THE USE OF TWO-DIMENSIONAL MOTION ANALYSIS AND FUNCTIONAL PERFORMANCE TESTS FOR ASSESSMENT OF KNEE INJURY RISK BEHAVIOURS IN ATHLETES

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Glossary of terms

2D	Two dimensional
3D	Three dimensional
ACL	Anterior cruciate ligament
ACL- D	Anterior cruciate ligament deficient
ACL-R	Anterior cruciate ligament reconstructed
BMI	Body mass index
CAI	Chronic ankle instability
DJ	Drop Jump
EMG	Electromyography
FPPA	Frontal Plane Projection Angle
FPT	Functional performance test
GRF	Ground reaction force
ITB	Illiotibial band
LCL	Lateral collateral ligament
LESS	Landing Error Scoring System
LSI	Limb Symmetry Index
MCL	Medial collateral ligament
MVIC	Maximal Isometric Voluntary Contraction
NMC	Neuromuscular control
OA	Osteoarthritis
PCL	Posterior cruciate ligament
PFJ	Patellofemoral joint
PFPS	Patellofemoral pain syndrome
SEBT	Star excursion balance test
SLL	Single leg landing

TFJ	Tibiofemoral joint
vGRF	Vertical ground reaction force
VL	Vastus lateralis
VM	Vastus medialis
VMO	Vastus medialis obliqus

Abstract

Dynamic knee valgus and limb asymmetry have been linked to greater risk of anterior cruciate ligament (ACL) or patellofemoral joint (PFJ) injury. Two-dimensional (2D) frontal plane projection angle (FPPA) is more clinically useful than three-dimensional (3D) motion analysis techniques used to assess dynamic knee valgus in the literature. Further, hop for distance tests and the star excursion balance test (SEBT) offer a clinically useful assessment of limb symmetry.

1. Reliability and validity of 2D FPPA

Within-day and between-session reliability of 2D FPPA during the drop jump (DJ), single leg land (SLL) and single leg squat (SLS) tasks was fair to good. Intra- and inter-tester reliability was excellent. Significant correlations were found between 2D FPPA and 3D measures of dynamic knee valgus. These results indicate that 2D FPPA is a reliable and valid measure of dynamic knee valgus.

2. Reliability of hop for distance tests and the SEBT

Between-session reliability of the hop for distance tests and SEBT was good. Error measurement values were calculated to evaluate future performance.

3. Investigation of factors contributing to 2D FPPA

Significant correlations were found between DJ FPPA and isometric hip abduction, external rotation and combined abduction/external rotation (clam) strength. Clam strength accounted for 20% of the variance in 2D FPPA. No significant correlations were found for SLL FPPA.

4. Use of feedback to modify movement patterns

Augmented feedback was shown to significantly improve landing patterns during the drop DJ and SLL tasks. In the DJ task a significant reduction in FPPA and increase in contact time were found post-feedback. A significant reduction in FPPA and vertical ground reaction forces were found for the SLL task.

5. Prospective assessment of ACL injury risk in women's sport

One women's footballer suffered an ACL injury and was found to demonstrate greater FPPA during the DJ, SLL and SLS tasks and lower crossover hop for distance scores than her peers. Limb asymmetry did not appear to predict ACL injury risk in this athlete.

Chapter 1
Introduction

Knee injuries are among the most common and problematic injuries in both professional and amateur sports people. Much research has been devoted to how these injuries occur, what factors contribute to them, and how this risk might be reduced. A key component of this is the identification of those who are more susceptible to such injuries, without the use of expensive laboratory equipment. This thesis focuses on building upon this area of sports injury expertise, in particular it aims to improve the identification of those athletes who are at greatest risk of injury. To achieve this, a variety of measurement tools for assessing injury risk in the field will be identified and evaluated for their clinical utility to recognise those at greatest risk. This will help clinicians to identify modifiable risk factors and plan preventative training to limit the occurrence of these injuries.

This introduction will provide an overview of the literature pertaining to knee injury risk in the athletic population and the risk factors for these injuries. Following this, methods to identify those who demonstrate high-risk movement patterns for use in the field will be identified and potential intervention strategies to improve these movement patterns will be reviewed.

1.1. Knee Injuries in Sport

Injury to the knee joint complex is one of the most common in sport (Hootman, Dick, & Agel, 2007; Starkey, 2000). In particular, injury to the anterior cruciate ligament (ACL) and patellofemoral joint (PFJ) are responsible for a significant amount of time-loss in sport (Starkey, 2000). ACL injuries can result in inability to return to previous activity levels and both injuries are associated with early onset of knee osteoarthritis (OA) (Lohmander, Englund, Dahl, & Roos, 2007; Lohmander, Ostenberg, Englund, & Roos, 2004; Myklebust, Holm, Maehlum, Engebretsen, & Bahr, 2003b; Utting, Davies, & Newman, 2005). The majority of ACL and PFJ injuries occur through non-contact and overuse mechanisms (Agel, Arendt, & Bershadsky, 2005; Finestone et al., 2008; Mountcastle, Posner, Kragh, & Taylor, 2007; Olsen, Myklebust, Engebretsen, & Bahr, 2004) which are widely regarded as avoidable if injury mechanisms and risk factors can be identified and preventative measures taken.

Non-contact ACL injuries commonly occur during decelerating manoeuvres such as cutting/turning and landing (Boden, Dean, Feagin, & Garrett, 2000; Boden, Torg, Knowles, &

Hewett, 2009; Krosshaug et al., 2007a). Altered neuromuscular control (NMC) of the lower limb during these movements has been suggested as an important component of such injuries (Hewett, Myer, & Ford, 2006b; Ireland, 1999). PFJ injuries are commonly overuse in nature and like ACL injuries, are thought to be the result of poor neuromuscular control during common tasks such as running, jumping and landing (Dierks, Manal, Hamill, & Davis, 2008; Souza & Powers, 2009a). Changes in frontal plane movement at the knee can alter the loads placed on the ACL and PFJ, leading to increased stress and microtrauma which over time can lead to pathology (Berns, Hull, & Patterson, 1992; Farrokhi, Colletti, & Powers, 2011a; Ireland, 1999; Lee, Anzel, Bennett, Pang, & Kim, 1994; Markolf et al., 1995; Powers, 2003). Dynamic knee valgus is a term which has been coined to reflect the numerous factors, including frontal and transverse plane motion at the hip, knee and ankle, which contribute to frontal plane motion of the knee during athletic tasks (Hewett et al., 2005). Moreover, increases in dynamic knee valgus may increase the risk of ACL and PFJ injury (Decker, Torry, Wyland, Sterett, & Richard Steadman, 2003; Hewett et al., 2005; Myer et al., 2010).

1.2. Frequency and causes of knee injuries in men and women

Women are typically at least twice as likely to suffer ACL or PFJ injury as men (Agel et al., 2005; Arendt, Agel, & Dick, 1999; Boling et al., 2010; Deitch, Starkey, Walters, & Moseley, 2006; Messina, Farney, & DeLee, 1999; Myer et al., 2010). This is thought in part to be a result of women frequently demonstrating postures which increase the loads imparted on the ACL and PFJ during athletic tasks, including increased dynamic valgus (Herrington & Munro, 2010; Kernozek, Torry, Van Hoof, Cowley, & Tanner, 2005; Zeller, McCrory, Kibler, & Uhl, 2003). This may be due to a number of factors including, increases in frontal and transverse plane hip and knee joint angles and decreases in hip muscle strength and activation compared to men (Beutler, de la Motte, Marshall, Padua, & Boden, 2009; Decker et al., 2003; Willson, Ireland, & Davis, 2006). Despite higher injury rates in women, there are likely to be common factors which may increase injury risk in both men and women. The identification of risk factors for ACL and PFJ injuries is paramount for injury prevention. Risk factor literature will be reviewed in chapter two.

1.3. Methods to identify high-risk athletes

The observed disparity in injury rates between the sexes has led to a surge in research assessing injury mechanisms and risk factors for ACL and PFJ injury. The majority of these studies have used three-dimensional (3D) motion analysis for quantifying lower limb biomechanics. These methods are seen as the 'gold standard' for analyses of this type.

However, due to the financial, spatial and temporal cost of 3D motion analysis it is not practical for most clinical settings or for use in large screening programmes useful to sport. Thus, there is a need for a simpler method of knee injury risk assessment to identify potentially high-risk athletes. Two-dimensional (2D) motion analysis of dynamic knee valgus, and functional performance tests commonly used in knee injury rehabilitation outcome measurement, may have the potential to identify these high-risk athletes.

It is important to ensure that any assessment method used in research or clinical assessment is valid and reliable. The ability of clinical tools to accurately measure the desired variable and also to detect differences within or between participants or test sessions is paramount to its utility in the field. A test which is not reliable will not provide consistent measurements in which the clinician or researcher can be confident, limiting the use of these measurements for comparison between sessions in which they are taken. It is desirable for measurement tools used with physically active participants to be able to detect small differences that may exist between populations or within an individual athlete's performance. In addition, it is important that the observation or measurement made by a clinician or researcher is actually representative of what they are trying to measure.

1.4. 2D motion analysis: reliability and validity

Qualitative and quantitative 2D analyses of frontal plane knee motion have been used in previous research. Qualitative 2D analyses provide a quick, subjective assessment of the specified movements. However, these subjective methods have only moderate intra- and inter-rater reliability when assessing frontal plane motion of the lower limb (Chmielewski et al., 2007; Ekegren, Miller, Celebrini, Eng, & Macintyre, 2009). In addition, a simple qualitative assessment failed to identify up to a third of individuals classified as 'high-risk' according to 3D analysis (Ekegren et al., 2009), which calls into question the sensitivity of qualitative assessment. The Landing Error Scoring System (LESS) is an in-depth qualitative screening tool where scores are allocated based on correct or incorrect positioning of trunk, hip, knee, ankle and foot during a drop jump task. Those with high (poor) LESS scores have been shown to demonstrate hip and knee kinetics and kinematics thought to be detrimental to the ACL (Padua et al., 2009). Despite this, a recent prospective study found the LESS was unable to predict ACL injuries (Smith et al., 2012). Despite analysing 28 ACL-injured individuals, the authors suggested that their study may not have had sufficient statistical power to detect differences in LESS scores between injured and uninjured populations. Additionally, the range of scores in the group was 0 to 11, rather than the full range of 0 of 17, which may have

reduced the likelihood of finding an association between LESS scores and injury risk. It may be that the sensitivity of the LESS means that only those with the highest scores are at high risk of injury.

Quantitative 2D analysis has been used to measure frontal plane knee motion in athletic, general and injured populations (Herrington, 2011; Herrington & Munro, 2010; Noyes, Barber-Westin, Fleckenstein, Walsh, & West, 2005; Stensrud, Myklebust, Kristianslund, Bahr, & Krosshaug, 2011; Willson & Davis, 2008b; Willson et al., 2006). Different methods of quantitative 2D analysis have been used, including knee separation distance (Barber-Westin, Galloway, Noyes, Corbett, & Walsh, 2005; Noyes et al., 2005) and frontal plane projection angle (FPPA) (Herrington, 2011; Willson & Davis, 2008b; Willson et al., 2006).

Knee separation distance has been used to quantify frontal plane lower limb motion in several studies. Sigward et al. (2011) recently investigated the relationship between knee separation distance and 3D knee valgus angles. They found that knee separation distance accounted for 52% of the knee valgus angle during a drop jump task, where those with smaller knee separation distances had greater knee valgus angles. However, the use of knee separation distance is limited to use during bilateral tasks only and does not allow for comparison between limbs. Considering that many ACL injuries occur during single leg landings and many individuals exhibit asymmetry between limbs, this limitation is likely to be significant when attempting to predict ACL injury using this method.

Two recent studies have examined at the validity of 2D video analysis in quantifying FPPA of the knee during single leg squats (SLS) and high speed cutting manoeuvres in comparison to existing 3D techniques (McLean et al., 2005b; Willson & Davis, 2008b). The studies found that FPPA was moderately associated with 3D frontal and transverse plane hip and knee kinematics. McLean et al. (2005) also noted that FPPA accounted for 58-64% of the variance in knee valgus angles during side-step and side-jump activities. The authors concluded that whilst 2D analysis of frontal plane knee motion is not able to quantify more subtle 3D measurements of lower limb kinematics, it is useful for screening of knee joint FPPA to identify high risk athletes and further analysis of 2D methods is required. The ability to use FPPA during a variety of bilateral and unilateral tasks, and for comparison between limbs, makes this method more clinically useful than knee separation distance.

Although validity of FPPA has been investigated during SLS and cutting manoeuvres, this relationship has not been established in other common screening tasks. Knee valgus motion exhibited during the drop jump (DJ) task has been prospectively linked to both ACL and PFJ injury. Additionally, ACL injury commonly occurs during unilateral landings (Faude, Junge, Kindermann, & Dvorak, 2005) and, whilst not confirmed prospectively, the single leg landing (SLL) task may be useful in identifying those at risk of injury. Investigation of the relationship between 2D FPPA and 3D variables during these tasks is therefore important.

Furthermore, only within-day ICCs for the SLS have been presented to demonstrate reliability of FPPA (Willson et al., 2006). Intra-tester, inter-tester, between-session reliability and measurement error values of 2D FPPA have not been established. Therefore, further investigation of the reliability of 2D FPPA is needed before it can be recommended for use in screening tests. Further discussion and analysis of 2D and 3D motion analysis can be found in chapter three.

1.5. Functional Performance Tests: reliability, validity and clinical utility

Functional performance tests (FPT) (Clark, 2001) have been used increasingly over recent years in both sport and clinical practice to provide an outcome measure when evaluating athletes returning from injuries. FPTs are closed chain in nature and therefore closely assimilate the joint loading forces and kinematics that occur functionally and require minimal space, time, expense and administration (Clark, 2001). A range of FPTs have been assessed in the literature. These include hop for distance tests, star excursion balance test (SEBT), anteromedial lunge, step-down, stairs hopple, vertical jump, carioca's, agility and sprint tests (Barber, Noyes, Mangine, McCloskey, & Hartman, 1990; Clark, 2001; Delextrat & Cohen, 2008; Goh & Boyle, 1997; Gribble, Hertel, Denegar, & Buckley, 2004; Herrington, Hatcher, Hatcher, & McNicholas, 2009; Loudon, Gajewski, Goist-Foley, & Loudon, 2004; Negrete & Brophy, 2000; Noyes, Barber, & Mangine, 1991; Petschnig, Baron, & Albrecht, 1998; Reid, Birmingham, Stratford, Alcock, & Giffin, 2007; Risberg & Ekeland, 1994; Rudolph, Axe, & Snyder-Mackler, 2000; Semenick, 1990). The vertical jump, carioca's and agility tests require both limbs to work simultaneously to complete the test and therefore do not allow for comparison between the injured and uninjured limb. In contrast, single limb tests such as the hop tests, single leg vertical jump, stairs hopple and SEBT, are able to utilise the uninjured limb as a control for within-subject comparisons, making it easy to quantify function of the injured limb.

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Each of these unilateral FPTs is able to detect differences in function between injured and uninjured limbs following ACL injury (Barber et al., 1990; Goh & Boyle, 1997; Risberg & Ekeland, 1994). However, the stair hopple test requires that a set of stairs, with at least 11 steps, are available for the test to be undertaken. This is not always available in a clinical environment and limits the convenience of this test for use in the field. The ability of the single leg vertical jump test to detect functional deficits in injured populations only (sensitivity) is questionable (Barber et al., 1990). In this study, over half of the normal population were unable to achieve 90% symmetry between limbs, whilst only 69% achieved 85% symmetry, suggesting this test may not be suitable for detecting lower limb functional limitations in injured populations.

Hop tests, which require the participant to hop as far as possible, are routinely used during rehabilitation from ACL injury. Hop tests can detect deficits between ACL reconstructed or deficient and uninjured limbs (Barber et al., 1990; Goh & Boyle, 1997; Reid et al., 2007). In order to compare and evaluate performance between limbs during the hop tests the limb symmetry index (LSI) is used. LSI gives a percentage value of the distance hopped on the injured limb versus the uninjured limb. An LSI of ≥85% indicates that 'normal' limb symmetry exists and function of the injured limb is being restored (Bandy, Rusche, & Tekulve, 1994; Barber et al., 1990). The 85% value was chosen as over 93% of the normal population were able to achieve this score (Barber et al., 1990). However, the validity of this value has not been investigated further and is not always sensitive to deficits in ACL injured participants (Barber et al., 1990; Noyes et al., 1991; Petschnig et al., 1998). This lack of sensitivity may be due to this arbitrary LSI value being too low. If hop tests are able to show functional deficits between limbs in injured populations, it would seem plausible to screen healthy individuals for LSI and investigate whether an abnormal LSI is a predisposing factor to injury and to help determine a minimal required LSI score to reduce injury risk.

The SEBT involves participants carrying out a number of reaching tasks with one lower limb whilst maintaining balance on the other, with distance reached being the marker of performance (Hertel, Miller, & Denegar, 2000). The SEBT has been shown to be sensitive enough to detect dynamic postural control deficits in patients with chronic ankle instability (CAI) and an ACL-deficient (ACL-D) limb (Herrington et al., 2009; Hertel, Braham, Hale, & Olmsted-Kramer, 2006a; Olmsted, Carcia, Hertel, & Shultz, 2002). In these studies, patients who were injured were shown to have lower SEBT scores compared to their uninjured limb and those of healthy participants. Specific reach directions have been shown to detect

functional deficits in CAI and ACL-D patients (Herrington et al., 2009; Hertel et al., 2006a). A link between SEBT performance and lower extremity injury occurrence in high school basketball players has also been reported (Plisky, Rauh, Kaminski, & Underwood, 2006). These studies suggest that the SEBT may be sensitive to both post-injury deficits between limbs and the prediction of future injury risk.

As both the hop tests and SEBT are indicated to be the most clinically applicable as well as relevant tests in which to potentially detect limb symmetry differences, deficits in functional performance and risk of injury, these will therefore be reviewed in more detail in chapter two. Considering the factors presented, further investigation and understanding of the potential of 2D video analysis and FPTs to identify athletes at high-risk of ACL or PFJ injury is warranted.

1.6. Causative factors of dynamic valgus and potential interventions

Identification of individuals who exhibit dynamic valgus and are at higher risk of ACL or PFJ injury is important. However, in order for this risk of injury to be reduced through interventions aimed at modifying movement patterns, an understanding of the factors that contribute to demonstration of dynamic valgus is required. Despite the frequent use of the drop jump, single leg drop landing, and single leg squat tasks for clinical screening, little is known about which factors contribute to dynamic knee valgus during these tasks. These contributory factors need to be identified, to enable targeted prevention strategies to reduce injury rates.

A number of studies have assessed the effect of intervention programmes aimed at modifying the risk factors identified for ACL and PFJ injury. Studies assessing the effectiveness of programmes for ACL injury prevention have used injury rates and changes in lower limb biomechanics as outcome measures. Those assessing PFJ injuries have mainly used changes in pain and function in those already diagnosed with patellofemoral pain syndrome (PFPS), limiting the application of the results to injury prevention strategies. However, the findings of the studies examining changes in biomechanics related to ACL injury could also be applied to the PFJ due to increased stress being brought about by similar movement patterns.

Several studies have shown that multifaceted interventions can bring about significant reductions in non-contact ACL injury rates (Hewett, Lindenfeld, Riccobene, & Noyes, 1999; Mandelbaum et al., 2005; Myklebust et al., 2003a). Although a large number of studies have

demonstrated no difference in injury rates between control and intervention groups (Heidt, Sweeterman, Carlonas, Traub, & Tekulve, 2000; Myklebust et al., 2003a; Pasanen et al., 2008b; Pfeiffer, Shea, Roberts, Grandstrand, & Bond, 2006; Soderman, Werner, Pietila, Engstrom, & Alfredson, 2000). Despite the relatively high incidence of PFPS, only one study has prospectively examined the effect of a multifaceted intervention programme on PFJ injury rates finding no difference between experimental and placebo groups (Brushoj et al., 2008).

Several studies have seen increases in hip and knee flexion angles and decreases in hip internal rotation, knee valgus and internal rotation motion and ground reaction force (GRF) after various training programmes (Barendrecht, Lezeman, Duysens, & Smits-Engelsman, 2011; Cochrane et al., 2010; Irmischer et al., 2004; Lephart et al., 2005; Myer, Ford, McLean, & Hewett, 2006; Pollard, Sigward, Ota, Langford, & Powers, 2006a). These changes are likely to reduce ACL and PFJ stress and therefore help to reduce injury risk. However, these changes in lower limb mechanics are not always evident (Cochrane et al., 2010; Grandstrand, Pfeiffer, Sabick, DeBeliso, & Shea, 2006; Herman et al., 2009; Lephart et al., 2005; Pollard et al., 2006a).

