS indicated that it is much better at identifying those at increased injury risk but not at identifying those at decreased injury risk. These results demonstrated a limited ability of using the FMS independently to assess injury risk (McCall et al., 2015; Teyhen et al., 2014).

7.2 Practical Recommendations of the research

McCall et al. (2015) reported that 77% of professional elite soccer teams in Europe, Oceania and the United States use the FMS as the principal method of assessing movement quality. A consortium of military medical professionals in the United States has advocated the use of the FMS as an assessment of movement ability in recruits (Teyhen et al., 2014). Therefore, the results of this programme of research also provide practical recommendations regarding the FMS and LESS that should enhance pre-participation testing for those dealing with sport and military populations.
First, this programme of research highlighted that the FMS and LESS are reliable screening protocols with experienced practitioners. However, as discussed in the literature review, reliability of both screens can be dependent on experience level. Those using the FMS and LESS in either a practical or research setting should first undertake a reliability study prior to testing to ensure they have acceptable levels of inter- and intra-rater reliability, especially if they are not certified or experienced with the two movement screens.

This programme of research recommends practitioners do not use FMS cut-off scores to determine who may have increased injury risk but rather practitioners should use scores of 1 on individual FMS sub-tests to help identify those at increased chance of injury. The finding that total FMS score was not significantly associated with injury contradicts early research related to the FMS that recommended cut-off scores of generally $\leq 14$ identify those at increased injury risk (Kiesel et al., 2007; O’Connor et al., 2011; Chorba et al., 2010).

This programme of research also recommends that coaches and health care professionals should not use the FMS as an independent measure of movement quality. The results described in this thesis demonstrate that using the FMS as an independent measure of movement quality will provide limited information on the ability of participants to undertake dynamic movement tasks. The inability of the FMS to identify participants who display 3D kinematics associated with injury during a drop jump, such as increased hip adduction, knee valgus and increased knee internal rotation (Hewett et al., 2010; Myer et al., 2011a; McLean et al., 2005) most likely explains the low sensitivity associated with the FMS reported in this thesis and in other studies (Moran et al., 2017; Kiesel et al., 2007; Letafatkar et al., 2014; Bushman et al., 2016; O’Connor et al., 2011). The LESS most likely had a stronger association to injury compared to the FMS due to its ability to identify participants who display 3D kinematics associated with injury during a drop jump task. A secondary reason for the superior association to injury of the LESS is the increased eccentric strength and dynamic control required to perform the LESS compared
to the FMS. Given the findings presented in this thesis practitioners should incorporate an additional dynamic screen, such as the LESS if using the FMS as their sole assessment of movement ability in order to get a more comprehensive assessment of movement quality and injury risk.

7.3 Method-related considerations- Population selection

This programme of research used an intervention with army recruits and sporting collegiate athletes for several reasons. First, military recruits, professional sporting and collegiate cohorts are the most examined groups assessed with the FMS and LESS in the literature (Teyhen et al., 2014; McCall et al., 2015; Padua et al., 2015). These three groups have been utilised in many validity and reliability studies involving the LESS and FMS (Teyhen et al., 2014; McCall et al., 2015; Padua et al., 2015). Therefore, using young, active individuals in the military, university or sports setting contributes to the extensive literature base related to this field of study. Furthermore, field-based movement screening was initially developed to help individuals involved in sport and active professions remain injury free (Bishop et al., 2015; Cook et al., 2006; McCall et al., 2015; Padua et al., 2009). Therefore, undertaking research with both of these populations helps to validate movement screening in the groups they were intended to be used.

There was a close similarity between army recruits and collegiate athletes recruited for this programme of research. The average age in the study involving army recruits was 22.4 ±4.2 years compared to an average age of 21 ±3.2 years in the study involving a collegiate cohort. Other demographics for the collegiate cohort (height=1.77 ±6.85 m; body mass= 77.27 ±10.4 kg) and the army cohort (height=1.77 ±0.35 m; body mass = 74.5 ±5.8 kg) were also very similar.