As a result of the inconsistent findings, it is unclear what types of training might consistently lead to decreased injury rates and changes in lower limb control. Therefore, studies which evaluate the effects of single training modalities would provide further information, although few studies of this type exist (Cochrane et al., 2010; Herrington, 2010; Irmischer et al., 2004; Myer et al., 2006; Soderman et al., 2000). Once again, the results of these studies have proven inconclusive. Cochrane et al. (2010) found that balance training had the greatest effect on improving lower limb mechanics during a cutting manoeuvre. Whilst Myer et al. (2006) found that both balance and plyometric training significantly reduced hip adduction, knee valgus and ankle eversion angles during drop landings. However, Soderman et al. (2000) found that a balance training protocol had no effect on ACL injury rates, despite a significant improvement in balance. When comparing the balance training protocols in these studies, it is clear that the interventions used in the Myer and Cochrane studies were much more dynamic in nature, compared to simple static holds used in the Soderman intervention, which may explain the differences in findings. The best form of training to help decrease ACL and PFJ injury risk is currently unknown. More information is needed on which factors affect lower limb control in order to inform future injury prevention programmes. Further analysis of these studies and interventions will be undertaken in chapter two.

Herman et al. (2008) found that a lower limb strength training intervention did not improve hip and knee kinetic and kinematics. However, a second study found that when feedback was introduced the strength training group improved more than a feedback only group (Herman et al., 2009). Recently, there has been an increase in research activity investigating how feedback can influence lower extremity movement patterns. Feedback is a fundamental tool for learning and performing of motor skills and has been shown to improve landing strategies across a number of studies (Cronin, Bressel, & Finn, 2008; Herman et al., 2009; Onate et al., 2005; Onate, Guskiewicz, & Sullivan, 2001). The use of simple verbal feedback decreases GRFs and knee abduction angles and moments during landing tasks (Cowling, Steele, & McNair, 2003; McNair, Prapavessis, & Callender, 2000; Mizner, Kawaguchi, & Chmielewski, 2008; Prapavessis & McNair, 1999).

The use of video to supplement verbal instructions given to participants can decrease GRF and improve frontal and sagittal plane landing mechanics during both simple and more complex sporting movements (Cronin et al., 2008; Herman et al., 2009; Onate et al., 2005; Onate et al., 2001). A combination of analysis of self and analysis of an expert has been shown to be the most effective type of video feedback for reducing GRF and increasing knee flexion displacement during vertical jump landing (Onate et al., 2005). Additionally, these improvements were retained one week later, suggesting motor patterns may have changed and the improvements would endure, therefore decreasing injury risk in the long-term (Onate et al., 2005). This expert and self-combination feedback protocol has also been found to decrease GRFs and increase knee flexion and hip abduction angles during a stop-jump task (Herman et al., 2009). It is clear that feedback can aid injury prevention by decreased GRFs and improving sagittal plane knee kinematics, however it is not known whether a similar feedback protocol results in changes to dynamic knee valgus. This will be evaluated in chapter six.

<u>1.7. Aims</u>

The aims of the thesis are therefore to:

1. Review the literature related to Anterior Cruciate Ligament and Patellofemoral Joint injuries, including their occurrence, mechanism and proposed risk factors (chapter 2).
2. Review the literature regarding screening tools to identify potential Anterior Cruciate Ligament or PFJ injury risk (chapter 2).
3. Establish the reliability and validity of 2D FPPA during the drop jump, single leg landing and single leg squat tasks (chapter 3).
4. Establish the reliability and measurement error of the SEBT and hop for distance tests (chapter 4).
5. Establish what factors contribute to the demonstration of 2D FPPA during screening tasks (chapter 5).
6. Establish whether a simple feedback intervention can modify landing strategies during screening tasks (chapter 6).
7. Prospectively examine the potential of 2D FPPA, hop for distance tests and the SEBT to identify individuals at high risk of Anterior Cruciate Ligament injury (chapter 7).

Chapter 2

Literature Review

2.1. Introduction

This literature review provides the background and rationale for the work conducted in this thesis. The following are therefore discussed:

- current trends in sport injury occurrence (2.1.1)
- injuries of the knee joint, specifically ACL (2.1.2) and PFJ injuries (2.1.3), their occurrence and comparison between sexes (2.1.4)
- mechanisms (2.2) and proposed risk factors (2.3) for ACL and PFJ injuries in relation to knee anatomy
- screening tools to identify those at greater risk of ACL and PFJ injuries (2.5)
- intervention strategies to reduce the risk of ACL and PFJ injuries (2.7)

2.1.1. Injuries in Sport

Physical activity is associated with a potential risk of injury. Increased sports participation leads to an inherent increase in injuries sustained, which results in costs to: the individual, in temporary or long-term disability and loss of earnings; the healthcare system; and the economy.

Typically, around 50-75% of injuries occur in the lower limb in both sexes and across a range of sports and playing levels (Agel et al., 2007; Hootman et al., 2007; Powell & Barber-Foss, 2000; Rauh, Macera, Ji, & Wiksten, 2007). The knee is one of the most commonly injured joints in the lower limb and frequently accounts for the greatest loss of training and playing time (Agel et al., 2007; Dallalana, Brooks, Kemp, & Williams, 2007; Starkey, 2000). Knee injuries typically account for 15-25% of all injuries in high school, college and professional players of football, basketball, floorball, Australian Rules football, volleyball and rugby (Agel et al., 2007; Dallalana et al., 2007; Deitch et al., 2006; Faude et al., 2005; Gabbe & Finch, 2001; Hagglund, Walden, & Ekstrand, 2009; Hawkins, Hulse, Wilkinson, Hodson, & Gibson, 2001; Le Gall, Carling, & Reilly, 2008; Pasanen et al., 2008a; Powell & Barber-Foss, 2000; Rauh et al., 2007; Starkey, 2000). In addition, knee injuries can result in individuals being unable to return to sport, developing OA or having to change employment (Blond & Hansen, 1998; Myklebust et al., 2003b; Utting et al., 2005).

The time-loss from training and competition associated with knee injuries is due to their seriousness. The knee joint consists of the tibiofemoral and patellofemoral (PFJ) joints which, due to their relatively shallow articulations, rely primarily on ligamentous and muscular restraints for stability. The anterior cruciate ligament (ACL) and posterior cruciate ligaments (PCL) primarily restrict anterior and posterior translation of the tibia on the femur respectively. The medial collateral ligament (MCL) restrains valgus forces and the lateral collateral ligament (LCL) restrains varus forces applied to the knee. The ligament restraints typically come into play towards the end range of these movements, with the muscles around the knee joint providing added stability. However, the muscles around the knee primarily create, rather than restrict, movement. Thus knee joint stability is heavily influenced by muscular action. Figure 2.1 and 2.2 show the knee joint muscles and ligaments.
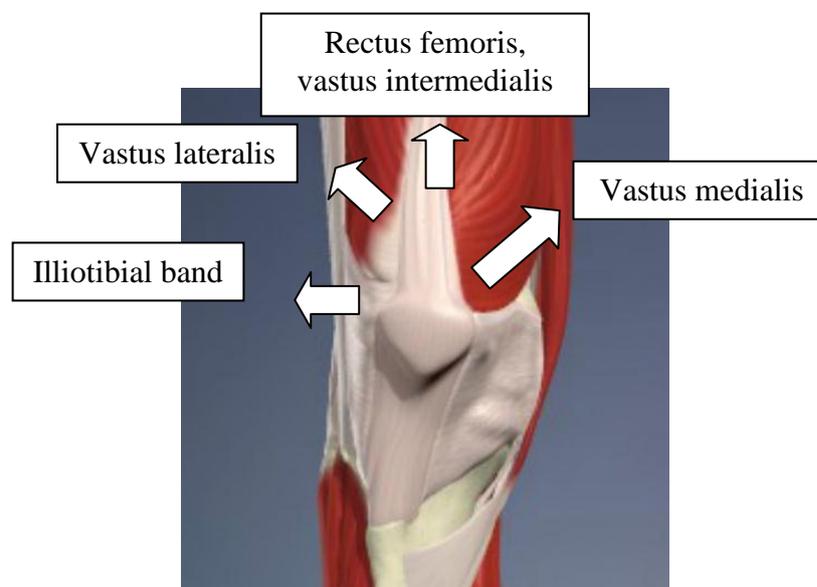
Figure 2.1 – The knee joint muscles and direction of action.
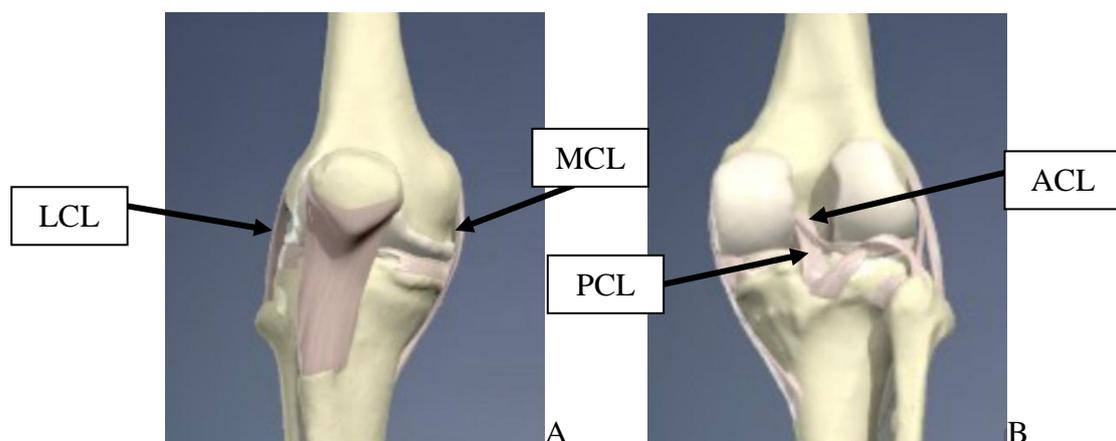
Figure 2.2 – The knee joint ligaments - A) anterior view; B) posterior view. ACL – anterior cruciate ligament; PCL – posterior cruciate ligament; LCL - lateral collateral ligament; MCL – medial collateral ligament (Primal Images, London, UK).

No study has evaluated the cost of sports injuries in the United Kingdom. Annual costs of such injuries are $222million in New Zealand (Gianotti & Hume, 2007), and $680million in the United States for people under the age of 24 alone (Burt & Overpeck, 2001). Using current exchange rates and assuming similar participation and injury rates, this equates to between £115-445 million in the UK (exchange rate at 19/07/2013).

2.1.2. Anterior Cruciate Ligament Injuries

ACL injury is catastrophic, resulting in an extended period away from sports participation. For example, only 58% of Norwegian elite handball players returned to the same level of competition after ACL reconstruction (Myklebust et al., 2003b). The remaining 42% either competed at a lower level or did not return to sport at all. Over half of Swedish women football players were unable to return to sport post-ACL injury, and only 15% reported returning to pre-injury activity levels (Lohmander et al., 2004). A recent study in American Football identified that 37% of players who underwent ACL surgery did not return to play (Shah, Andrews, Fleisig, McMichael, & Lemak, 2010).

Most individuals who suffer ACL injury also experience early onset of OA with associated pain and limited function (Fink, Hoser, Hackl, Navarro, & Benedetto, 2001; Lohmander et al., 2007; Lohmander et al., 2004; Myklebust et al., 2003b). Around 40% of ACL patients have signs of early onset OA of the tibiofemoral joint or PFJ six to eleven years post injury (Jarvela, Paakkala, Kannus, & Jarvinen, 2001; Keays, Bullock-Saxton, Keays, Newcombe, & Bullock, 2007; Myklebust et al., 2003b). Studies where follow-up has been conducted after 10-15 years have shown around 75-80% of patients who suffered an ACL injury have radiographic changes in the knee joint complex (Fink et al., 2001; Lohmander et al., 2004; Oiestad et al., 2010; von Porat, Roos, & Roos, 2004). Within-subject comparisons show radiographic changes in only 37% of uninjured knees, suggesting that the ACL injury was the reason for the majority of early onset OA cases (Lohmander et al., 2004).

However, radiographic changes to the knee joint complex do not necessarily correlate with incidence of symptomatic OA. For example, Oiestad et al. (2010) found 74% of ACL injured patients had radiographic changes, but only 41% were symptomatic 10-15 years post-op. Correlations between radiographic signs of OA and patient reported knee function are also low (Myklebust et al., 2003b). However, patient outcome scores on knee function scoring systems, such as the International Knee Document Committee and Lysholm scales (assessing subjective and objective knee function), are also worse in ACL injured than uninjured

subjects (Jarvela et al., 2001; Lohmander et al., 2004; Myklebust et al., 2003b). Overall, it is evident that ACL injury can lead to detrimental changes to the knee joint complex and/or changes in knee function which may not happen if the injury did not occur.

2.1.3. Patellofemoral Joint Injuries

Retropatellar and peripatellar pain resulting from injury to the PFJ, clinically referred to as patellofemoral pain syndrome (PFPS), is a common pain disorder experienced by athletes (Boling et al., 2010; Loudon et al., 2004; Myer et al., 2010; Natri, Kannus, & Jarvinen, 1998; Starkey, 2000; Taunton et al., 2002; Witvrouw, Lysens, Bellemans, Cambier, & Vanderstraeten, 2000). PFPS results in significant time-loss from training and competition (Starkey, 2000) and causes athletes to limit or cease their sport activities (Blond & Hansen, 1998; Witvrouw et al., 2000). Athletic activity of 74% of PFPS patients is affected in some way, either through taking a break, playing at a lower level or being forced to stop (Blond & Hansen, 1998). In some cases, PFPS patients are forced to change their employment as they cannot meet the physical demands of their job (Blond & Hansen, 1998).

Symptomatic knee OA is more likely to occur in the PFJ than the TFJ and also has a greater impact on daily activities (Duncan et al., 2008; Risberg & Ekeland, 1994). It has been reported that those who experience anterior knee pain during adolescence or early adulthood are more likely to suffer from PFJ OA (Utting et al., 2005). This suggests PFPS can have a large negative impact on an individuals' short-term athletic activities and, perhaps more importantly long-term, on employment and quality of life.

2.1.4. Incidence of Anterior Cruciate Ligament and Patellofemoral Joint Injury

The incidence of ACL injuries is only 0.1-0.3 per 1000 athlete exposures (Gwinn, Wilckens, McDevitt, Ross, & Kao, 2000; Mihata, Beutler, & Boden, 2006; Myklebust, Maehlum, Holm, & Bahr, 1998). Incidence of PFPS is greater at 1.09 injuries per 1000 exposures (Myer et al., 2010). This seems a small problem in comparison to common injuries, such as ankle ligament and hamstring muscle strains, with incidence rates up to 3.19 per 1000 exposures (Agel et al., 2007; Deitch et al., 2006). However, the consequences of ACL and PFJ injuries, in terms of time-loss, future participation and increased risk of OA, make these among the most serious and problematic injuries in sport.

Of greatest concern is the disparity in ACL and PFJ injury rates between sexes. With women at least twice as likely to suffer ACL or PFJ injuries across a range of sports and competition

levels (Agel et al., 2005; Arendt et al., 1999; Boling et al., 2010; Deitch et al., 2006; Hewett et al., 1999; Messina et al., 1999; Myklebust et al., 1998; Powell & Barber-Foss, 2000; Taunton et al., 2002). Perhaps most importantly, women consistently suffer a higher rate of non-contact ACL injuries than men (Agel et al., 2005; Hewett et al., 1999; Mountcastle et al., 2007). The findings of previous studies are summarised in Figures 2.3 and 2.4.
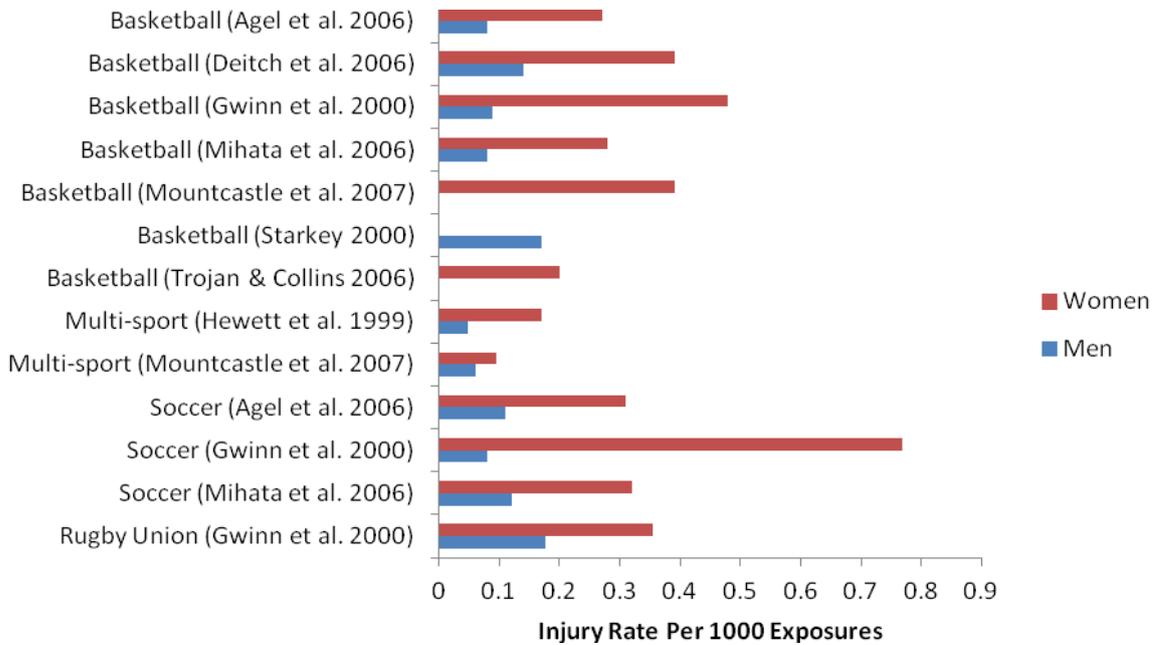
Figure 2.3– Comparison of overall Anterior Cruciate Ligament injury rates per 1000 exposures between men and women across a number of sports and levels of competition.
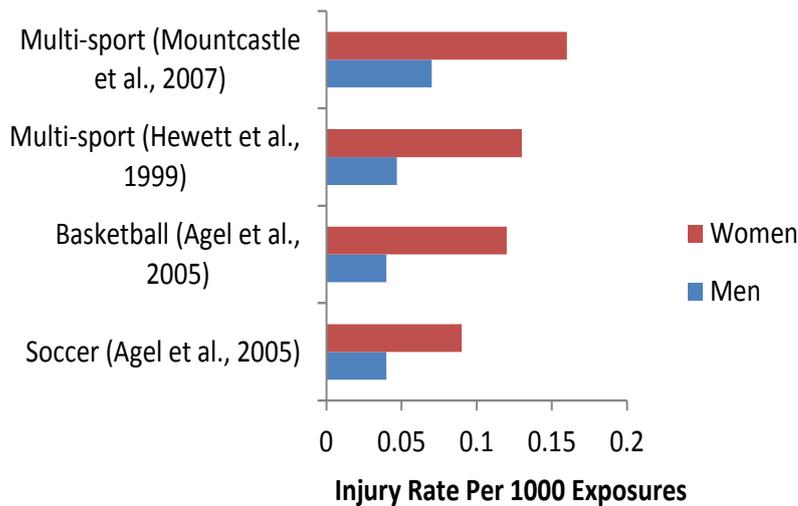
Figure 2.4 - Comparison of non-contact Anterior Cruciate Ligament injury rates per 1000 exposures between men and women across a number of sports and levels of competition.

2.2. Mechanisms of Knee Injury

The mechanisms of ACL (2.2.1) and PFJ (2.2.2) injury will now be discussed in detail.

2.2.1. Mechanisms of Anterior Cruciate Ligament Injury

60-70% of ACL injuries occur in non-contact situations (Agel et al., 2005; Faude et al., 2005; Giza, Mithöfer, Farrell, Zarins, & Gill, 2005; Mountcastle et al., 2007; Pasanen, Parkkari, Rossi, & Kannus, 2008c). Non-contact injuries may be avoidable and as these are the most common types of ACL injury, it is important to understand the injury mechanism to help reduce their occurrence.

Early studies used questionnaires to investigate ACL injury mechanisms. Most participants reported injury occurring during decelerating activities, such as changing direction (cutting) and unilateral and bilateral landing (Boden et al., 2000; Myklebust et al., 1998). The utility of questionnaires in this instance may be limited as it based on the individual's ability to recall the event. However, analysis of videotape footage of ACL injury occurrences support that cutting and landing account for the majority of non-contact injuries (Boden et al., 2000; Koga et al., 2010; Krosshaug et al., 2007a; Olsen et al., 2004). For example, non-contact injuries

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accounted for 16/20 incidents reviewed by Olsen et al. (2004), and 27/39 videos analysed by Krosshaug et al. (2007a). It was also noted that ACL injury occurs during the deceleration phase of these movements (Koga et al., 2010; Krosshaug et al., 2007a). Figures 2.5 and 2.6 show the cutting and landing mechanisms of non-contact ACL injury in Team Handball.

As well as the type of action performed at the time of injury, it is also important to understand the position of the body during these actions. Several studies have estimated lower limb joint angles through video-analysis of injury occurrence by experienced researchers (Boden et al., 2000; Krosshaug et al., 2007a; Olsen et al., 2004). The results show that athletes often land with the hip slightly flexed, adducted and internally rotated, with minimal flexion of the knee, the tibia externally rotated and evidence of a valgus knee collapse. This position can be seen in figures 2.5-2.7 and has been termed dynamic knee valgus or the 'position of no-return' (Hewett et al., 2005; Ireland, 1999).

Figure 2.5 – Dynamic knee valgus during the plant and cut mechanism of ACL injury in Team Handball (adapted from Olsen et al., 2004).

Figure 2.6 – Dynamic knee valgus during the one-legged landing mechanism of ACL injury in Team Handball (adapted from Olsen et al., 2004)
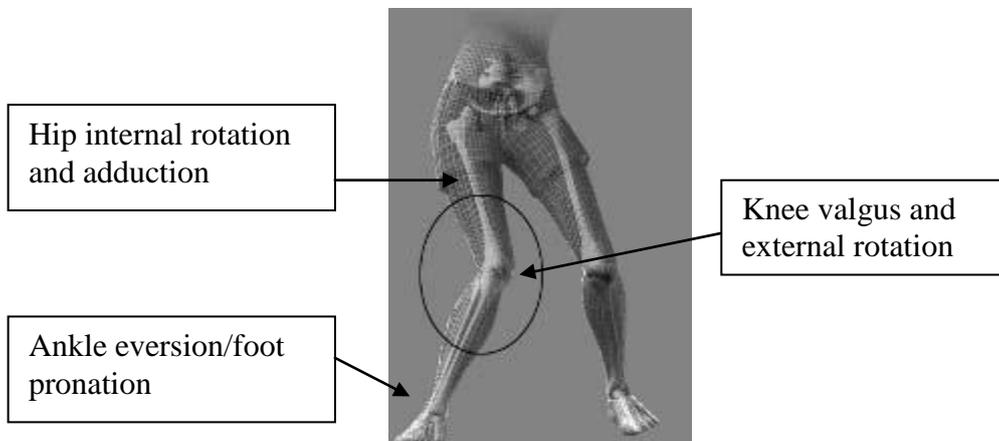
Figure 2.7 – Dynamic knee valgus (adapted from Hewett et al., 2006)

Most recently, a technique called model-based image-matching, which extracts joint kinematics from video recordings, has been used in an attempt to greater explain ACL injury mechanism (Koga et al., 2010). Difficulties in matching body parts, due to occlusion by other players or clothes, and assessment of axial rotations mean the methodology and joint angles calculated are not 100% accurate. However, they provide the most detailed and accurate description of injury mechanism to date. Despite the limitations of this method it produced

consistent results for knee kinematics during non-contact ACL injury situations (Krosshaug, Slauterbeck, Engebretsen, & Bahr, 2007b). It also confirmed previous findings that the knee flexion angle at initial contact tends to be low (<25º) with knee external rotation (external rotation of the tibia in relation to the femur) and valgus also being evident (Koga et al., 2010). Only knee joint kinematics were observed in this study therefore confirmation of previous findings at the hip is not possible.

Support for the dynamic knee valgus injury mechanism has also come in the form of in-vitro and 3D modelling studies which have explored the strain imparted on the ACL during specific movements at the knee joint. As knee joint stabilisation is achieved through a number of active muscular and passive ligament controls, it would seem plausible that more than one particular excessive movement would be required to bring about enough force to disrupt the ACL. Forces of at least 1500-2000N are required to cause disruption to the ACL (Chandrashekar, Mansouri, Slauterbeck, & Hashemi, 2006; Woo, Hollis, Adams, Lyon, & Takai, 1991). However, tensile properties of the ACL are not uniform throughout the population and forces as low as 1200N may cause ACL injury in women compared to 1700N in men (Chandrashekar et al., 2006). Anterior tibial shear causes the most strain on the ACL, but not with enough force to cause ligament rupture (Berns et al., 1992; McLean, Huang, Su, & Van Den Bogert, 2004b). Even in a 'worst-case scenario' sagittal plane injury mechanism computer simulation the resultant force on the ACL never exceeded 900N (McLean et al. 2004). However, anterior tibial shear with combined knee valgus and/or rotational moments cause significantly greater strain on the ACL, increasing the potential for injury (Berns et al., 1992; Markolf et al., 1995; McLean et al., 2004b). This is especially true at angles closer to full knee extension, further supporting the proposed mechanism of ACL injury (Berns et al., 1992; Ireland, 1999).

2.2.2. Mechanisms of Patellofemoral Joint Injury

Unlike ACL injury which has a traumatic onset and specific mechanism of injury, those with PFPS tend to suffer an insidious and gradually worsening onset of non-specific pain (Fulkerson, 2002). PFPS is commonly believed to be caused by maltracking of the patella on a stable femur during knee flexion and extension activities (MacIntyre, Hill, Fellows, Ellis, & Wilson, 2006; Powers, 2003). This maltracking causes abnormal increased PFJ contact pressures and over time leads to pathology. However, this does not take into account how the positions of the femur or tibia, relative to the patella, may influence PFJ contact forces (Barton, Levinger, Crossley, Webster, & Menz, 2012). More recently, this relationship has

been investigated and has shown that increases in hip adduction, hip internal rotation and tibial external rotation can decrease PFJ contact area and increase PFJ contact pressures (Lee et al., 1994; Lee, Morris, & Csintalan, 2003; Powers, Souza, Draper, & Fredericson, 2010; Salsich & Perman, 2007). Figure 2.8 shows a diagrammatic representation of how changes in patella position, resulting from either patella maltracking or changes in tibial or femoral position, can reduce the load bearing surface of the patella and increase PFJ contact pressures.
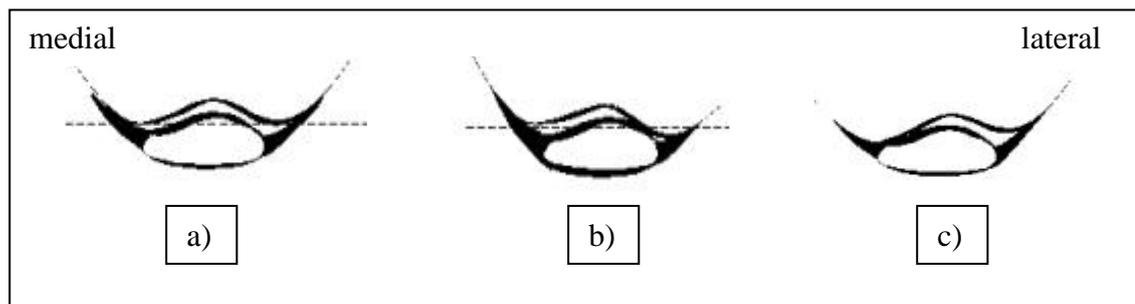
Figure 2.8 – The effect of changes in patella, tibial or femoral position on the load bearing surface of the patella – a) neutral position with equal load bearing at both the medial and lateral patella facets; b) increased lateral displacement with resultant increased load bearing of the lateral patella facet; c) increased medial displacement with resultant increased load bearing of the medial patella facet (adapted from Lee et al., 2004)

Abnormal motion of the patella, femur or tibia can decrease the size of the load bearing surface of the patella, resulting in altered distribution of forces and excessive PFJ stress. Continuous overload of the PFJ in this way can lead to a loss of peripatellar tissue homeostasis, leading to pain (Dye, Staubli, Biedert, & Vaupel, 1999). Patients with PFPS demonstrate greater PFJ stress during walking and squatting as a result of reduction in PFJ contact area (Brechter & Powers, 2002; Farrokhi, Keyak, & Powers, 2011b). Changes in PFJ contact area can cause wear of the articular cartilage (Salsich & Perman, 2007). However, articular cartilage is not an innervated structure and cannot be a source of pain (Biedert, Stauffer, & Friederich, 1992). Therefore, it is thought that the subchondral bone is a source of pain in PFPS (Biedert & Sanchis-Alfonso, 2002; Dye, Vaupel, & Dye, 1998). This is supported by the presence of significantly decreased patella cartilage thickness in PFPS patients, suggesting that by the time symptoms arise, the degenerative process is likely to be well underway (Farrokhi et al., 2011a). The higher incidence of PFJ OA in adults who suffered from anterior knee pain during adolescence also reflects this (Utting et al., 2005). Hence, chronic overloading of the PFJ resulting from changes in lower limb motion causes

cartilage wear, increasing symptoms and decreasing activity levels (Blond & Hansen, 1998; Fulkerson, 2002).

2.3. Risk Factors for Anterior Cruciate Ligament Injuries

This section reviews the proposed risk factors for non-contact ACL injuries only. If the risk factors for non-contact ACL injuries are better understood, some may be modified and injuries prevented. Extrinsic and intrinsic risk factors linked to ACL injuries include: shoe type, hormonal and anatomical factors and poor NMC (Ireland, 1999). Extrinsic factors will be briefly discussed in section 2.3.1. Intrinsic risk factors will be reviewed in greater detail in section 2.3.2. Neuromuscular control, which is a proposed risk factor for both ACL and PFJ injuries, will be reviewed later in section 2.3.4.

2.3.1. Extrinsic Risk Factors for Anterior Cruciate Ligament Injury

Extrinsic factors are those external to the individual and include; surface type; shoe type; and weather conditions. Injury rates on synthetic surfaces, where the coefficient of friction is greater, are significantly higher than on wooden floors (Olsen, Myklebust, Engebretsen, Holme, & Bahr, 2003; Pasanen et al., 2008c). More cleats on the boots of American football players, which increases torsional resistance between shoe and surface, is associated with greater risk of ACL injury (Lambson, Barhnill, & Higgins, 1996). It has been reported that ACL injuries occur more frequently during periods of lower rainfall when friction between shoe and surface is greater (Orchard, Seward, McGivern, & Hood, 1999; Orchard & Powell, 2003). Increases in friction through these mechanisms mean that the foot is fixed and minimises the rotation available between shoe and surface, which may then transfer to the ankle and knee joints. Thus increased friction may lead to increased risk of sustaining ACL injury risk. Changes in surface and shoe types to decrease friction may be possible, however this may come at the detriment to performance.

2.3.2. Intrinsic Factors for Anterior Cruciate Ligament Injury

Intrinsic risk factors for ACL injury are summarised in table 2.1. Each will be discussed in the section referenced, including potential differences between men and women that may influence their disparity in injury rates.

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Table 2.1 – Summary of section content for intrinsic risk factors for Anterior Cruciate Ligament injury.

Intrinsic risk factors	Section
Anatomical	**2.3.2.1**
• Femoral notch width and shape	2.3.2.1a
• Joint laxity	2.3.2.1b
Hormonal	**2.3.2.2**
Sagittal plane mechanics	**2.3.2.3**

2.3.2.1. Anatomical Risk Factors

a) Femoral intercondylar notch size:

This is potentially important as the ACL is housed in this notch. Studies investigating femoral intercondylar notch width and its relationship to ACL injury have reported conflicting results (Harner, Paulos, Greenwald, Rosenberg, & Cooley, 1994; Herzog, Silliman, Hutton, Rodkey, & Steadman, 1994; Laprade & Burnett, 1994; Shelbourne, Davis, & Klootwyk, 1998; Souryal, Freeman, & Daniel, 1993; Uhorchak et al., 2003). This conflict is likely due to use of the femoral intercondylar notch width in some studies and the notch width index, i.e. the ratio of the notch width to the femoral bicondylar width in others (Shelbourne et al., 1998). These two measures are demonstrated in figure 2.6. Femoral bicondylar width is influenced by an individual's height whereas notch width is not. Therefore the notch width index is inherently influenced by the person's height (Shelbourne et al., 1998). As a result, Shelbourne and colleagues recommended the use of the femoral intercondylar notch width rather than notch width index.
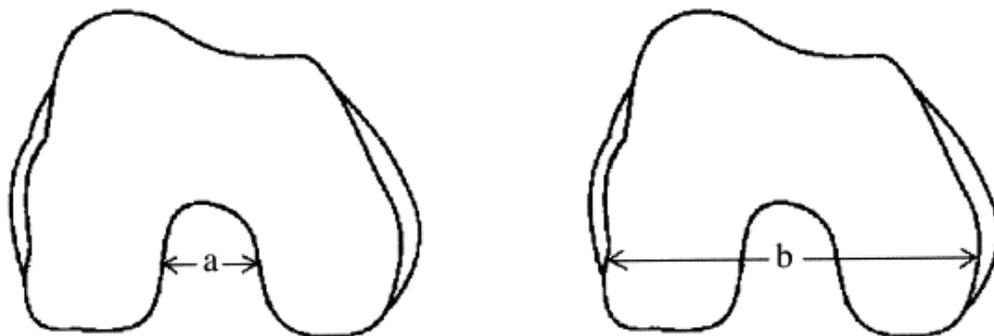
Figure 2.9 –Femoral condyle notch width measures. A - femoral intercondylar notch width; B – femoral bicondylar width: A:B – notch width index (adapted from Tillman et al. (2002).

A relationship between smaller intercondylar notch width and ACL injury has been shown (Uhorchak et al., 2003). However, the reason for this relationship is unclear with two theories having been proposed; ACL impingement upon the intercondylar notch wall, and smaller ACL size.

Impingement:

3D modelling of the knee joint has shown that the ACL may be impinged against the lateral wall of the femoral notch during movements which include knee valgus and tibial external rotation, as shown in figure 2.10 (Fung, Hendrix, Koh, & Zhang, 2007; Fung & Zhang, 2003). This impingement may cause disproportionate loading of a specific portion of the ACL, leading to an increased risk of injury. Fung et al. (2007) created 3D models of the knees of several uninjured and ACL injured patients from magnetic resonance (MR) images. The participants included five women (two injured) and two men (one injured). Impingement and elongation of the ACL was assessed in each knee during combined knee valgus and external rotation movement at approximately 40-45° knee flexion. Three out of five female knees, including both ACL injured participants, showed impingement with 8º of knee valgus and 5º of tibial external rotation. Four of the five female knees and the injured male knee demonstrated impingement during the simulation, whereas no impingement was detected in the final female and male uninjured knees. When impingement of the ACL occurred, a modest increase in strain of up to 1% was seen. While this is only a small increase and is unlikely to cause rupture alone, any increase in strain is likely to increase injury risk. Furthermore, the movement patterns in this study were based upon a previous study, in which strain was measured during manual manipulation of the cadaveric knee. Therefore, this increased strain created by impingement is likely to be substantially greater during functional activities. It was also noted that the knees in which substantial ACL impingement was present showed no common geometric features that were different to those with little or no impingement. The results of the study indicate that combined knee valgus and external rotation movement can cause impingement of the ACL in some, but not all, knees and it is unclear whether this impingement is a result of specific geometry of the intercondylar notch.
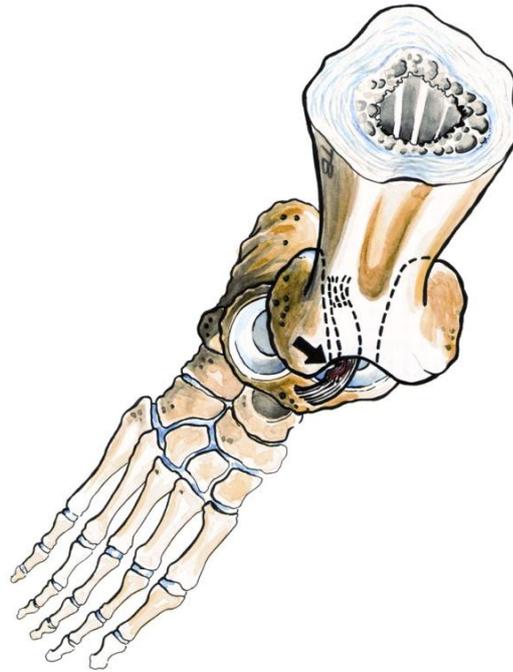
Figure 2.10 – ACL impingement on the femoral condyle caused by tibial external rotation and knee valgus (adapted from Olsen et al., 2004).

ACL size:

Shelbourne et al. (1998) hypothesised that notch width alone does not account for differences in injury rates, rather the smaller notches found in women house a smaller ACL, which may be weaker and more susceptible to injury. The basis for this theory followed their study in which they found that patients who undergo ACL reconstruction with the same size ACL graft have similar graft failure rates regardless of notch width and sex (Shelbourne et al., 1998). It has been reported however that femoral notch width is correlated to ACL size in men but not in women (Chandrashekar, Slauterbeck, & Hashemi, 2005). Notwithstanding this, the female ACL has been found to be smaller in length, cross-sectional area and volume and to have lower load resistance than the male ACL (Chandrashekar et al., 2005; Chandrashekar et al., 2006). Therefore, it seems likely that a combination of the difference in ACL properties and smaller intercondylar notch width would contribute to increased injury risk in women.

b) Joint Laxity:

Increased knee-joint anterior laxity has been linked to an increased risk of ACL injury in both men and women (Myer, Ford, Paterno, Nick, & Hewett, 2008; Uhorchak et al., 2003). However, despite increases in ACL injury risk due to increased knee joint anterior laxity in both men and women, differences in knee joint laxity between ACL-injured and uninjured participants were only evident in women (Uhorchak et al., 2003). Greater anterior laxity in the

knee can result in altered NMC via changes in muscular activity, such as delayed activation of the hamstrings (Shultz, Carcia, & Perrin, 2004), Additionally, participants with greater frontal and trasverse plane knee joint laxity demonstrate greater hip internal rotation, hip adduction and knee valgus angles than those with lower laxity values (Shultz & Schmitz, 2009). Increases in knee joint laxity may therefore lead to greater instability, increased anterior tibial translation and resultant shear force, and increase in dynamic knee valgus therefore increasing ACL strain.

Women tend to exhibit greater knee joint laxity and diminished proprioception compared to men (Myer et al., 2008; Rozzi, Lephart, Gear, & Fu, 1999; Uhorchak et al., 2003) which may increase their injury risk. A combination of smaller intercondylar notch width, high body mass index (BMI) and increased knee joint laxity was able to predict all ACL injuries in women, but none in men (Uhorchak et al., 2003). However, dynamic stability of the knee is affected by both passive and active restraints (Rozzi et al., 1999; Shultz et al., 2004). This further emphasises the complexity of the ACL injury risk paradigm. It would seem that smaller notch widths, structurally weaker ACL's and increased knee joint laxity in women play a part in explaining some of the disparity in injury rates between men and women. However, each of these anatomical factors cannot be modified, therefore limiting the ability to influence injury rates as a result of their understanding.

2.3.2.2. Hormonal Risk Factors

The different hormonal profile of men and women may contribute to disparity in injury rates. The primary drivers behind this theory are:
   a) the changes in hormonal profile during the menstrual cycle
   b) differences in neuromuscular characteristics post-puberty (Barber-Westin, Noyes, & Galloway, 2006; Hewett, Myer, & Ford, 2004)

a). Changes in hormonal profile during the menstrual cycle

There is growing consensus that ACL injury risk does not remain constant throughout the menstrual cycle, although the time when risk is greatest and the exact mechanism for this are still debateable. A number of studies have suggested that injury risk is greatest during the pre-ovulatory phase (Arendt et al., 1999; Slauterbeck et al., 2002; Wojtys, Huston, Boynton, Spindler, & Lindenfeld, 2002; Wojtys, Huston, Lindenfeld, Hewett, & Greenfield, 1998). Whilst Myklebust et al. (2003a) found ACL injury risk to be greatest in the week before or

just after onset of menstruation. Arendt et al. (1999) reported injuries were spread evenly between pre and post ovulatory phases with fewest injuries occurring during the ovulatory phase. These differences in injury susceptibility within the menstrual cycle led to the suggestion that use of the oral contraceptive pill may have a protective effect. However, Agel et al. (2006) found that it had no effect on non-contact ACL injury rates.