Finally, the use of two groups was in the main part due to the availability of participants. The correlation study examining field-based scores to 3D analysis of a drop jump, required
participants to be available during the day, at particular times and on site at the university. Given
the nature of their training, this arrangement was not possible with the military recruits. Therefore, a sporting, collegiate population was chosen for that correlation study. An army cohort was chosen over the collegiate group for the prospective injury association study for several reasons: First, a key limitation of any prospective study is the influence that confounding factors may have on the results reported (Hopkins, 2008). Several confounding factors that may impact on the number of injuries reported in a collegiate cohort are controlled and standardised in the military setting (Hopkins, 2008). Military recruits do not participate in any sports during their recruit training, therefore there is no variety in the training undertaken by participants during the chosen period. In order to achieve sufficient numbers, the collegiate group would have comprised of individuals involved in multiple sports with varying training loads. This confounding factor alone would severely limit the ability to judge association between poor screening scores and injury rates (Hopkins, 2008). In addition to the training being standardised, factors such as living arrangements, managing studies and nightlife activities that may vary considerably for collegiate students were all standardised and uniform for the military recruit cohort chosen. Therefore, due to the similarities between the groups and the much more controlled training and living environment, a military cohort was used in the prospective injury study in this programme of research.

7.4 Limitations

While this thesis helps to clarify several topics related to the LESS and FMS that were previously unknown there are still limitations with this research and future research questions that require further investigation.

One limitation of this thesis is that this it is a programme of research examining associations/correlations. Correlation does not equal causation (Hopkins et al., 2009). Therefore, while this research provides novel insight regarding the relationship between the
FMS, LESS and their associations to injury and 3D kinematics during a drop jump task, it remains unclear whether improving FMS or LESS scores would result in a subsequent reduction of injury or better 3D kinematics displayed a drop jump. Another limitation of this thesis was using only a drop-jump to examine 3D kinematic dynamic actions. While 3D kinematics of a drop jump is widely recognised as a gold standard assessment (Renström et al., 2008) it is only one type of dynamic movement pattern. The LESS is a modified drop jump and while the drop jump conducted for the 3D kinematic analysis involved an overhead distraction to mimic real life conditions both jumps are nearly identical. It is unclear what the relationship of the FMS and LESS would be to other dynamic actions, such as a single leg land or a cutting action.

Another limitation of dynamic movement screens in general is that the mechanics associated with injury can be considerably different than the mechanics required for performance. This programme of research did not examine whether there was a relationship between jump height and good mechanics displayed during the LESS or in the 3D kinematic drop jump. Future research should examine the relationship between LESS scoring criteria and jump performance to further refine this screening protocol and others in the future.

The prospective injury study outlined in chapter five examined military recruits during introductory fitness training. This limits the ability to generalise the results and so it is unclear whether a sporting population would respond similarly. Furthermore, the prospective injury study did not perform further analysis to examine the relationship between FMS or LESS scores and different sub-categories of injury (location, severity, onset etc.) due to the relatively low number of injuries in the cohort.

Finally, this research only selected male participants due to the disparity that can exist between the sexes (Ford et al., 2005; Nagano et al., 2007). Several studies examining dynamic tasks and jump-landing screens have reported significant differences between sexes (Ford et al., 2005; Nagano et al., 2007). Nagano et al. (2007) reported that healthy, sporting females can display
landing mechanics five times worse than their male counterparts (Nagano et al., 2007). Therefore, females were not included in this programme of research to prevent this influencing the results reported.

7.5 Future research

Based on the limitations of this research outlined in the previous section it is apparent that future research is required to fully examine the FMS and LESS. Future intervention studies are required to examine which interventions improve screening scores most effectively and also to investigate whether improving FMS and LESS scores results in a subsequent reduction in injury rates. Answering these questions will add further clarification to the true value of screening protocols in the pre-participation testing setting.

Future studies should also examine the relationship between LESS and FMS scores and other dynamic tasks, such as change of direction drills or single leg landing. Finally large scale studies using males and females are required to examine the FMS and LESS to individual injury sites. Answering these future research questions will further enhance our knowledge about the benefit of the FMS and LESS as pre-participation screening protocols in a wider population.
Chapter 8

Conclusion
The FMS is the most popular field-based movement screen in the research and practical setting (McCall et al., 2015; Moran et al., 2017; Teyhen et al., 2014). Despite its popularity, the literature review of this thesis identified several gaps that needed to be addressed. This programme of research answered several of these gaps and presented a framework for future research to provide further clarity related to value of movement screening.