The effect of hormones on injury risk may not be direct, for example an increase in oestrogen concentration may not automatically increase risk of injury. Rather, changes in ligament properties and NMC have been proposed. ACL laxity progressively increases up to the time of peak oestrogen and progesterone levels (Heitz, Eisenman, Beck, & Walker, 1999), potentially increasing injury risk. However, changes in knee joint laxity and NMC are not evident (Chaudhari et al., 2007; Hertel, Williams, Olmsted-Kramer, Leidy, & Putukian, 2006b). Furthermore, use of the contraceptive pill has no effect on hip and knee angles or moments during several jump landing tasks (Chaudhari et al., 2007). The lack of consensus regarding effects of the menstrual cycle on injury risk may be due to the lack of consistency in terms and phases used to describe the cycle itself.

b). <u>Neuromuscular characteristic differences post-puberty</u>

Prior to puberty, ACL injury rates, knee valgus motion and lower limb strength are similar in boys and girls (Barber-Westin et al., 2005; Barber-Westin et al., 2006; Ford, Shapiro, Myer, Van den Bogert, & Hewett, 2010; Gottschalk & Andrish, 2011; Hewett et al., 2004). However, changes in neuromuscular characteristics are evident between men and women post-puberty along with subsequent differences in ACL injury rates previously described. As they mature women demonstrate significantly greater valgus motion (Ford et al., 2010; Hewett et al., 2004) and no changes in strength and power (Barber-Westin et al., 2006; Wikholm & Bohannon, 1991). Whereas men demonstrate increases in strength and power (Barber-Westin et al., 2006; Wikholm & Bohannon, 1991) and no changes in knee valgus (Barber-Westin et al., 2006; Ford et al., 2010; Hewett et al., 2004) as they mature. Furthermore, post-pubertal women exhibit greater valgus motion and lower strength and power than men (Barber-Westin et al., 2006; Ford et al., 2010; Hewett et al., 2004; Wikholm & Bohannon, 1991). The growth spurt associated with puberty increases lever lengths of the lower limb. The corresponding increase in strength in males during puberty enables them to counteract the changes in biomechanics and maintain or improve NMC of the knee. In contrast, females do not make the same adaptations in strength with decreased NMC of the

knee as a result. The changes in NMC between men and women post-puberty correlate with, and may be partly responsible for, the divergence in injury rates between the sexes.

The complexity of the female hormonal profile, the effect of the contraceptive pill and different varieties, and individual differences in hormone concentrations and their effects on psychological state, the ACL and neuromuscular system makes this area difficult to study adequately. However, it seems that the change in overall hormonal profile during puberty, which leads to changes in NMC, correlates with higher injury rates in the female athlete. Therefore a greater understanding of the contribution of NMC to injury risk is important.

2.3.2.3 Sagittal Plane Risk Factors

As described earlier it has been reported that movements in the sagittal, frontal and transverse planes contribute to ACL injury. The following section will review the factors that arise in the sagittal plane of movement and how they might influence non-contact ACL injury risk. The frontal and transverse planes of movement will be examined later in section 2.3.4.1.

Anterior tibial shear:

Cadaveric studies have demonstrated that anterior tibial shear causes the single most strain on the ACL (Berns et al., 1992; Markolf et al., 1995). Contraction of the quadriceps muscle group can cause significant anterior translation of the tibia via its attachment to the patella tendon (DeMorat, Weinhold, Blackburn, Chudik, & Garrett, 2004; Li et al., 1999; Shoemaker, Adams, Daniel, & Woo, 1993). In-vitro and in-vivo studies have shown that anterior translation and ACL strain caused by quadriceps contraction peaks between 15º and 30° of knee flexion (Arms et al., 1984; Beynnon et al., 1995; Beynnon, Howe, Pope, Johnson, & Fleming, 1992; Draganich & Vahey, 1990; Li et al., 1999; Pandy & Shelburne, 1997; Shoemaker et al., 1993). At angles close to full extension, large anterior shear forces as a result of quadriceps contraction are possible due to the angle between the patella tendon and axis of the tibia (Pandy & Shelburne, 1997). This relates to the position often observed during ACL injury episodes (Koga et al., 2010; Krosshaug et al., 2007a; Olsen et al., 2004). However, as the knee flexion angle increases the line of action of the quadriceps changes, decreasing its potential to cause anterior tibial shear, as shown in figure 2.11. DeMorat et al. (2004) showed that a 4500N quadriceps force applied via the patella tendon can cause ACL injury at 20° knee flexion. However, quadriceps force has been estimated to be less than 2000N, and never greater than 3124N at time of ACL injury (Faul, Erdfelder, Lang, & Buchner, 2007). These values fall short of the 4500N quadriceps force previously cited to

cause ACL injury via quadriceps contraction (DeMorat et al., 2004). In addition, disruption of the ACL only occurred in 6 out of 11 cadaveric knees subjected to the 4500N force (DeMorat et al., 2004), suggesting that 4500N quadriceps force does not equate to a 1500-2000N load at the ACL. Furthermore, the synergistic action of the hamstrings and quadriceps muscle groups, joint compression forces, and dissipation of landing forces at the ankle and hip are likely reduce the forces experienced by the ACL (McLean et al., 2004b). Therefore, it is unlikely that anterior shear alone will result in 1500-2000N load required to injure the ACL (Chandrashekar et al., 2006; Woo et al., 1991).
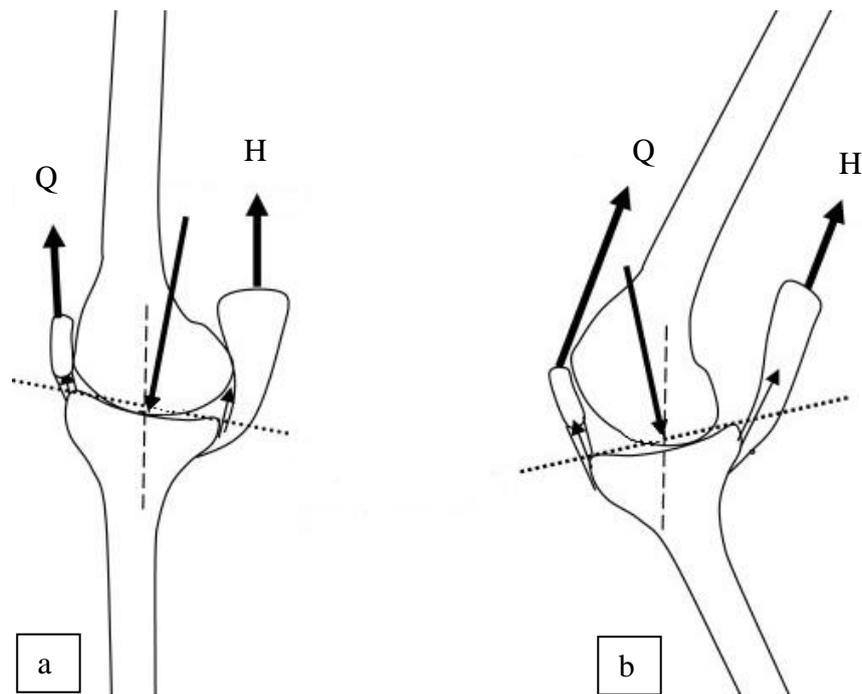
Figure 2.11 – A free-body diagram of the quadriceps (Q) and hamstring (H) forces acting upon the proximal tibia in the sagittal plane during different degrees of knee flexion (a) with the knee at full extension; (b) with the knee in a moderately flexed position (adapted from Hashemi et al., 2011).

Hamstring strength:

Contraction of the hamstring muscle group may help to prevent ACL injury by decreasing anterior shear (Draganich & Vahey, 1990; Li et al., 1999; Renstrom, Arms, Stanwyck, Johnson, & Pope, 1986). When working in isolation the hamstrings can decrease ACL strain throughout knee motion (Renstrom et al., 1986). However, changes in ACL strain and anterior shear when the hamstrings are acting synergistically with the quadriceps are inconsistent.

In-vitro studies have shown that antagonistic hamstring contraction can reduce ACL load and anterior shear at knee flexion angles greater than 10º (Draganich & Vahey, 1990; Li et al., 1999). The reduction in ACL load was 30, 43 and 44% at knee flexion angles of 15, 30 and 60° respectively (Li et al., 1999). Other studies have noted that ACL strain is significantly decreased from 30° to 90° of knee flexion but not at angles of 0, 15 and 30° (Pandy & Shelburne, 1997; Renstrom et al., 1986). As demonstrated in figure 2.11, when the knee is close to full extension the angle between the line of action of the hamstrings and the tibia is low, meaning the hamstrings are unable to generate large enough posterior shear forces to counteract anterior shear forces to protect the ACL (Pandy & Shelburne, 1997). It is therefore unclear whether the hamstrings can protect the ACL up to 30° knee flexion, the range in which ACL injury often occurs.

Whilst the hamstrings may decrease ACL strain in-vitro, whether this occurs during dynamic movements is questionable. Quadriceps and hamstring strength and ratio do not predict the amount of anterior tibial shear force exhibited during a drop jump task (Bennett et al., 2008). Evidence has shown that the hamstrings are recruited during running, turning and landing activities (Colby et al., 2000; Gehring, Melnyk, & Gollhofer, 2009) although hamstring electromyography (EMG) activity can be more than 50% lower than the quadriceps during these tasks (Colby et al., 2000). If hamstring muscle activity is low, particularly in comparison to the quadriceps, then increases in hamstring strength are likely to have negligible effects on reducing ACL load.

Increased hamstring torque demonstrated after a jump training intervention has been linked to decreases in vertical ground reaction forces (vGRF) which may decrease injury risk (Hewett, Stroupe, Nance, & Noyes, 1996). However, these decreases in vGRF could also be attributed to increased hip and knee flexion angles which have been seen after similar jump training programmes (Lephart et al., 2005; Myer et al., 2006).

The fact that women consistently display inferior relative hamstring strength and decreased hamstring to quadriceps peak torque ratios (Beutler et al., 2009; Hewett et al., 1996; Willson et al., 2006) suggests it may play a part in the overall injury risk profile. Perhaps of more importance is that women tend to recruit their hamstrings 15-20% less than men during dynamic movements (Malinzak, Colby, Kirkendall, Yu, & Garrett, 2001; Zeller et al., 2003). This would further jeopardise any potential for the hamstring muscles to decrease anterior shear and may contribute to increased injury risk in women.

<u>Knee flexion angles:</u>

Changes in sagittal plane angles at the knee can alter the load imparted on the ACL. As previously noted ACL strain is often greatest at angles nearer to full extension (Berns et al., 1992; Markolf et al., 1995). The potential for the quadriceps to cause anterior tibial shear, and therefore greater ACL strain, is also greatest at angles close to full extension (Arms et al., 1984; Beynnon et al., 1995; Beynnon et al., 1992; Draganich & Vahey, 1990; Li et al., 1999; Pandy & Shelburne, 1997; Shoemaker et al., 1993). Women often land with 20-25º knee flexion, which on average is 5-10º less than men (Chappell et al., 2005; Decker et al., 2003; Huston, Vibert, Ashton-Miller, & Wojtys, 2001; Malinzak et al., 2001). Additionally, women display decreased flexion angles and absorption of force at the hip which results in increased loads on the knee (Chappell et al., 2005; Decker et al., 2003). The greater sagittal plane loads exhibited by women, coupled with increased quadriceps activation and decreased hamstring activation may all contribute to increased ACL strain and likelihood of injury.

<u>Summary</u>

It has been questioned whether sagittal plane loading alone is able to cause ACL rupture. Whilst it is clear that increased anterior tibial shear forces, as a result of large quadriceps forces acting at relatively low knee flexion angles during decelerating manoeuvres, play a role in increasing ACL strain, factors such as posterior ground reaction forces and synergistic muscle contraction may also protect the ACL (Markolf et al., 1995; McLean et al., 2004b). As such, forces caused by these sagittal plane mechanisms, may have been overestimated with regards to their potential to cause ACL injury. Biomechanical modelling has suggested that frontal plane loading is more important in ACL injuries (McLean et al., 2004b). As mentioned previously, knee valgus or rotational motion can significantly increase ACL strain and may also cause impingement of the ACL on the lateral wall of the intercondylar notch causing further supra-physiological loading conditions (Berns et al., 1992; Fung et al., 2007; Fung & Zhang, 2003; Markolf et al., 1995). This increase in ACL strain resulting from transverse and frontal plane movements of the lower limb emphasises the potential importance of dynamic valgus during functional tasks as a potential risk factor for increased ACL injury risk. Dynamic knee valgus as a risk factor for ACL injury will be discussed in further detail in section 2.3.4.1.

2.3.3. Risk Factors for Patellofemoral Joint Injury

Proposed risk factors relating specifically to PFJ injury have focused on patella malalignment as a major risk factor for injury. Two factors which may directly influence patella alignment will be discussed in this section:

- vastus medialis muscle properties (2.3.3.1)
- Illiotibial band tightness (2.3.3.2).

2.3.3.1. Vastus Medialis Muscle Properties

Weakness of the quadriceps muscle group, and in particular vastus medialis (VM) and vastus medial obliqus (VMO), is believed to affect the alignment of the patella. Figure 2.12 shows the muscles which interact with the patella and the action of each. VMO has an attachment on the medial side of the patella and is therefore viewed as a medial stabiliser to counteract the lateral pull of the vastus lateralis (VL) (Phornphutkul, Sekiya, Wojtys, & Jacobson, 2007). As a result variables such as VMO strength and contraction timing have been investigated to establish their effect on patella postion, contact pressures and correlation to PFPS.
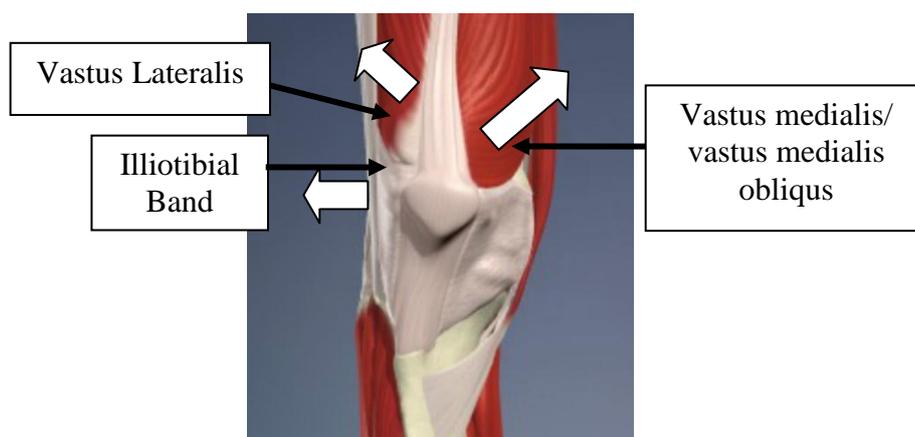
Figure 2.12 – Muscles affecting motion of the patella. (Primal Images, London, UK)

Decreases in VMO strength have been shown to increase lateral patella shift and PFJ load (Neptune, Wright, & van den Bogert, 2000; Sakai, Luo, Rand, & An, 2000). A decrease in VMO torque of 25% was enough to increase lateral patella shift by 0.24cm at 0-15° of knee flexion in cadavers (Sakai et al., 2000). An increase in VMO strength of 10% decreased peak lateral PFJ load by 4.5% in a running simulation model (Neptune et al., 2000). Additionally, Neptune et al. (2000) found that a delay in VMO contraction of 5ms could significantly increase peak lateral PFJ load. However, the authors conceded that differences in individual anatomy were not accounted for, meaning that differences in PFJ orientation between

individuals could result in different contact forces. Therefore the magnitudes and significance of PFJ load resulting from changes in VMO timing in the model cannot be inferred to the wider population. How these findings may relate to PFJ mechanics in-vivo has not been investigated.

A delay in the timing of VMO contraction relative to VL may play a role in the development of PFPS (Boling, Bolgla, Mattacola, Uhl, & Hosey, 2006; Cowan, Bennell, Hodges, Crossley, & McConnell, 2001; Cowan, Hodges, Bennell, & Crossley, 2002; Van Tiggelen, Cowan, Coorevits, Duvigneaud, & Witvrouw, 2009). It has been hypothesised that a delay in VMO contraction might increase lateral PFJ load via lateral shift of the patella (Chester et al., 2008), although this hypothesis has not been tested. Whether a difference in VMO contraction timing is consistently evident between PFPS patients and healthy controls is not clear (Boling et al., 2006; Cavazzuti, Merlo, Orlandi, & Campanini, 2010; Cowan et al., 2001; Cowan et al., 2002; Pal et al., 2011; Witvrouw et al., 2000). Even in studies where significant differences in contraction timing have been found, the standard deviations are often relatively large and show a great deal of overlap between groups.

Prospective studies have also shown contradictory results with regards to whether differences in VMO and VL contraction timing exist between those who develop PFPS and those who do not (Van Tiggelen et al., 2009; Witvrouw et al., 2000). According to Van Tiggelen et al. (2009), those who developed PFPS had a delay in VMO contraction of 1.67ms compared to the VL, whereas healthy subjects VMO contraction preceded VL by 4.86ms, a difference of 6.15ms. In contrast, Witvrouw et al. (2000) found both healthy and PFPS subjects exhibited a delay in VMO contraction compared to VL, with a difference of only 0.25ms between the groups. The functional value of the tasks employed in both studies is questionable; Van Tiggelen et al. (2009) measured EMG activity during a static toe raise exercise, whilst Witvrouw et al. (2000) measured activation when the knee jerk reflex was activated via a patella tendon tap. Therefore it is unclear whether a VMO delay of 1.67ms, as observed by Van Tiggelen et al. (2009), would be clinically significant or measurable, or indeed whether such a small difference can be reliably detected using surface EMG. Additionally, a delay in VMO contraction timing does not necessarily correlate with force of the VL being high enough to change patella tracking in such a short space of time.

Tang et al. (2001) found that PFPS patients exhibited significantly decreased VMO:VL ratio of activation compared to asymptomatic subjects during an open kinetic chain knee extension

exercise. However, this was not evident during a closed chain squat exercise. In contrast, greater VL activation and decreased VMO:VL ratio has also been noted in PFPS subjects during closed chain static lunge, step-up and step-down and wall squat tasks (Miller, Sedory, & Croce, 1997). The findings of these studies must be interpreted with caution due to low sample sizes. Additionally, whether the difference in activation between VMO and VL is accompanied by decreased VMO strength is unclear and therefore the significance of these findings cannot be determined.

Pal and colleagues reported that women exhibit significantly greater patella maltracking measures than men in both the control and PFPS groups (Pal et al., 2011). Women also exhibit decreased VMO and VL activity and a lower VMO:VL activity ratio than men (Kim, Yoo, & Yi, 2009). These findings suggest that women may have increased likelihood for lateral patella translation due to decreased VMO activity which may increase their risk of PFJ injury. However, the presence of differences in patella translation between healthy men and women suggests that this does not always lead to pathology.

As with all cases of injury, individual differences play an important role. Despite the research interest into VMO and PFPS, there is currently insufficient evidence that VMO exists as a separate muscle with unique function, innervation and structure from the VM muscle (Hubbard, Sampson, & Elledge, 1997; Nozic, Mitchell, & de Klerk, 1997; Peeler, Cooper, Porter, Thliveris, & Anderson, 2005; Smith, Nichols, Harle, & Donell, 2009). This may in part account for the conflicting results regarding VMO and its effect on the patella. Furthermore, the lack of clarity evident in the literature to date is likely due to inconsistencies between studies with regards to populations studied, EMG recording methodologies, exercise selection and levels of loading used. In light of this, the current trend in research and clinical practice to focus on specific VMO strengthening as a general treatment for those with PFPS may be oversimplistic.

2.3.3.2. The Illiotibial Band

Alongside VL, the illiotibial band (ITB) is seen as a lateral stabiliser of the patella. The ITB is a continuation of the tensor fascia lata proximally and attaches to the lateral side of the patella via the lateral retinaculum (Terry, Hughston, & Norwood, 1986) (fig. 2.7). Loading of the ITB causes lateral patella translation in cadaveric knees (Kwak et al., 2000). This has lead to shortening or tightness of the ITB being postulated to cause lateral translation of the patella, thereby increasing lateral PFJ load and increased likelihood of pathology.

Obers test measures hip adduction in a side-lying position, and is commonly used as an indirect measure of ITB length (Herrington, Rivett, & Munro, 2006; Hudson & Darthuy, 2009; Melchione & Sullivan, 1993). A moderate correlation has been shown between the modified Obers test, where the test leg is bent to 90º of knee flexion, and lateral patella displacement (Herrington et al., 2006). In addition, PFPS patients exhibit a significantly decreased ITB length, measured using modified Obers test (Hudson & Darthuy, 2009; Puniello, 1993). These results imply that there is a relationship between ITB length, measured via the modified Obers test, and patella position and that tightness of the ITB may play a role in the development of PFPS. However, the evidence presented is not strong enough to suggest that ITB length alone is the only factor causing lateral patella displacement and prospective work is needed to investigate this link.

Summary

In summary, there is insufficient evidence to suggest that the VMO or ITB alone can cause PFPS, although they may form part of the clinical picture. Whilst PFPS patients tend to demonstrate more lateral translation of the patella (Herrington, 2008; MacIntyre et al., 2006), this is not always evident (Pal et al., 2011). Large variability and overlap in patella position in all individuals has been noted (MacIntyre et al., 2006; Pal et al., 2011). Therefore other factors which increase PFJ load, such as tibial and femoral movement relative to the patella, may play a part in increasing the likelihood of injury.

2.3.4. Neuromuscular control

Abnormal or poor NMC of the lower limb during functional activities has been suggested as an important component of ACL and PFJ injuries (Boling et al., 2009b; Hewett et al., 2006b; Ireland, 1999; Myer et al., 2010; Stefanyshyn, Stergiou, Lun, Meeuwisse, & Worobets, 2006). Despite significantly different non-contact ACL and PFJ injury rates between men and women post-puberty, there is no evidence to suggest this difference is apparent prior to puberty (Clanton, Delee, Sanders, & Neidre, 1979; Tursz & Crost, 1986). In addition, differences in strength and frontal plane knee motion are only evident post-puberty (Barber-Westin et al., 2005; Barber-Westin et al., 2006; Ford et al., 2010; Hewett et al., 2004). This divergence in injury rates and NMC post maturation has lead to changes in NMC being proposed as a major risk factor for ACL and PFJ injury. Furthermore, whilst the anatomical risk factors mentioned previously are largely unmodifiable, NMC of the lower limb may change in response to training thus helping to decrease injury risk (Barendrecht et al., 2011;

Hewett et al., 1999). Understanding of risk factors related to NMC is therefore paramount and this section will address:

- Dynamic knee valgus (section 2.3.4.1)
- Muscular strength (section 2.3.4.3).

2.3.4.1. Dynamic Knee Valgus and Anterior Cruciate Ligament and Patellofemoral Joint Injury Risk

Dynamic knee valgus, which is a combination of movements of the lower limb, has been proposed as an important risk factor in ACL and PFJ injury. Factors contributing to dynamic knee valgus (figure 2.13) will be discussed. Differences in these contributory factors between men and women will be detailed in section 2.3.4.2.

Hip internal rotation (a) and adduction (b)

Knee valgus (c)

External tibial rotation (d)

Foot pronation (e)
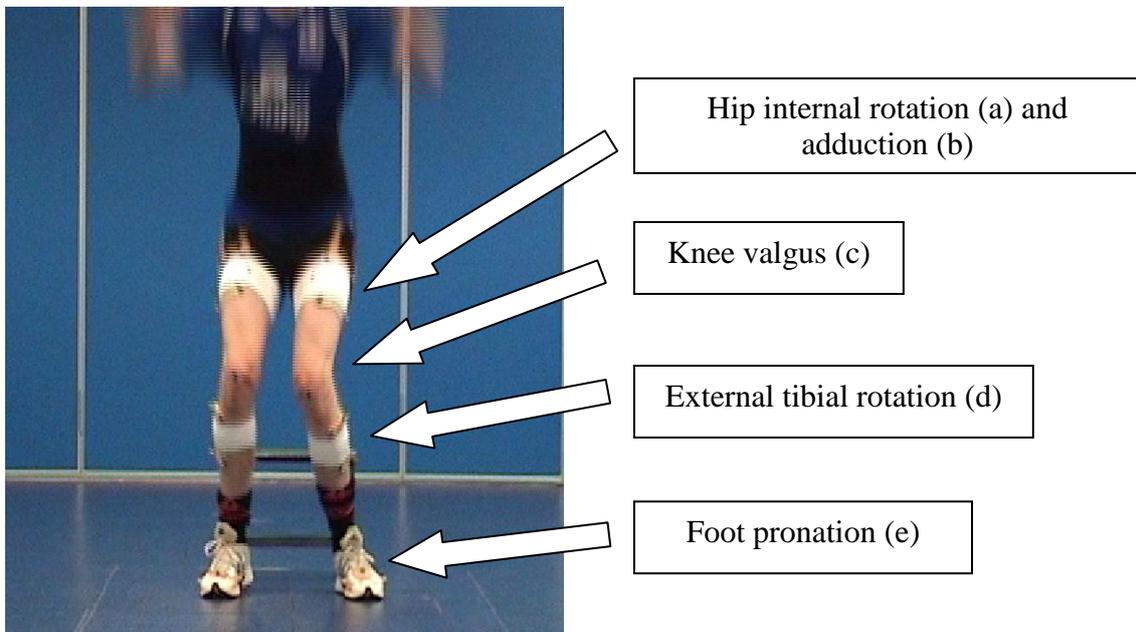
Figure 2.13 – Dynamic valgus of the lower limb

a) Hip Internal Rotation:

Hip internal rotation has been cited as a contributing factor to dynamic valgus (Ireland, 1999; Powers, 2003; Powers, 2010). Internal rotation of the femur will result in relative external rotation of the tibia at the knee joint, which can cause impingement of the ACL on the lateral femoral condyle wall, as shown in figure 2.10 earlier, thus increasing the strain and potentially increasing injury risk (Fung et al., 2007; Fung & Zhang, 2003). Increasing hip internal rotation can also influence patella alignment (Powers et al., 2010; Tiberio, 1987), decrease PFJ contact area (Salsich & Perman, 2007) and increase PFJ forces (Lee et al., 1994;

Lee et al., 2003). Figure 2.14 shows how rotation of the femur can influence the position of the patella and patella facet pressures. An increase in internal rotation of the femur (hip internal rotation) can increase the contact of the lateral patella facet on the lateral femoral condyle, causing increased pressure on the lateral patella facet (Lee et al., 2003).
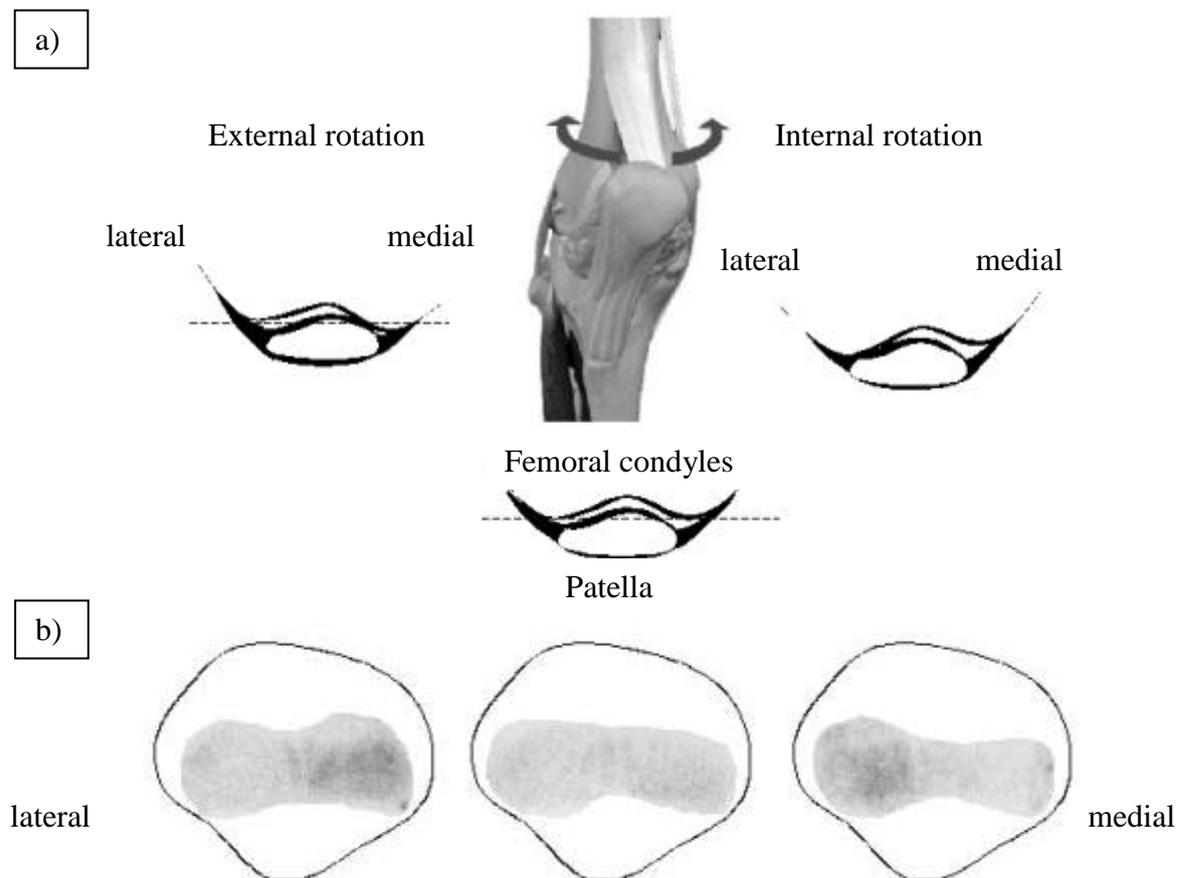
Figure 2.14 – The influence of femoral rotation on a) position of the patella and b) contact pressures of the patella facets; darker shades indicate higher pressure (adapted from Lee et al., 2003).

Women with PFPS have been shown to exhibit peak hip internal rotation angles between 5 and 8° greater than control subjects during running, drop jump, single leg squat and step-down tasks (McKenzie, Galea, Wessel, & Pierrynowski, 2010a; Nakagawa, Moriya, Maciel, & Serrao, 2012; Souza, Draper, Fredericson, & Powers, 2010; Souza & Powers, 2009a; Souza & Powers, 2009b). The greatest differences of 7.6-7.9° were noted during running (Souza & Powers, 2009a; Souza & Powers, 2009b). PFPS patients have also demonstrated 17% greater lateral displacement of patella accompanied by greater hip internal rotation during a single leg squat task (Souza et al., 2010). Increases in internal femoral rotation explain 29% of the variance in PFJ contact area, with increasing internal rotation correlated with decreased

contact area (Salsich & Perman, 2007). While this leaves 71% of the variance unexplained, it does account for a significant proportion.

Increases in hip internal rotation motion during landing and decreased available external rotation ROM also correlate with increased knee valgus motion (McLean, Huang, & van den Bogert, 2005a; Sigward, Ota, & Powers, 2008). McLean et al. (2005a) noted that hip internal rotation accounted for 56-60% of the variance in peak knee valgus moments during a sidestep cut. A prospective study recently found no difference in hip internal rotation between PFPS patients and healthy controls (Boling et al., 2009b). However a regression model which included hip internal rotation, knee flexion, vGRF and navicular drop was able to significantly predict the development of PFPS (Boling et al., 2009b).

Further links between hip internal rotation and PFPS patients are lacking, with several studies showing no difference between women with PFPS and control subjects across a number of tasks (Bolgla, Malone, Umberger, & Uhl, 2008; Willson, Binder-Macleod, & Davis, 2008; Willson & Davis, 2009). The contradictory findings to date may be due to the decreased reliability and increased error associated with measuring hip motion in the transverse plane (McGinley, Baker, Wolfe, & Morris, 2009). Additionally, it is difficult to determine whether changes noted in studies examining PFPS patients are a cause or effect of the injury itself and further prospective studies are needed to confirm this link.

b) <u>Hip adduction:</u>
Powers (2003) suggested that apparent increases in knee valgus may be caused by increases in hip adduction. This relationship has not been formally investigated, although hip adduction has been correlated to dynamic knee valgus measured via 2D FPPA (Willson & Davis, 2008b). It has also been noted that increases in hip adduction moment demonstrated a strong correlation with knee valgus moment in those who subsequently suffer ACL injury, but not in those who do not (Hewett et al., 2005). However, this was not the main aim of the study and little information was reported regarding this link. Additionally, excessive hip adduction has been observed during ACL injury episodes (Boden et al., 2000; Krosshaug et al., 2007a; Olsen et al., 2004). PFPS patients often demonstrate greater hip adduction compared to healthy controls during a number of tasks, although this is not always evident (Bolgla et al., 2008; Dierks et al., 2008; McKenzie et al., 2010a; Nakagawa et al., 2012; Souza & Powers, 2009a; Willson et al., 2008; Willson & Davis, 2008a; Willson & Davis, 2009). Where greater hip adduction angles are seen, they ranged from 2.4 to 5.5° greater in PFPS patients

(McKenzie, Galea, Wessel, & Pierrynowski, 2010b; Willson & Davis, 2009). In studies where no significant difference was noted, hip adduction values were generally greater in PFPS subjects. Once again, the cause-effect relationship cannot be determined in these studies. For example, Dierks et al. (2008) noted contralateral pelvic elevation in PFPS patients during running, which resulted in an overall abduction angle at the hip, despite the femur being adducted relative to the vertical. The authors suggested this may have occurred via ipsilateral side-lean of the trunk as a compensatory mechanism for decreased hip abduction strength. To date, no link between hip adduction and subsequent development of PFPS has been found prospectively (Boling et al., 2009b). Whilst hip adduction alone may not account for increased injury risk, its relation to knee valgus and dynamic knee valgus during movement may help to explain the possible link to injury.

An increase in hip adduction may lead to an increase in Q angle. The Q angle is a static approximation of the orientation of force of the quadriceps muscle group acting on the patella (Mizuno et al., 2001). A greater Q angle is believed to increase the likelihood of suffering PFPS by increasing the lateral pull of the quadriceps on the patella and therefore increasing the lateral patellofemoral contact pressure (Mizuno et al., 2001; Schulthies, Francis, Fisher, & Vandegraaff, 1995). However, no link between Q angle and PFJ injury has been found (Boling et al., 2009b; Pantano, White, Gilchrist, & Leddy, 2005; Witvrouw et al., 2000). This may be due to the static nature of the Q angle measure and its lack of correlation to dynamic measures (Pantano et al., 2005).

c) Knee valgus:

Knee valgus motion is also referred to as knee abduction. Here the term knee valgus will be used for consistency. Increased knee valgus angles and moments during landing, running and cutting tasks are related to, and predict ACL and PFJ injury (Boling et al., 2009b; Hewett et al., 2005; Myer et al., 2010; Stefanyshyn et al., 2006).

Isolated knee valgus angle and moment alone would not create sufficient load to injure the ACL without causing injury to the MCL first (Bendjaballah et al. 97, Matsumoto et al. 2001). It is the addition of knee valgus load to anterior tibial shear which has been shown to significantly increase strain on the ACL in-vitro (Berns et al., 1992; Markolf et al., 1995). Valgus collapse is often reported during ACL injury episodes (Boden et al., 2000; Krosshaug et al., 2007a; Olsen et al., 2004). In a prospective study of 205 women's soccer, basketball and volleyball players, 9 suffered non-contact ACL injuries (Hewett et al., 2005). Those who

suffered ACL injury exhibited significantly greater knee valgus angles and moments during a bilateral drop jump task at the beginning of the study (Hewett et al., 2005). ACL-injured women exhibited 5º knee valgus at initial contact and peak valgus of 9º, which was 8.4º greater than uninjured participants at initial contact and 7.6º greater at peak valgus. Whilst both ACL-injured and uninjured participants demonstrated peak valgus moments during the drop jump, valgus moments were 26.9Nm greater in those who suffered ACL injury. The addition of 10Nm of isolated valgus load causes significant increases in ACL loads in cadaveric knees (Fukuda et al., 2003; Markolf et al., 1995). In the study by Fukuda et al. (2003), the addition of 10Nm of valgus torque at knee flexion angles of 15-45° more than doubled ACL load to 35-40N compared with the load when 5Nm of valgus torque was added. It is possible that the 26.9Nm greater valgus moment in ACL injured subjects could increase ACL load by almost 100N. It is likely therefore that the greater peak valgus moments demonstrated by ACL-injured knees was a contributing factor to injury.

Prospective studies have shown that the presence of high knee valgus loads during running and landing tasks can predict PFPS (Myer et al., 2010; Stefanyshyn et al., 2006). The relationship to PFPS may be due to increased lateral patellar displacement observed during knee valgus postures (Noehren, Barrance, Pohl, & Davis, 2012). The increased PFJ stress caused by knee valgus alignment also increases the likelihood of lateral PFJ OA (Shultz, Schmitz, Nguyen, & Levine, 2010). Retrospective studies do not always support the notion of increased knee valgus in participants with PFPS compared to healthy controls (Bolgla et al., 2008; Dierks et al., 2008) although it could be argued that PFPS patients would avoid knee valgus positions due to pain.

Stefanyshyn et al. (2006) also noted that 20 PFPS patients demonstrated significantly greater knee valgus impulses than a matched control group. Knee valgus impulse was calculated as the amount of knee valgus moment demonstrated over time. The mean valgus impulse for PFPS patients was 17Nm/s compared to 12.5Nm/s in uninjured subjects, indicating a greater valgus load was experienced over the same period of time, thus increasing lateral PFJ load. However, further analysis of individual knee abduction impulse showed an equal distribution of injured participant's with impulse values higher or lower than those in the control group. This suggests that knee abduction impulse alone does not account for all instances of PFPS and the potential importance of other lower limb positions and individual anatomical differences.

d) <u>Tibial rotation:</u>

Ireland (1999) suggested that external rotation of the lower leg plays a role in ACL injury. External rotation of the tibia significantly increases ACL strain (Berns et al., 1992; Markolf et al., 1995), can cause ACL impingement (Fung et al., 2007; Fung & Zhang, 2003) and has been seen during injury episodes (Olsen et al., 2004). Internal tibial rotation results in greater ACL strain than external rotation (Berns et al., 1992; Oh, Lipps, Ashton-Miller, & Wojtys, 2012), however, external rotation can cause impingement of the ACL, leading to disproportionate increases in ACL in load, whereas internal rotation does not (Fung & Zhang, 2003). Additionally, internal rotation has not previously been identified during ACL injury episodes.