Despite previous assumptions to the contrary, this programme of research discovered that FMS scores are limited in their ability to predict jump-landing performance. It is inaccurate to suggest that performance on the FMS provides insight into performance of more dynamic actions. This is an important finding as it highlights that the FMS should not be used in isolation due to the lack of information it provides related to dynamic landing, which is an integral part of sport and physical training (Padua et al., 2009; Hewett et al., 2010).

There was conflicting evidence related to the ability of the FMS to predict injury in the literature. The majority of studies examining the association between injury and FMS scores had reported that scoring poorly on the FMS was associated with a significant increased chance of injury. The results of the large, well-controlled prospective injury study in this thesis supports this finding. Despite the consensus regarding low FMS scores, there was debate in the literature about the ability of good FMS scores to identify those at decreased risk of injury rule due to low sensitivity in several FMS injury studies (O'Connor et al., 2011; Moran et al., 2017; Bushman et al., 2016). In addition, there was conflicting evidence about the ability of total FMS scores to predict injury (Mokha et al., 2016). The low sensitivity reported for FMS scores in chapter five are supported by other large prospective injury studies (O'Connor et al., 2011; Bushman et al., 2016).

Unlike previous research that could only speculate as to why the FMS may have low sensitivity, this programme of research was the first to be able to determine a potential rationale for the low sensitivity. The limited relationship of FMS scores to dynamic tasks as outlined in chapter six
provides a rationale for the low sensitivity associated with FMS scores and injury risk. Aberrant movement during dynamic tasks, such as a drop jump has been established as a predictor of lower limb injury (Hewett et al., 2010; Powers, 2010). The inability of the FMS to identify individuals with aberrant movements during dynamic tasks is most likely the reason for the low sensitivity associated with the FMS. This explanation is further supported by the strong association between LESS scores and 3D kinematics of a drop jump. The ability of the LESS to identify those with poor mechanics during a dynamic drop jump as outlined in chapter six is a likely reason that it had higher sensitivity and greater association with injury than the FMS.

In conclusion, this programme of research provided novel insights into the reliability of the FMS and LESS. In addition, it provided clarity about the relationship of the FMS and LESS to each other, their association with injury and their relationship with 3D kinematics of a dynamic jump. The FMS as a standalone screening tool has limited capacity as an injury prediction tool. While scoring poorly on the FMS is significantly associated with an increased chance of injury, the low sensitivity of the FMS means that the screen fails to detect some participants who may have increased chance of injury. This appears to be due to the weak association between FMS scores and dynamic movements as measured by the LESS and 3D kinematics of a drop jump. All of these findings were previously unknown and subsequently provide practitioners with greater clarity and increases our understanding of two of the most commonly used field-based screens in the practical setting.
Chapter 9

References


• Frost DM, Beach TAC, Callaghan JP. & McGill SM. (2015) FMS scores change with performers' knowledge of the grading criteria—are general whole-body movement screens capturing “dysfunction”? *Journal of Strength Conditioning Research*; 29(11): 3037-44.


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Chapter 10

Appendices
Appendix 1- Publications from the programme of research

Dropbox Link:
https://www.dropbox.com/sh/n1vwee4qxz47erw/AAC74NOGgAnykXLuh6hGdGgMa?dl=0
Appendix 2- Search terms and Prisma Flow Diagrams

Appendix 2A- Search terms and Prisma Flow diagram related to movement screening.


PRISMA Flow Diagram

Records identified through database searching (n =1092)  Additional records identified through other sources (n = 23)

Records after duplicates removed (n = 375)

Records screened (n = 375)  Records excluded (n =286)

Full-text articles assessed for eligibility (n =89)  Full-text articles excluded, with reasons (n =23)

Studies included in qualitative synthesis (n =66)
Appendix 2B- Search strategy and Prisma Flow diagram for FMS and LESS


**PRISMA Flow Diagram**

Records identified through database searching 
(n =1074)

Additional records identified through other sources 
(n = 19)

Records after duplicates removed 
(n = 362)

Records screened 
(n = 362)

Records excluded 
(n =269)

Full-text articles assessed for eligibility 
(n =73)

Full-text articles excluded, with reasons 
(n =27)

Studies included in qualitative synthesis 
(n =46)
Appendix 3- Testing Procedures

Appendix 3A- Set up of 3D analysis

Figure 11- Marker set for 3D motion analysis set up
Figure 12- Camera Set up and volume observed.
Figure 13- Testing protocol of 3D motion analysis drop jump.
Instructions for 3D motion analysis drop jump

- Start standing on the box with feet shoulder width apart.
- Step off the box and onto the force plates as was demonstrated by the instructor.
- Try jump as high as you can touching the object overhead.
- Land on the force plates.
Appendix 3B- Testing and scoring procedures of the FMS

https://www.dropbox.com/sh/fc7hs3sjkr4rm7i/AABVtT8sZb38HhI8oI4KhdN7a?dl=0

Appendix 3C- Testing and scoring procedures of the LESS

https://www.dropbox.com/sh/lb73rggf07ysybs/AAA94eZgCMwnqDS5nKG-bs8Ea?dl=0
## INJURY CLASSIFICATION FORM

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### Injury

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### Setting

- Training: The injury occurred during military training
- Non-training: The injury occurred outside of military training

### Onset

- Immediate: Symptoms manifested within 24 hours of the injury
- Delayed: Symptoms manifested after 24 hours of the injury

### Course

- Acute: Abrupt onset with symptom duration not exceeding 7 days
- Chronic: Gradual onset with symptom duration exceeding 7 days

### Mechanism

- Traumatic: A direct external force caused the injury
- Non-traumatic: A direct external force did not cause the injury

### Tissue type

- Soft tissue:
  - Muscle: Clinical diagnosis acceptable
  - Tendon: Clinical diagnosis acceptable
  - Ligament: Clinical diagnosis acceptable
- Hard tissue:
  - Bone: Diagnosis following imaging only
  - Joint: Diagnosis following imaging only

### Occurrence

- First time injury: This particular structure has been injured for the first time
- Recurrent injury: This particular structure has previously been injured

### Causative Factors

- Exogenous: The main causative factor of the injury was in the immediate environment
- Endogenous: The main causative factor of the injury was inherent to the recruit, e.g. a previous injury

### Severity

- Mild: Unlikely to require more than a week off training with little treatment input
- Moderate: Likely to require significant treatment input and lead to more than a week absent from training
- Severe: Serious enough to jeopardise the completion of recruit training. The injury may require surgery

### Presentation

- Immediate: Attended for medical care within 24 hours of injury
- Delayed: Attended for medical care greater than 24 hours after injury

### Disposal

- M&D: Returned to full duty status after the consultation
- LD: Placed on light duties for a specified period
- ED: Excused duties for a specified period
- SL: Given a specified period of sick leave

### Notes
Appendix 4- SPSS data output
Dropbox link: https://www.dropbox.com/sh/d989fdqabgo8ves/AAArJgzp3RGsr8k_EwLdEZ4Na?dl=0
Appendix 5 - Ethics Procedures

5A- Ethics Application

Dropbox link to PDF of accepted ethics application:
https://www.dropbox.com/s/z92u6zmb8j8kp9z/Final%20Ethics%20Application.pdf?dl=0
5B- Ethics Approval

Faculty of Education and Health Sciences Research Ethics Committee

Research Ethics Committee Feedback

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Section 1: Eligibility for Chair’s Action

Section 2: Ethical Issues

Section 3: Approved Procedures

Section 4: Study Design and conduct of the study

a. What are the aims of this research? Provided
b. Include a short justification for choosing this study Provided
c. Provide a description of the study Provided

d. Provide details of financial remuneration or any other form of reward which the participants will receive Provided

e. Where will the research work be done? Provided

Section 5: Recruitment of research participants

a. Describe the population you will recruit from Provided
b. How will you source or identify your participants? Provided
c. How many participants Provided
d. Provide details of financial remuneration or any other form of reward which the participants will receive Provided
### Section 6: Consent

| Details of how you will obtain consent (where relevant) | Provided |

### Section 7: Care and protection of research participants

| a. Participation time for each participant | Provided |
| b. If there are multiple testing sessions for each participant, please provide breakdown | Provided |
| c. Provide detailed information on potential risks to participant or researcher from procedures or techniques to be employed in this research. | Provided |
| d. Provide justification of the predictable risks and inconvenience to participants | Provided |