External tibial rotation also results in greater lateral patella translation (Noehren et al., 2012), decreased PFJ contact area and increased PFJ forces (Lee et al., 1994; Lee et al., 2003; Shultz, Dudley, & Kong, 2012). Figure 2.15 shows how rotation of the tibia can influence the position of the patella and patella facet pressures. Greater tibial external rotation results in a relative lateral shift of the patella and greater lateral patella facet pressure (Lee et al., 2003). Internal rotation of the tibia also results in thinning of the cartilage of the medial PFJ compartment (Salsich & Perman, 2007). It is likely that external rotation would bring about the same changes in the lateral compartment due to associated changes at the PFJ. Tibial external rotation can also cause an increase in Q angle due to lateral movement of the tibial tuberosity (Powers, 2003), which will increase lateral PFJ contact pressure (Mizuno et al., 2001). Despite the evidence that tibial rotation can increase ACL and PFJ loading, there is no research which has investigated the effect of tibial rotation on injury risk.
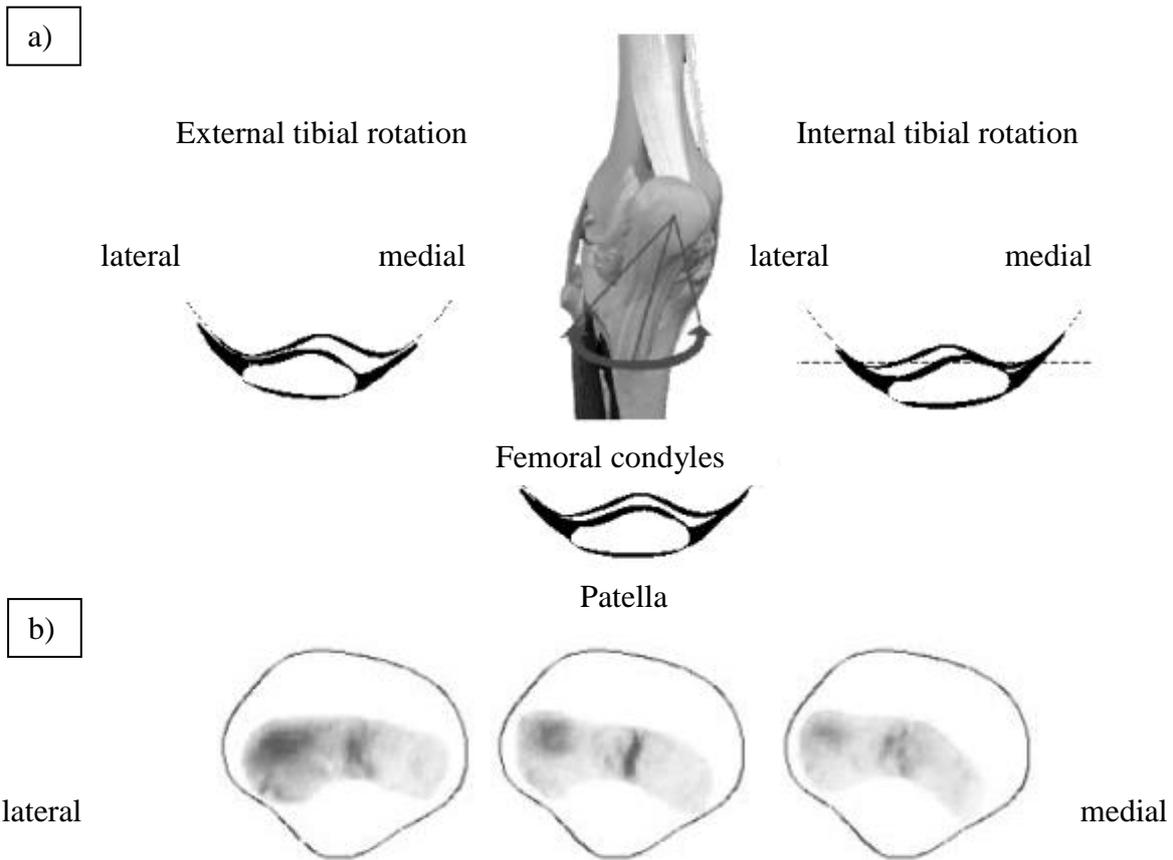
Figure 2.15 – The influence of tibial rotation on a) position of the patella and b) contact pressures of the patella facets; darker shades indicate higher pressure (adapted from Lee et al., 2003).

e) Foot pronation:

Subtalar joint eversion, a component of foot pronation, is coupled with internal rotation of the tibia during movement (Nawoczenski, Saltzman, & Cook, 1998). It has been postulated that for the knee to extend while the tibia is internally rotated the femur must also internally rotate causing both increased hip adduction (Tiberio, 1987) and lateral PFJ contact pressure (Lee et al., 1994; Lee et al., 2003). A recent study has confirmed the correlation between rearfoot eversion and hip adduction during gait (Barton et al., 2012). The authors suggested that the influence of foot kinematics on femoral motion may therefore lead to increased pronation being a risk factor for PFPS. Another potential influencing factor is decreased flexibility of the gastrocnemius and soleus muscles, which can lead to compensatory foot pronation in order to achieve required range of dorsi-flexion motion at the ankle (Piva, Goodnite, & Childs, 2005; Witvrouw et al., 2000).

Only one study has prospectively linked increased navicular drop, a static measure of pronation, with PFPS occurrence (Boling et al., 2009b). Navicular drop was almost 1cm greater in participants who subsequently suffered from PFPS. Retrospective links between arch height index, another static pronation measure, and PFPS have been conflicting (Dierks et al., 2008; Duffey, Martin, Cannon, Craven, & Messier, 2000). The static nature of these measures may not provide enough information about pronation during dynamic movement and its contribution to dynamic knee valgus. This may be demonstrated by the lack of association between arch height index and knee valgus angle during running (Dierks et al., 2008).

Therefore, studies which assess foot pronation during movement, rather than static measures provide a more valid assessment of the relationship between pronation and PFPS. As such, runners with anterior knee pain have been shown to demonstrate greater pronation during the first 10% of stance during running (Duffey et al., 2000). However, static measures of pronation provide a useful clinical tool, if they are linked to dynamic movement.

2.3.4.2. Differences in Dynamic Valgus between Men and Women

Women commonly demonstrate increased dynamic knee valgus and frontal plane lower limb motion during functional activities, as summarised in tables 2.2 and 2.3. (Ford, Myer, & Hewett, 2003; Herrington & Munro, 2010; Kernozek et al., 2005; Willson et al., 2006).

PFPS has a gradual onset and is often associated with running and squatting (Fulkerson, 2002). Women have been shown to exhibit significantly greater hip adduction, hip internal rotation and knee valgus angles during running (Ferber, Davis, & Williams, 2003; Malinzak et al., 2001) which is likely to cause an increase in PFJ contact pressures and load, potentially leading to injury. Additionally, Zeller et al. (2003) found that women perform the single leg squat task with greater hip adduction, knee valgus and foot pronation. Zeller et al. (2003) also found that women displayed lower hip internal rotation angles than men, although the authors did explain that this was mainly due to women exhibiting contralateral pelvic rotation which may have been interpreted as external rotation of the femur. Significant correlations between kinematics during the SLS and running suggest that this will lead to increased PFJ loads in women during running (Whatman, Hing, & Hume, 2011).

Differences in lower extremity motion between men and women during landing and change of direction tasks may relate to likelihood of sustaining an ACL injury. Bilateral and unilateral

landing, cutting and change of direction are common mechanisms of non-contact ACL injury (Boden et al., 2000; Olsen et al., 2004). Malinzak et al. (2001) assessed knee joint angles of recreational athletes (11 men and 9 women) during 45° side-cut and cross-cut manoeuvres. The side-cut task required participants to run and step off their dominant leg towards their non-dominant side, whilst the cross-cut required participants to step to the dominant side. The aim of both tasks was to simulate situations similar to common ACL injury mechanism. Women were found to demonstrate greater valgus angles than men in both tasks, with the average difference being 11° across tasks. Despite the small sample size of the study, similar results have been found in studies on collegiate athletes (McLean et al., 2007; McLean et al., 2005a; McLean, Lipfert, & van den Bogert, 2004a), suggesting that differences in knee valgus motion between men and women is common in the wider population. Although the magnitude of differences between men and women in collegiate athletes was lower than the 11° noted in recreational athletes. Furthermore, McLean et al. (2004a) found women also exhibited greater hip adduction and pronation angles than men during cutting manoeuvres. A number of studies have shown that women demonstrate increases in hip adduction, hip internal rotation, knee valgus and foot pronation motion during landing tasks (Barber-Westin et al., 2005; Barber-Westin et al., 2006; Brown, Palmieri-Smith, & McLean, 2009; Ford et al., 2003; Ford et al., 2010; Herrington & Munro, 2010; Hewett, Ford, Myer, Wanstrath, & Scheper, 2006a; Jacobs, Uhl, Mattacola, Shapiro, & Rayens, 2007; Kernozek, Torry, & Iwasaki, 2008; Kernozek et al., 2005; McLean et al., 2005a; Pappas, Hagins, Sheikhzadeh, Nordin, & Rose, 2007; Schmitz, Shultz, & Nguyen, 2009) all of which have the potential to increase ACL load.

Hewett et al. (2005) found that knee valgus angles and moments were able to predict future ACL injury. Several studies have shown that women demonstrate greater knee valgus angles than men during the drop jump task (Ford et al., 2003; Ford et al., 2010; Hewett et al., 2004). This trend has also been noted during stop jump tasks, bilateral and unilateral drop landings and hop landing tasks (Chappell, Yu, Kirkendall, & Garrett, 2002; Hewett et al., 2004; Jacobs et al., 2007; Kernozek et al., 2008; Kernozek et al., 2005; Pappas et al., 2007; Sell et al., 2006). Ford et al. (2010) found that high-school athletic women landed with at least 5° greater knee valgus angle and up to 11Nm greater valgus moments than men. Similar differences in knee valgus values of 4.5° were noted in the Pappas et al. (2007) study, whereas Kernozek et al. (2008) found differences of only 2.4°. These differences between sexes are at least 2° lower than those found between injured and uninjured women in Hewett et al. (2005) earlier prospective study, and it is unclear how much these differences would increase load on the ACL.

Overall, the increases in hip adduction, hip internal rotation, knee valgus and foot pronation commonly exhibited by women may lead to increases in dynamic knee valgus and therefore loads on the ACL and PFJ. This may, in part, explain some of the disparity in injury rates seen between men and women.

Table 2.2. Summary of the studies using 2D motion analysis that have shown differences in the dynamic knee valgus between men and women.

Study	Task	Measure	Results
Barber-Westin et al. 2005	30cm drop jump	Knee separation	W 4cm smaller knee separation distance = greater knee valgus
Willson et al. 2006	Single leg squat	FPPA	W greater FPPA (~4°)
Schmitz et al. 2009	30cm drop jump	Frontal plane dynamic valgus	Pre-puberty – no difference Post-puberty – W 3.8-6.3° greater dynamic valgus angle
Herrington and Munro 2010	30cm drop jump	FPPA	W 2.9-4.3° greater FPPA

W= women; FPPA = frontal plane projection angle

Table 2.3. Summary of the studies using 3D motion analysis that have shown differences in the dynamic valgus kinematics and kinetics between men and women.

Study	Task	Results
Ford et al. 2003	31 cm drop jump	W 2.5cm lower knee separation distance, therefore greater maximum valgus knee motion and ROM
Hewett et al. 2004	31cm drop jump	Pre-puberty- no differences. Post-puberty – W greater valgus at IC (4º) and peak (11º)
Ford et al. 2010	31cm drop jump	Pre-puberty – no differences between boys and girls Post-puberty – W 5.7º greater knee valgus angle and 19Nm/kg moment
Chappell et al. 2002	Stop jump task	W greater valgus moments during landing
Sell et al. 2006	Stop jump task	W 3.1-3.3º greater peak knee valgus angle
Malinzak et al. 2001	Running, 45°cut and 45° cross-cut	W 11º greater valgus angles in all tasks
Ferber et al. 2003	Running	W greater peak hip adduction (3.6º) and internal rotation (4.1º) and knee valgus (2.1º) angles
McLean et al. 2004	30 - 40° sidestep cut	W greater peak hip adduction, knee valgus and pronation angles. M greater peak hip internal rotation angle
McLean et al. 2005	30 - 40° sidestep cut	W 0.21Nm/kg/m greater peak knee valgus moment
Zeller et al. 2003	Single leg squat	W greater pronation (2.7º), valgus (1.9º) and hip adduction (3.2º) angles
Jacobs et al. 2007	Single leg hop landing	W 4º greater knee valgus angle
Kernozek et al. 2005	60cm drop landing	W greater peak knee valgus (24º) and pronation (21º) angles.
Kernozek et al. 2008	50cm single leg drop landing	W 2.4º greater peak knee valgus angles
Pappas et al. 2007	40cm drop landing (bilateral and unilateral)	W 4.5º greater peak knee valgus angle in both bilateral and unilateral tasks
Brown et al. 2009	Jump landing with 90° cut	W greater IC hip adduction, internal rotation and knee valgus angles. W greater PS hip internal rotation angle. M greater PS knee internal rotation angle. W lower hip abduction moment.

W = women; M = men; IC = initial contact; ROM = range of motion; PS= peak stance

2.3.4.3. Muscle Strength

Increased hip adduction and internal rotation causes increases in dynamic valgus (Hewett et al., 2005; Myer et al., 2010; Powers, 2003; Willson & Davis, 2008a). The hip musculature may play an important role in controlling hip motion and therefore reducing loads experienced at the knee. It has been suggested that hip muscle weakness demonstrated by women may account for the increases in hip motion they display (Hewett et al., 2005; Zeller et al., 2003). The hip musculature includes the gluteal muscles and hip external rotators, the strength of which may affect dynamic valgus of the lower limb during activity. Decreased strength of the hip abductors for example, may lead to increased hip adduction during activity as the muscles are unable to control the movement.

Decreased hip abduction and external rotation strength correlate with increases in hip adduction, knee valgus angles and 2D FPPA in healthy and PFPS participants (Claiborne, Armstrong, Gandhi, & Pincivero, 2006; Dierks et al., 2008; Lawrence, Kernozek, Miller, Torry, & Reuteman, 2008; Willson et al., 2006). Claiborne et al. (2006) studied the correlations between concentric and eccentric strength of hip muscles and knee valgus angles during the single leg squat task. In this study, concentric hip abduction alone significantly correlated (r= -0.37, r²= 0.13) with knee valgus angle. In contrast, (Willson et al., 2006) found that isometric hip external rotation strength demonstrated a significant correlation (r=0.4) to FPPA during a single leg squat, whereas hip abduction strength did not. Additionally, in a study by Lawrence et al. (2008) women identified as having strong hip external rotation values demonstrated decreased vGRF, knee valgus and hip adduction moments during single leg drop landings compared to a 'weak' group . In the Willson et al. (2006) and Lawrence et al. (2008) studies, isometric strength was measured, whereas Claiborne et al. (2006) measured concentric and eccentric strength which may account for the differences in results. Furthermore, it is unclear how the populations studied influenced the results; however, no information was given regarding the participants activity levels in the Claiborne or Lawrence studies, making evaluation of the effect of populations on results difficult.

The relatively low correlations for each strength variable across these studies indicate that, while lower limb strength may influence lower body mechanics, there are other factors which also contribute. Furthermore, the measurement of maximum isometric strength may not be relevant to dynamic movements. These notions are supported by a lack of relationship between isometric hip muscle strength and hip adduction, hip internal rotation and knee

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valgus motion in several studies (Beutler et al., 2009; Jacobs et al., 2007; Sigward et al., 2008; Willson & Davis, 2009).

Numerous retrospective studies have investigated hip strength in PFPS patients and healthy controls. PFPS patients have been shown to demonstrate 15-36% lower strength values in isometric hip abduction and external rotation strength tests compared to those of healthy participants (Bolgla et al., 2008; Bolgla, Malone, Umberger, & Uhl, 2011; Dierks et al., 2008; Ireland, Willson, Ballantyne, & Davis, 2003; Robinson & Nee, 2007; Willson & Davis, 2009). However, two studies have found hip muscle strength deficits not to be present in PFPS patients (Cowan, Crossley, & Bennell, 2009; Piva et al., 2005). The validity of the results of these two studies may be questionable however as the handheld dynamometer used to measure muscle strength was held by the experimenter and not secured with an immovable strap, whereas in the studies in which differences were found an immovable strap was employed. The use of an immovable strap improves reliability of the measure (Katoh & Yamasaki, 2009; Wikholm & Bohannon, 1991). Inadequate stabilisation of the handheld dynamometer and experimenter strength can adversely affect the participant's ability to exert maximum force, in the absence of an immovable strap, therefore resulting in an invalid test (Wikholm & Bohannon, 1991). Two studies which did not use immovable straps have shown differences in hip strength between PFPS and control subjects (Cichanowski, Schmitt, Johnson, & Niemuth, 2007; Robinson & Nee, 2007). However, the differences of 0.05N/kg and 0.03N/kg between the groups in the Cichanowski study are likely within measurement error of this method (Lu et al., 2011). The 6-8% difference between control and PFPS groups hip strength in the Robinson and Nee (2007) study is also low.

It could be argued that retrospective studies do not offer a valid picture of what caused the injury, rather a snapshot of the injured limb at that time, with strength decreases possibly a consequence of injury. However, deficits observed between injured and uninjured limbs of PFPS patients provides further evidence that hip strength plays a role (Cichanowski et al., 2007; Robinson & Nee, 2007). Neither of these studies used an immovable strap to secure the dynamometer and improve reliability and validity. In a similar fashion to the differences between PFPS patients and control subjects mentioned earlier, the 0.01N/kg and 0.04N/kg differences between injured and uninjured limbs in the Cichanowski et al. (2007) study are likely to be within the methods measurement error. However, Robinson and Nee (2007) quoted the intra-tester ICC reliability values of their method as greater than 0.94, suggesting that the method was in fact reliable. Furthermore, the LSI in PFPS subjects was 78% for hip

abduction strength and 79% for hip external rotation, showing large differences between limbs. Control subjects also demonstrated 93-101% LSI values, further supporting that the difference in strength between limbs was a potential causative factor of PFPS.

The significance of the role of the hip musculature in PFPS has been questioned by prospective studies (Boling et al., 2009b; Thijs, Pattyn, Van Tiggelen, Rombaut, & Witvrouw, 2011). Decreased hip external rotation strength has not been shown to be a predisposing factor for PFPS (Boling et al., 2009b; Thijs et al., 2011). Hip adduction strength was found to be significantly lower in those who subsequently suffered PFPS by Boling et al. (2009a). However, the difference between injured and uninjured participants was only 0.03% of body weight, suggesting a lack of true significance. In addition, Thijs et al. (2011) found isometric hip abduction not to differentiate between subsequent PFPS and uninjured female runners. Once again, the validity of the results is questionable due to both studies relying on the strength of the tester, rather than the use of an immovable strap. Furthermore, each of these studies assessed isometric hip strength using a handheld dynamometer in a lying position, which is a common method of strength assessment for the hip. However, this assessment method is not a true reflection of how the hip muscles function during activity, and the use of a fixed dynamometer would improve the reliability and validity of results, which may explain the lack of significant differences.

Kawaguchi and Babcock (2010) argued that the handheld dynamometer was a valid measure of isometric hip extensor and abductor muscle strength. In this study isometric hip strength measured using a handheld dynamometer was compared to that taken by an isokinetic dynamometer. Significant Pearsons correlation coefficients of 0.42 and 0.83 were found between the dynamometers for hip extension and hip abduction respectively. Whilst this shows some agreement between the measures, it also demonstrates that 31-82% of the variance in isometric hip strength scores on the isokinetic dynamometer was unexplained by the handheld dynamometer. One of the reasons for this may have been the lack of consistency in testing positions between the dynamometers; subjects were tested whilst standing on the isokinetic dynamometer compared to lying with handheld dynamometer. Therefore this study did not provide a clear assessment of the validity of the handheld dynamometer compared to the isokinetic dynamometer; rather it underlined the potential pitfalls of assuming that measures taken using a handheld dynamometer are a true representation of those taken using a fixed dynamometer. The assessment of concentric/eccentric muscle function or isometric function in a weight-bearing position using a fixed dynamometer may provide more

information about the role of the hip musculature with regards to frontal plane knee valgus motion during athletic tasks.

2.3.4.4. Muscular fatigue

The effect of muscular fatigue on factors which contribute to dynamic knee valgus may also provide information on the role of muscle strength. Assessment of overall lower limb system fatigue, using protocols which include running, cycling or compound exercises until a decrease in performance is observed, allows us to see what influence this has on overall lower limb biomechanics. This can help to assess the likely effect of overall fatigue on injury risk but does not allow for development of specific interventions to reduce this risk as the reason for the change in biomechanics is not apparent. No consensus can be seen on how overall system fatigue affects sagittal plane hip, knee or ankle motion (Benjaminse et al., 2008; Borotikar, Newcomer, Koppes, & McLean, 2008; Coventry, O'Connor, Hart, Earl, & Ebersole, 2006; Madigan & Pidcoe, 2003; McLean et al., 2007; Moran & Marshall, 2006; Orishimo & Kremenic, 2006; Tsai, Sigward, Pollard, Fletcher, & Powers, 2009) or regarding knee valgus motion (Benjaminse et al., 2008; Borotikar et al., 2008; Kernozek et al., 2008; McLean et al., 2007). One problem with comparing the results of these studies is the varying fatigue protocols, participants and assessment methods used. It would seem sensible that running would be a useful method of instigating fatigue in athletes who participate in sports such as football or basketball. However, only three studies have used this method of fatigue and they analysed the changes in lower limb mechanics using different tests (Benjaminse et al., 2008; Moran et al., 2009; Moran & Marshall, 2006). Overall, they found no changes occurred in peak knee flexion angles after fatigue, and Benjaminse et al. (2008) noted that peak knee valgus decreased. It is unclear at this time what affect overall system fatigue has on lower limb biomechanics during athletic tasks. Dierks et al. (2008) noted that runners with PFPS demonstrated strong correlation (r= -0.74) between isometric hip abduction strength and hip adduction angles at the end of a prolonged run, but no relationship was evident at the start, whereas the control group displayed no correlations before or after the run. This suggests that fatigue of the hip musculature may play a role in the aetiology of PFPS.

Assessing the effect of fatigue of specific muscle groups can help to ascertain the targeted muscle group's contribution to lower limb biomechanics. It has been suggested that strength of the gluteal muscle groups can influence lower limb biomechanics (Claiborne et al., 2006; Ireland et al., 2003; Willy & Davis, 2011) and so fatigue of these muscles may alter biomechanics. Few studies to date have assessed the effect of isolated hip abductor fatigue.

Those which have found that knee valgus tends to increase across a number of tasks, whilst hip adduction angle increased in landing activities but not cutting (Carcia, Eggen, & Shultz, 2005; Geiser, O'Connor, & Earl, 2010; Jacobs et al., 2007). Again the difficulty with comparison of these studies is the different measures of fatigue used in each, meaning that it is unclear whether participants across all studies were at the same level of fatigue and if these changes would be evident across the wider population. Thomas et al. (2011) also assessed the effect of hip external rotator fatigue on lower limb biomechanics during single leg landings and found only hip internal rotation angle to significantly increase. Any changes which do result from isolated muscle group fatigue would appear to be detrimental to the ACL and PFJ.

2.3.4.5. Gender differences in muscle strength

Women consistently demonstrate significantly lower relative hip abduction, external rotation and extension strength values than men (Beutler et al., 2009; Claiborne et al., 2006; Willson et al., 2006). Further analysis of these studies actually shows that the majority of the differences between men and women in isometric strength are small. Significant differences of only 1-6% body weight have been reported (Beutler et al., 2009; Leetun, Ireland, Willson, Ballantyne, & Davis, 2004; Willson et al., 2006). Concentric and eccentric torque of the hip abductors and external rotators has been shown to be 38.5-39Nm and 16-22Nm greater in men respectively (Claiborne et al., 2006). Although, Jacobs and Mattacola (2005) found that peak eccentric hip abductor torque relative to body weight was not different between recreationally active men and women. Whether these differences are due to different populations being studied cannot be determined due to this information not being present within the Claiborne et al. (2006) study.

When considered in the context of how this may affect lower limb motion during athletic tasks, it would be reasonable to assume that any decrease in strength would leave women at greater risk of ACL and PFJ injury.

2.4. Summary

Although incidence of ACL injury and PFPS is relatively low in comparison to other injuries, the short-term disablement and increased risk of OA associated with these injuries have made investigation into their mechanism, risk factors and prevention a focus for research. Despite this interest, no distinct profile of the ACL or PFJ injured athlete has been determined; many factors can potentially influence and cause injury to the ACL or PFJ.

A number of these factors are non-modifiable; hormonal concentrations and differences between sexes, femoral notch width and joint laxity. So whilst their effect on injury risk is important to understand, their potential to impact on injury rates is limited. NMC, which incorporates muscular strength and lower limb biomechanics, can be modified, and therefore understanding of these factors has greater potential to reduce injury risk. Assessment of NMC is commonly undertaken in laboratory environments, and as a result does not lend itself to large-scale screening of athletes in the field. In addition, assessment of strength and lower limb biomechanics separately is time-consuming. Therefore, further investigation of how to conduct large scale screening of athletes to identify those who demonstrate poor NMC associated with increased injury risk is warranted. The modifiable factors are summarised in figure 2.16.
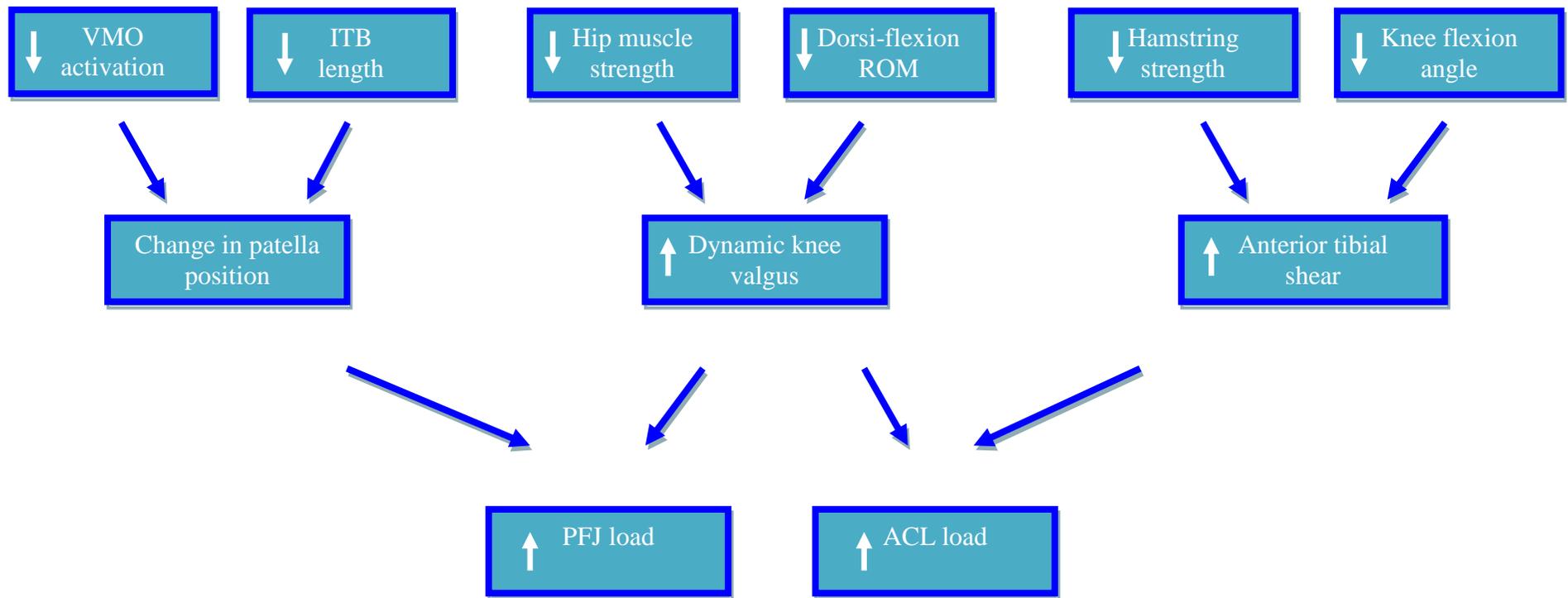
Figure 2.16. Summary of the potential modifiable intrinsic risk factors for Anterior Cruciate Ligament and Patellofemoral Joint injury.

2.5. Intervention Studies

Considering the modifiable factors mentioned in figure 2.16, intervention programmes have been developed to assess their effect on NMC and injury rates. This section will review the intervention studies undertaken to date. Section 2.5.1 will review those aimed at ACL injuries, whilst section 2.5.2 will review those aimed at the PFJ.

2.5.1 ACL Intervention Studies

Training programmes are the most common intervention strategy used to try and alter movement patterns which are regarded as high-risk for ACL injuries. These training programmes seek to modify numerous factors believed to relate to abnormal lower limb biomechanics such as strength, balance and flexibility (Chappell & Limpisvasti, 2008; Hewett et al., 1999; Noyes et al., 2005; Pfeiffer et al., 2006). Due to this scatter-gun approach they are often time and labour intensive with some programmes taking up to 90 minutes to complete, which eats into normal practice and training schedules and may have limited their uptake within sport. Furthermore, the results of the intervention programmes to date with regards to reducing injury rates and improving movement patterns have been conflicting and have consistently focused upon female athletes.

ACL Injury Rates

Significant reductions in non-contact ACL injury rates have been shown post intervention compared to previous injury rates and to control groups (Hewett et al., 1999; Mandelbaum et al., 2005; Myklebust et al., 2003a; Walden, Atroshi, Magnusson, Wagner, & Hagglund, 2012). However, numerous studies have demonstrated no difference in injury rates between control and intervention groups (Heidt et al., 2000; Myklebust et al., 2003a; Pasanen et al., 2008b; Pfeiffer et al., 2006; Soderman et al., 2000). Table 2.4 provides a summary of the intervention studies aiming to reduce injury rates which have taken place to date.

Hewett et al. (1999) investigated the effects of a six-week neuromuscular training programme, which included flexibility, strengthening and plyometric exercises, on injury rates in 1263 high-school soccer, basketball and volleyball players. The programme was 60-90 minutes in length and was completed three times per week, becoming progressively harder throughout. There were no non-contact ACL injuries in the trained females group, whereas five non-contact ACL injuries occurred in the untrained female group. Furthermore the trained females injury rate was similar to that of untrained males (Hewett et al., 1999). Despite the high

number of athletes in the study, only 6 non-contact ACL injuries were seen overall, limiting the strength of the findings. Additionally, there was an uneven spread of athletes from each sport. The trained group was made up of 185 volleyball, 97 soccer and 84 basketball players, whereas the untrained group had 81, 193 and 189 from each sport respectively. Considering that no volleyball players suffered an ACL injury, and previous research has shown lower ACL injury rates in volleyball players (Hootman et al., 2007), the fact that there was a greater number of volleyball players in the trained group is likely to have biased this group towards a lower injury rate.

Myklebust et al. (2003) assessed the effect of a continuous programme which aimed to improve balance and landing technique in women handball players over three seasons. The first season acted as a control season, in which 29 ACL injuries occurred at a rate 0.14 per 1000 player hours. The intervention programme was then implemented in the following two seasons. 23 ACL injuries occurred at a rate of 0.13 per 1000 player hours during the first season, which was similar to the control season. In the second intervention season the number of ACL injuries was reduced (17 injuries at 0.09 per 1000 player hours); however this change was not significant. Although the change in overall ACL injuries was not significant, the number of non-contact ACL injury reduced significantly from 18 in the control season to 7 in the second intervention season. Despite the significant reduction in non-contact ACL injuries, it could be argued that those who were at greatest risk of ACL injury may have been injured in the control season, therefore decreasing the likelihood of further ACL injuries in the intervention season. However, it has been noted that ACL injury rates have not changed significantly and may have in fact increased during the past two decades (Agel et al., 2005; Hootman et al., 2007) and therefore this is unlikely to be the case.

Two studies have used the Prevent Injury and Enhance Performance (PEP) warm-up programme in female soccer players with differing results (Mandelbaum et al., 2005; Gilchrist). Mandelbaum et al. (2005) studied 5703 high school soccer players, of which 1885 undertook the PEP programme, over a two-season period. The control group suffered 67 non-contact ACL injuries at a rate of 0.49 per 1000 athletic exposures (AE) overall, whereas the intervention group suffered only six injuries at a rate of 0.09 per 1000 AE. This equated to a significant reduction of 88% and 74% in years one and two respectively. In contrast, Gilchrist et al. (2008) found the PEP programme did not lead to a significant reduction in non-contact ACL injuries in collegiate soccer players; despite there being only two injuries (0.057/1000 AE) in the intervention group, compared to ten injuries (0.189/1000 AE) in the control group.

This equated to a 70% decrease in injuries in the intervention group. The low number of non-contact injuries in the study may have meant that statistical power was not sufficient to detect a significant difference despite the obvious reduction.

Several studies have found that other intervention programmes aiming to improve balance, strength, landing technique and agility, have had no effect on ACL injury rates (Heidt et al., 2000; Pfeiffer et al., 2006; Steffen, Myklebust, Olsen, Holme, & Bahr, 2008). In some studies, the small sample size and low number of injuries may have contributed to there being insufficient power to detect differences. For example, Heidt et al (2000) found that the intervention group in their study suffered one ACL injury, compared to eight in the control group. Despite the obvious difference, no statistically significant difference was found. In contrast, Pfeiffer et al. (2006) found that non-contact ACL injury rates were higher in the intervention group (0.107/1000 AE) than the control group (0.078/1000 AE) in a sample of over 1400 female high school athletes. Unlike in the earlier Hewett et al. (1999) study, there was a similar number of athletes from each sport, therefore there is unlikely to be any bias in injury rates between the groups as a result. These findings are supported by Steffen et al. (2008), who found injury rates to be similar between control and intervention groups in female soccer players aged 13-17 years. The authors in both studies commented on the low compliance rates with the intervention programmes and the potential for this to decrease their influence. The potential influence of programme compliance was further outlined by Walden et al. (2012) who found that injury rates were significantly reduced only in the subjects who completed the intervention programme more than once per week.

Modifying Risk Factors

A number of studies have assessed the influence of interventions on lower limb biomechanics. Increases in hip and knee flexion angles and decreases in hip internal rotation, knee valgus and internal rotation motion and GRF have been observed after various training programmes (Barendrecht et al., 2011; Cochrane et al., 2010; Irmischer et al., 2004; Lephart et al., 2005; Myer et al., 2006; Pollard et al., 2006a) although these changes are not always evident (Cochrane et al., 2010; Grandstrand et al., 2006; Herman et al., 2009; Lephart et al., 2005; Pollard et al., 2006a). Table 2.5 provides a summary of studies which have aimed to influence specific risk-factors for ACL injury.

High knee valgus angles and moments are seen as a key component of ACL injuries (Hewett et al., 2005). Several intervention programmes have been shown to reduce these deleterious

knee loads (Barendrecht et al., 2011; Chappell & Limpisvasti, 2008; Cochrane et al., 2010; Myer, Ford, Brent, & Hewett, 2007; Myer et al., 2006; Myer, Ford, Palumbo, & Hewett, 2005). The majority of these studies used a combination of different training modalities, such as plyometrics, balance, strengthening, agility and core stability, limiting the understanding of which aspect of training is able to bring about positive changes most efficiently. Additionally, some programmes took up to 90 minutes to complete (Myer et al., 2007; Myer et al., 2005) or were required to be completed daily (Chappell & Limpisvasti, 2008), which is likely to limit their uptake outside of research. Barendrecht et al. (2011) studied the effect of a 20 minute neuromuscular training programme - which included agility, balance, co-ordination, strengthening and plyometric exercises - on knee separation distances during the drop jump task in adolescent female handball players. The results showed that a programme undertaken two times per week over a ten week period was able to significantly reduce dynamic knee valgus, via an increase in knee separation distance. Furthermore, those with the greatest amount of valgus prior to commencement of training were found to have the greatest reduction in knee valgus. However, other studies which have used programmes with similar combinations of training modalities and time requirements have found no changes in knee valgus (Grandstrand et al., 2006; Lephart et al., 2005; Pollard, Sigward, Ota, Langford, & Powers, 2006b).

The PEP programme is the only intervention which has been assessed for its effects on both lower limb biomechanics and injury rates (Gilchrist et al., 2008; Mandelbaum et al., 2005; Pollard et al., 2006b). The PEP programme is used during warm-ups for all activities and has been shown to reduce hip internal rotation and increase hip abduction angles during a drop jump landing in high school female footballers (Pollard et al., 2006b). As previously discussed, injury rates in this same population have been shown to decrease as a result of using the programme (Mandelbaum et al., 2005). In contrast, injury rates in collegiate football players were found not to be significantly reduced, although there was a 70% decrease (Gilchrist et al., 2008). Whilst the PEP programme can affect lower limb biomechanics the findings of these studies can only be applied to female footballers. The lack of influence of the programme on knee valgus might reduce its effect on injury rates in other sports or populations.

Overall, it is unclear what types of training consistently lead to decreased injury rates and changes in lower limb control that may reduce injury risk. Therefore, studies evaluating the effects of single aspects of training are needed to assess how each modality may affect injury

risk. However, a limited number of studies to date have done this (Cochrane et al., 2010; Herrington, 2010; Irmischer et al., 2004; Myer et al., 2006; Soderman et al., 2000). Soderman et al. (2000) assessed the effects of 15 minutes of balance training undertaken throughout a season using a balance board on subsequent traumatic injuries in female soccer players. Despite a significant difference between groups in balance, measured via postural sway, no differences were observed in overall injury rates between the control and intervention groups. Of the five ACL injuries sustained during the study period, the intervention group suffered four, suggesting that balance training does not decrease the likelihood of sustaining an ACL injury. However, the study did not report whether the ACL injuries were sustained through contact or non-contact mechanisms, with contact ACL injuries generally unavoidable regardless of training undertaken. This, coupled with the low injury numbers mean it is unclear in this case whether balance training alone can affect non-contact ACL injury rates.

Cochrane et al. (2010) attempted to compare the effect of different types of training on lower limb mechanics during a side-step cutting manoeuvre. Aussie Rules Football players (n=50) were recruited and randomly allocated to five twelve-week training regimes;

a) control, who undertook their normal training only

b) machine-weights, which led to decreased valgus moments

c) free-weights, which did not show any improvements that would decrease ACL load

d) balance only, which led to decreased knee flexion, valgus and internal rotation moments during cutting tasks and showed the greatest potential to decrease ACL load

e) a combination of balance and machine-weights, which decreased peak flexion moments only.

The fact that the balance training programme included coordination in all three planes of motion, whereas the strength training programmes only consisted of two exercises working in the sagittal plane, may in part explain the greater effect of the balance programme. Furthermore, the weights programmes aimed to strengthen the quadriceps and hamstrings muscle groups and did not include the gluteal muscle groups which may have a greater impact on frontal and transverse plane motion. The balance training programme in the Cochrane et al. (2010) study was more demanding and varied than that used in the Soderman et al. (2000) study, which may account for the positive changes seen in this study compared to Soderman et al. However, low subject numbers of Aussie Rules footballers only in this study make it difficult to generalise the results to the wider population.

Myer et al. (2006) studied 18 high school female athletes who were divided into a plyometric group (n=8) and a balance group (n=10). Each programme consisted of 18 sessions over a seven week period, with each session lasting around 90 minutes. Hip adduction, knee valgus and ankle eversion angles during drop landings were reduced in both groups, with no significant differences between them. Despite the small sample size and lack of control group, these results support the use of balance training. Additionally, the study demonstrates the potential for plyometric training to improve lower limb biomechanics. Plyometric or jump training is commonly included in neuromuscular training programmes (Hewett et al., 1999; Irmischer et al., 2004; Noyes et al., 2005; Pfeiffer et al., 2006) and has previously been shown to decrease vGRF experienced during landing tasks and to increase hamstring strength (Hewett et al., 1996; Irmischer et al., 2004). Perhaps surprisingly though, the potential of jump training alone to improve lower limb mechanics and decrease ACL injury rates has not drawn significant attention. Herrington (2010) found significant decreases in knee valgus angles and increases in hop performance after a four-week jump training programme in female basketball players. The decreases in knee valgus in these studies coupled with decreases in vGRF shown previously (Hewett et al., 1996; Irmischer et al., 2004) suggest a decreased injury risk from jump training alone, although the actual influence on injury rates is unknown.

It is unclear what the best form of training to help decrease ACL injury risk is, further information on the factors which affect lower limb control are needed in order for the design of optimal injury prevention programmes to be achieved.

Table 2.4 – Summary of prevention programmes aimed at reducing ACL injury rates.