### Section 8: Protection of participant confidentiality

| a. Who will have access to data collected from participants? | Provided |
| b. How will confidentiality be ensured | Provided |
| c. How long will the data be kept? Destruction Method? | Provided |
Section 9: Feedback to Participants and Relevant Communities

Describe how the results of the research will be made available to the participants and to the concerned communities

Provided

Section 10: Indemnity

Is research covered by UL insurance Y/N

Y

Section 11: Document Checklist:

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<td>EHSREC or PESSREC Procedures</td>
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**Notes**
5C- Information sheet

Department of Physical Education and Sport Sciences: EHSREC

Subject Information Sheet

Title of the Project: To examine the relationship between field-based movement screens, 3D lower limb mechanics in athletic actions.

What is the study about?
This study sets out to examine the relationship between field-based screening scores (Functional Movement Screen and the Landing Error Scoring System) and 3D mechanics during complex athletic actions, such as jumping and changing direction.

What will I have to do?
In agreeing to participate, you will be requested to attend the biomechanics teaching laboratory (PG0-40; PESS building) on two separate occasions for testing. The first occasion will be to familiarise you with all the testing procedures and take information such as height and mass. On the second visit when you arrive at the laboratory, reflective markers will be placed at eleven locations (shoulder, chest, hip, knee, ankle and foot) on both sides of your body. These will be secured using double-sided tape (and electrical tape where necessary). Testing procedures within each testing session will last approximately 1 hour 25 minutes and will involve collecting video and force information as you perform a series of tasks. These will include:

- Ten minutes of jogging and stretching to warm up for the tests.
- 3 repetitions of seven body weight movement tests; Squat, lunge, step, a core test, push up, shoulder flexibility, straight leg raise test.
- Five repetitions of two jump tests which will involve jumping on to a force plate for one of the tests.
- Three repetitions of a strength test where you will stand on a force plate and try to lift an immovable bar upwards for 4 seconds.
- Three repetitions of a speed test where you will sprint maximally for 30m.
What are the benefits?
As a participant in this study you will receive feedback on various aspects of your basic movements (as assessed by the movement tests) and jumping technique following the study. You will also gain insight into the equipment used within the PESS department to conduct research and provide sport science support to athletes and members of the population.

What are the risks?
There may be a slight risk of developing Delayed Onset of Muscle Soreness (DOMS) after testing and training. The discomfort and stiffness associated with DOMS are harmless and usually subside within 2-3 days.

What if I do not want to take part?
You are not obliged to take part in this study. Also, please be assured that you, as the participant, reserve the right to withdraw from the study at any stage (without explanation) and completely without prejudice towards you.

What happens to the information?
All recorded information will be treated with the strictest confidence and will not be disclosed to any party other than the investigator, supervisor or yourself (if desired). Your results will also remain completely anonymous at all times and will be stored on the investigators password protected personal computer. After 7 years, the information will be destroyed by the principal investigator.

Who else is taking part in the study?
There will be a total of 200 participants taking part from the University of Limerick and Limerick Institute of Technology.

What happens at the end of the study?
On completion of the study, results / research findings may be published within peer reviewed publications (e.g. journals / conference proceedings), however all data presented will remain completely anonymous. You as a participant in the study, reserve the right to view your data at any stage (if so desired).
What if I have more questions or do not understand something?

If you have any questions regarding any aspect of this study please contact the principal investigator via e-mail / telephone (details listed below).

What happens if I change my mind during the study?

Please be assured that you, as the participant, reserve the right to withdraw from the study at any stage (without explanation) if so desired and completely without prejudice towards you.

Contact Details of Study Investigators:

**Student Researcher:** Eoin Everard  eoin.everard@ul.ie

**Principle Investigator:** Dr. Drew Harrison  drew.harrison@ul.ie  061202809

**Academic Supervisor:** Dr Mark Lyons  mark.lyons@ul.ie  061202819

This study has been approved by the ethics committee of the Faculty of Education and Health Sciences. If you have any concerns about this study and wish to contact someone independent, you may contact:

Chairman Education and Health Sciences Research Ethics Committee, EHS Faculty Office, University of Limerick
Tel (061) 234101  Email : ehsresearchethics@ul.ie
Title of the Project: To examine the relationship between field-based movement screens, 3D lower limb mechanics in athletic actions.

Please read the statements listed below. If you agree to these statements please sign the consent form where relevant. Your cooperation is greatly appreciated.

- I have read and understand the subject information sheet.
- I understand what the study is about and what the results will be used for.
- I have completed the ‘Health Screening’ questionnaire.
- I am fully aware of the procedures involving myself and of any risks and benefits associated with the study.
- I know that my participation is voluntary and that I can withdraw from this project at any stage without explanation and without prejudice towards me.

After agreeing to all of the above statements, I consent to my involvement in the research project.

Participant’s Name (Please print): .................................................................................................

Participant’s Signature: .............................................. Date: ........../......./..............

Investigator’s Signature: .................................................. Date: ........../......./..............

This study has been approved by the ethics committee of the Faculty of Education and Health Sciences. If you have any concerns about this study and wish to contact someone independent, you may contact:

Chairman Education and Health Sciences Research Ethics Committee, EHS Faculty Office, University of Limerick
Tel (061) 234101 Email : ehsresearchethics@ul.ie
4E- Recruitment Poster

University of Limerick

Department of Physical Education & Sport Sciences: EHSREC

Recruitment E-mail / Poster

To examine the relationship between field-based movement screens, 3D lower limb mechanics in athletic actions

Are you physically active and aged between 18 – 30 years of age?

Are you interested in receiving feedback on aspects related to your strength and movement?

Would you like to learn about some of the equipment used within the Physical Education and Sport Science department, to conduct research and provide support to athletes?

If interested in participating or would like more information contact eoin.everard@ul.ie
This study is examining if the scores you receive doing simple movement screening tests influence the score you receive in more dynamic jumping tests. Your testing will be recorded and analysed and you will be given an athletic profile based on your individual results. If interested in participating or would like more information contact eoin.everard@ul.ie or

This study has been approved by the ethics committee of the Faculty of Education and Health Sciences. If you have any concerns about this study and wish to contact someone independent, you may contact:

Chairman Education and Health Sciences Research Ethics Committee, EHS Faculty Office, University of Limerick
Tel (061) 234101 Email: ehsresearchethics@ul.ie
Health Screening Questionnaire:

As you agreed to participate in this study, you are required to complete the following questionnaire. Please be assured that any information contained herein will remain completely confidential. Your cooperation in this is greatly appreciated.

**Participant’s Name:** ..................................................  
**Date of Birth:** ..................................................

**Age:** ..................................................

**Height:** ..................................................

**Weight:** ..................................................

**Persons to contact in case of emergency:**

**Name:** ..................................................

**Phone Number:** ..................................................

**Physician’s Name:** ..................................................

**Physician’s Phone:** ..................................................

**Have you had to consult your doctor within the last six weeks?**  
Yes □  No □

**If ‘yes’ please give details:**

..........................................................................................................................................................................................
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**Have you currently or ever had:**

□ Diabetes  □ Asthma  □ Bronchitis  □ Heart complaints
If so, please give details:

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Injury History:

Have you experienced an injury within the last six weeks that has resulted in the termination of your normal exercise activities and has forced you to consult a sports medicine professional (e.g. physiotherapist)?  Yes □       No □

If yes please provide details of:

- Type of injury; ..............................................................................................................................................................
- How it occurred; ..............................................................................................................................................................
- When it occurred; ..............................................................................................................................................................

Could these injuries prevent / limit your performance in the forthcoming exercise testing? Yes □       No □

If you have answered NO to all questions then you can be reasonably sure that you can take part in the physical activity requirement of the testing procedures.

I ............................................................................................................. declare that the above information is correct at the time of completing this questionnaire          Date ....../....../......

Participant’s signature ................................................................. Date ....../....../......

Investigator’s signature ............................................................... Date ....../....../......
Please Note: If your health changes so that you can then answer YES to any of the above questions, please inform the experimenter / laboratory supervisor. You should also consult with your doctor regarding the level of physical activity you can conduct.

If you have answered YES to one or more questions:

Please consult your doctor and discuss with him / her, those questions you answered yes. Ask your doctor if you are able to conduct the physical activity requirements.

Investigator’s signature ................................. Date ........../......./...........

Doctor’s signature ............................................... Date ........../......./...........