Author	Participants	Intervention	Control Injuries	Intervention injuries	Results	Notes
Hewett et al. (1999)	366 F athletes INV. 463 CON F, 434 CON M	6 weeks jump training	5 non-contact ACL (F). 1 non-contact ACL (M)	0 non-contact ACL	Significantly reduced non-contact ACL injuries in trained F compared to untrained	Trained F similar injury rate to untrained males. Low injury number. Uneven spread of athletes.
Heidt et al. (2000)	300 F soccer players (14-18 yrs). 42 INV, 258 CON	Plyometrics, speed, strengthening, agility	8 ACL (3.1% of players injured)	1 ACL (2.4% of players injured)	Decrease in overall injuries, no difference ACL - small INV group	Non-contact ACL injuries not defined. Low number of injuries
Soderman et al. (2000)	221 F soccer players. 100 CON, 121 INV	Balance training	1 ACL injury	4 ACL injury	Significantly improved balance but no difference in injury rates	Non-contact ACL injuries not defined.
Myklebust et al. (2003)	F handball. CON season - 942. INV season 1 - 855. INV season 2 – 850	Balance and landing	29 ACL (0.14/1000PH)	Season 1 - 23 ACL (0.13/1000 PH). Season 2 - 17 ACL (0.09/1000 PH)	Significant decrease in non-contact ACL injuries from control (n=18) to 2nd season (n=7) only	No differences between control and season 1. Greater control of programme in second season and greater influence over time.
Mandelbaum et al. (2005)	5703 F soccer players (14-18 yrs)- 3818 CON, 1885 INV	PEP program; stretching, strengthening, plyometrics, agility)	67 ACL (0.49/1000AE)	6 ACL (0.09/1000AE)	Significant reduction in non-contact ACL injuries of 88% and 74% in years 1 & 2 respectively	Voluntary enrolment in INV programme - non-randomised - bias
Pfeiffer et al. (2006)	1439 high school F athletes- 862 CON, 577 INV	9 week jump and agility	3 non-contact ACL (0.078/1000 AE)	3 non-contact ACL (0.107/1000 AE)	20 minute jump and agility programme had no significant effect on ACL injury rates	Low number of injuries. Short programme, limited influence
Gilchrist et al. (2008)	1435 collegiate F soccer players; 852 CON, 583 INV	PEP program; stretching, strengthening, plyometrics, agility)	10 non-contact ACL (0.189/1000 AE)	2 non-contact ACL (0.057/1000 AE)	70% decrease in non-contact ACL injuries, although not statistically significant	Low number of injuries

Pasanen et al. (2008)	F floorball. 256 INV, 201 CON	Running, balance, plyometrics, strengthening	3 non-contact ACL	3 non-contact ACL	No difference between CON and INV groups	Low compliance. No ACL injuries in 5 teams who completed full training schedule. Low number of injuries
Steffen et al. (2008)	2092 F soccer players (13-17 yrs). 1001 CON, 1091 INV	FIFA 11; core stability, agility, balance, strengthening	5 ACL	4 ACL	No significant difference in injury rates	Low compliance. Low number of injuries. Non-contact ACL injuries not defined.
Walden et al. (2012)	4564 F soccer players (12-17 yrs). 2479 INV, 2085 CON	Core stability, balance and knee alignment	8 non-contact ACL	5 non-contact ACL	A significant reduction in ACL injury rates overall.	Significant reduction only in those who completed programme >1 per week.

F = female; M = male; CON = control group; INV = intervention group; PEP = Prevent Injury and Enhance Performance Program

Table 2.5 – Summary of prevention programmes aimed to modify risk factors for ACL injury.

Author	Participants	Targeted risk factor	Intervention	Outcome measures	Results	Notes
Irmischer et al. (2004)	28 F recreational athletes. 14 CON, 14 INV	High vGRF	2 times/week, 9 weeks jump training	vGRF, jump height during step-land	INV significant reduction in vGRF. INV significantly greater jump height than CON post training	Jump training programme can decrease landing forces and increase jump height.
Lephart et al. (2005)	27 high school F.	Detrimental lower extremity biomechanics and strength, vGRF	3 times/week, 8 weeks. 1 group plyometric (n=14), 1 resistance (n=13).	Hip and knee kinetics and kinematics in VJ. Hip abductor, knee flexor and extensor PT.	Significant increases in knee extensor PT. Increased hip flex and knee flex angles and decreased knee flex moments. No changes in vGRF. No differences between groups	Resistance and plyometric programmes can improve sagittal plane mechanics but did not influence frontal plane. No control group.
Myer et al. (2005)	53 F high school athletes. 41 INV, 12 CON	Knee flexion and valgus	3 times/week, 6 weeks plyometrics, landing technique, core stability, strengthening	Knee flexion ROM and knee valgus moments during 31cm DJ	Training significantly increased knee flexion ROM and decreased knee valgus moments. Valgus moment decrease significant in right limb only	Also resulted in increased performance measures
Grandstand et al. (2006)	21 F soccer players (9-11 yrs). 12 INV, 9 CON	Knee valgus	Sportsmetrics WIPP - 2 times/week, 8 weeks. Agility, strengthening, plyometrics and flexibility.	Knee separation distance during 31cm DJ	No change in knee separation distance post training, no differences between groups	Low sample size.
Myer et al. (2006)	18 F high school athletes	Frontal and sagittal plane hip, knee and ankle angles	18 sessions over 7 weeks. Plyometric group (n=8), balance group (n=10).	Hip, knee and ankle angles during 31cm DJ and medial drop landing	All decreased hip adduction and ankle eversion angles in DJ, and knee valgus in medial drop landing. Plyometric increased knee flexion in DJ, balance increased knee flexion in medial drop landing.	Small sample sizes, no control group or combined training group.

Pollard et al. (2006)	18 F soccer players (14-17 yrs)	Frontal, sagittal and tranverse plane hip and knee angles	PEP warm-up programme (stretching, strengthening, plyometrics and agility) during season	Hip and knee angles during DJ	Significantly decreased hip IR and increased hip abduction. No changes in knee flexion or valgus.	Small sample, no control group. Limited to soccer players
Myer et al. (2007)	27 F high school soccer and basketball players. High-risk group (12 INV, 4 CON) and low risk group (6 INV, 7 CON).	Knee valgus moment	18 sessions over 7 weeks neuromuscular training programme	Knee valgus angle and moment during 31cm DJ	High-risk' INV athletes decreased knee valgus moments. No changes in 'low-risk' athletes or CON	13% (5Nm) decrease in knee valgus moments, not reduced to same as low-risk mean. Small sample, no information on training programme used.
Chappell & Limpivasti (2008)	30 F collegiate soccer and basketball players	Hip and knee kinetics and kinematics	6 times/week, 6 weeks core stability, balance, jump training, plyometrics	Hip and knee kinetics and kinematics in 31cm DJ and stop-jump	DJ - Increased peak knee flexion angle only. Stop-jump - decreased knee valgus moment only.	Changes after training are not consistent across tasks. No control group.
Herman et al. (2008)	66 F recreational athletes. 33 CON, 33 INV.	Lower extremity biomechanics	3 times/weeks, 9 weeks strength training for Gmax, Gmed, H and Q.	Hip and knee kinetics and kinematics during stop jump	Significant increase in strength but no changes pre to post or differences between groups for any measure	Strength training did not change hip or knee kinetics or kinematics. Limited to F. Training based on muscle hypertrophy
Cochrane et al. (2010)	50 M Aussie Rules footballers. 10 players per group	Knee valgus, rotation and flexion loads	3 times/week, 12 weeks. CON, Machine-weights, free-weights, balance, balance and machine-weights combination	Knee moments in 60° side-step	Machine- weights - decreased valgus moments; free-weights - no changes; balance - decreased flexion, valgus and IR moments; combination - decreased flexion moments	Balance training showed greatest potential to reduce moments which increase ACL load. Low sample size.

Barendrecht et al. (2011)	80 handball players (13-19 yrs). 49 INV, 31 CON	Knee flexion and valgus angle	2 times/week, 10 weeks agility, balance, strengthening and plyometrics	Knee separation distance, knee flexion angle in 31cm DJ	Significant increase in knee separation distance in INV group. No change in knee flexion angle	10 weeks of NMT can reduce knee valgus. This reduction was greatest in those with above average knee valgus pre-training.
Leporace et al. (2013)	15 M volleyball players	Sagittal plane hip and knee angles	3 times/week, 6 weeks core stability, balance and plyometrics	Hip and knee kinematics in double and single legged landings from VJ	No change in jump height, hip or knee angles	Small sample, not known whether frontal plane angles changed. Short training period.

F = female; M = male; CON = control group; INV = intervention group; GRF = Ground Reaction Force; NMT = neuromuscular training; PEP = Prevent Injury and Enhance Performance Program; VJ = vertical jump; WIPP; warm-up for injury prevention and performance; Gmax = gluteus maximus; Gmed = gluteus medius; H= hamstrings; Q = quadriceps.

2.5.2 PFPS Intervention Studies

PFPS intervention studies have mostly focused on changes in pain and function. Only one study to date has examined the effect of an intervention programme on injury incidence. Brushoj et al. (2008) studied the effect of a three month programme which included body-weight resistance exercises, quadriceps stretches and a balance task, compared to a placebo group in Danish Army recruits. At the end of the intervention, a similar number of recruits in both the experimental and control groups suffered from PFPS during the study period. This was also noted for other lower limb overuse injuries assessed in the study. The aim of the training programme was to address known intrinsic risk factors for lower limb overuse injury, although none of these factors were specifically identified or measured in the study. Therefore, it is unclear whether the programme was sufficient to address these risk factors, limiting the evaluation that can be made.

Crossley et al. (2002) assessed the effect of a physical therapy intervention on pain and function of PFPS patients. 71 PFPS patients were divided into experimental and placebo groups. The experimental group received a six-week programme which included quadriceps retraining, patella taping and gluteal muscle strengthening and patella mobilisation, whilst the placebo group received a sham intervention. After the intervention, the experimental group had significant improvements in pain and function (assessed via questionnaire), whilst the placebo group remained unchanged. Although it is clear that this intervention was successful, it is not clear whether the combination of treatments, or a single treatment alone caused the changes. For example, patella taping alone has been shown to significantly reduce pain and improve function (Herrington, 2000). In order for more targeted and streamlined interventions to be devised, understanding of the effect of each individual treatment is important.

Intervention studies which have aimed to improve hip muscle strength may give further insight into their role within PFJ injuries, although few studies which have focused purely on strength exist. Earl and Hoch (2011) assessed the effect of an eight-week programme which aimed to improve hip and core muscle strength on nineteen women with PFPS. After the programme, hip abduction and external rotation isometric strength significantly improved by 4kg/kg and 2kg/kg of body mass respectively. This was coupled by a decrease in knee valgus moments during running; although no changes in hip adduction or internal rotation angles or moments were found. The decrease in knee valgus moments was a significant finding, as high valgus moments have been linked to development of PFPS. Seventeen of the nineteen women in this study also reported improvements in pain and function. One of the patients' who did

not show improvements, showed no increase in hip muscle strength, adding further support to the importance of the hip musculature. Other studies which have aimed to improve hip muscle strength have also noted improvements in pain and function (Earl & Hoch, 2011; Fukuda et al., 2010; Khayambashi, Mohammadkhani, Ghaznavi, Lyle, & Powers, 2012; Tyler, Nicholas, Mullaney, & McHugh, 2006).

Strengthening of the hip abductors and external rotators has also been found to reduce hip adduction and internal rotation during a single leg squat task (Willy & Davis, 2011). In this study, females with excessive hip adduction (>20°) during running were given an eight-week programme aimed at improving hip abduction and external rotation strength. Hip abduction strength improved by 3% of body weight and was accompanied by a 6.7° decrease in hip adduction during the squat. Hip external rotation strength also improved, although only by 0.5% of body weight, but was also accompanied by a 5.4° decrease in hip internal rotation. However, the changes in single leg squat kinematics did not translate to running. The kinematic changes during the single leg squat may have resulted from skill acquisition rather than increases in muscular strength, as the squat task was used in the training programme along with feedback on how to improve performance. Herman et al. (2008) also found that significant improvements in strength did not have an effect on lower limb motion during a stop-jump task. It may be that while hip strength improves through interventions, performances in other tasks do not automatically improve in conjunction, although hip abduction strength after the intervention in the Herman et al. (2008a) study was lower than at baseline in the Willy and Davis (2011) study. This suggests that there may be a minimum requirement in terms of relative strength of the hip muscles, or for the subject to learn how to perform the skill correctly, either via the use of feedback or other interventions.

2.5.3 Feedback

Feedback is a fundamental tool for learning and performing of motor skills and is seen as a quick and simple alternative to more time-consuming and labour intensive training programmes previously investigated. Early studies assessed the effect of feedback in its most simple verbal form, which is often used to supplement training programmes. Papavessis and McNair (1999) compared the effect of specific verbal instruction to one group of participants to 'land on their toes and bend their knees' against another group who were instructed to use sensory feedback from previous jumps to 'minimise the stress of landing' during a bilateral drop landing task. The results showed that the verbal feedback group reduced vGRFs by 0.96BW, whereas the sensory group only reduced forces by 0.18BW. Significant reductions

in vGRF were also noted in several further studies where simple verbal instructions were given (Cowling et al., 2003; McNair et al., 2000; Mizner et al., 2008). In addition, Cowling et al. (2003) noted that a simple instruction to 'bend your knees' during a unilateral landing brought about significant increases in knee flexion angles. Mizner et al. (2008) conducted a study which utilised similar verbal instructions as previously used by Papavessis and McNair (1999) to assess their effect on frontal and sagittal plane hip, knee and ankle angles and moments during a drop jump task. Reductions in vGRF were accompanied by increases in hip and knee flexion angles, and decreases in knee valgus angle and moments, hip and knee flexion moments and ankle dorsi-flexion and eversion moments. Cronin et al. (2008) also showed that the use of physical demonstration to supplement verbal instructions can result in decreased vGRF during a volleyball spike. These results suggest that decreases in vGRF noted in previous studies would reduce risk of injury to the ACL and PFJ through positive changes in lower limb mechanics.

The use of video to supplement verbal instructions given to participants can decrease GRF and improve frontal and sagittal plane landing mechanics and is thought to give the participant's greater knowledge of their performance (Cronin et al., 2008; Herman et al., 2009; Onate et al., 2005; Onate et al., 2001). Different forms of video feedback can be used. Onate et al. (2005) investigated whether a performer watching and receiving feedback on either a video of themselves, that of an expert model, or a combination of self and expert, would result in greater changes in GRF and sagittal plane knee kinetics and kinematics. The combination of analysis of self and analysis of an expert was found to be the most effective type of feedback, reducing GRF and increasing knee flexion displacement during the vertical jump landing (Onate et al., 2005). These improvements were also retained one week later, suggesting motor patterns may have changed and the improvements would endure, therefore decreasing injury risk in the long-term (Onate et al., 2005).

Herman et al. (2009) found that augmented feedback, based on the Onate (2005) expert and self-combination protocol, resulted in decreased GRFs and increased knee flexion and hip abduction angles during a stop-jump task. However, no changes were noted in other variables relating to dynamic knee valgus, such as hip internal rotation, knee valgus or knee rotation angles. An interesting finding of this and an earlier study was that a combination of strength training and feedback had the greatest impact on improving lower limb mechanics compared to strength training or feedback alone (Herman et al., 2009; Herman et al., 2008). It would seem therefore that a combination of strength training and feedback would help reduce ACL

and PFJ injury risk. However, it not clear whether changes in dynamic valgus will result from a similar feedback protocol as no other studies based on Onate et al.'s (2005) protocol have evaluated such measures. In addition, the Onate protocol is based on criteria which have been theorised to reduce injury risk. Greater improvements may be seen using feedback criteria based on identification of high-risk movement patterns such as the Landing Error Scoring System (LESS) (Padua et al., 2009).

2.6. Screening for ACL and PFJ Injury Risk

A number of screening tools have been used to assess knee injury risk, including 3D and 2D motion analysis and FPTs. This chapter will provide an overview of these screening tools, how they can be used for assessment of ACL and PFJ injury risk and their clinical utility:

   i) motion analysis, including frontal plane projection angle (FPPA) (2.6.1)
   ii) functional performance tests (2.6.2), including the hop for distance tests (2.6.2.1) and Star Excursion Balance Test (2.6.2.2).

Reliability, Validity and Clinical Utility

Knowledge of the reliability and validity of measurement tools is imperative for their use within the field of research and clinical practice. Validity can be defined as the extent to which the observed value agrees with the actual value of a measure (Hopkins, 2000). Three types of validity can be assessed when assessing measurement tools in sport and exercise:

   I. logical validity – whether the test involves the performance that is being measured,
   II. criterion validity – how the scores on a test relate to a recognised standard or criterion. This also includes concurrent and predictive validity
   III. construct validity – how a test measures or relates to a hypothetical construct (Thomas, Nelson, & Silverman, 2005).

Clinical utility is another important factor to consider when assessing screening tools. It is important that any test which is intended to be used in the field is simple, quick and cheap whilst being reliable and valid. Having greater clinical utility is likely to increase the impact of a screening tool across the sporting environment.

Knowledge of the reliability and measurement error associated with screening tools is important. Reliability indicates the extent to which scores for a subject sample can be reproduced in the same participants in subsequent tests (Batterham & George, 2003). If a test cannot provide reproducibility in the same conditions it cannot be considered a reliable test. A

number of factors can influence the reliability of a test. These can be broadly grouped into random error and systematic bias. Random error is the 'noise' in a measurement, typically seen as within-subject variation, inconsistencies in the measurement protocol or the examiner's measurements (Atkinson & Nevill, 1998; Hopkins, 2000; Tyson, 2007). Systematic bias refers to a trend for measures to be different due to learning effects or fatigue (Atkinson & Nevill, 1998; Batterham & George, 2003).

Intra-tester reliability indicates the consistency of measures with repeated trials assessed by the same examiner. Inter-tester reliability indicates the consistency with which different testers achieve the same score on the same participants. Between-session or test-retest reliability indicates the reproducibility of the observed value when the test is repeated (Hopkins, 2000). Considering that screening tests may be conducted in the field by either a single or multiple examiners and across different time points, knowledge of these types of reliability is required.

The use of Intraclass Correlation Coefficients (ICCs) to assess reliability is widespread practice in sports medicine research. The advantage of ICCs over the Pearson Product Moment Correlation (Pearson's r) is the inclusion of both systematic bias and random error in its calculation. Pearson's r does not take account of systematic bias and may therefore overestimate reliability (Denegar & Ball, 1993). The univariate nature of the ICC means it can be used when more than one retest is compared with a test, whereas Pearson's r cannot (Atkinson & Nevill, 1998). A number of models of the ICC can be calculated, each producing different results (Shrout & Fleiss, 1979). The decision on which of these models is used should be clearly presented in parentheses. ICC values are interpreted according to the following criteria (Coppieters, Stappaerts, Janssens, & Jull, 2002):

- Poor = <0.40
- Fair = 0.40 – 0.70
- Good = 0.70 – 0.90
- Excellent = >0.90

The drawback of ICC is the lack of information regarding the actual difference between measures and its sensitivity to sample heterogeneity (Atkinson & Nevill, 1998; Rankin & Stokes, 1998). Therefore, calculation of the standard error of measure (SEM) should also be

included (Rankin & Stokes, 1998). Ideally, a high ICC with low SEM would indicate good reliability of a measure.

When assessing the change in an individual's score on a test, it cannot be assumed that the difference observed is a true change. The scores observed will include some variability, either due to random or systematic error (Atkinson & Nevill, 1998; Tyson, 2007). Therefore, for a true change in performance to be observed, the difference in scores must be greater than the measurement error associated with the test (Tyson, 2007). Knowledge of the measurement error of a test is important when assessing the effect of an intervention, as this allows the clinician to accurately evaluate an individual's performance. Without these values, changes in performance cannot be properly evaluated, as it is unknown whether the difference was due to measurement error or a true change in performance.

SEM provides an estimate of measurement precision and is presented in the unit of measurement (Denegar & Ball, 1993). This allows for a greater understanding of the measurement reliability and also comparison to other studies where SEM is presented. The SEM is calculated from the standard deviation (SD) and reliability coefficient (i.e. the ICC) of the measured sample, as shown in the formula below:

- SD(pooled) * ($\sqrt{}$ (1-ICC)) (Thomas et al., 2005)

As such, the SEM provides a range from the observed score within which the true score of a measure is likely to lie (Eliasziw, Young, Woodbury, & Frydayfield, 1994; Thomas et al., 2005). Some researchers have cited the SEM as being able to distinguish whether changes seen between tests are real or due to measurement error (Denegar & Ball, 1993). However, only 68% of all test scores fall within one SEM of the true score, rather than the 95% criterion commonly used (Atkinson & Nevill, 1998; Thomas et al., 2005). As a result, the smallest detectable difference (SDD) statistic has been proposed to allow determination of the change needed to signify statistical significance (Atkinson & Nevill, 1998; Eliasziw et al., 1994). SDD is calculated from the following formula:

- 1.96 * ($\sqrt{2}$) * SEM (Kropmans, Dijkstra, Stegenga, Stewart, & de Bont, 1999)

SDD is the minimum value which should be exceeded to distinguish from random error in measurement and report a real change (Atkinson & Nevill, 1998; Eliasziw et al., 1994). The

SDD is a product of the SEM and standard normal distribution and as such is more accurate than taking only the 95% confidence range of the SEM (Eliasziw et al., 1994). For a statistically significant difference between two measures to be assumed, the difference should be greater than the SDD. This gives clinicians greater knowledge with which to evaluate changes made during treatment, rehabilitation or training.

2.6.1. Motion Analysis

Identifying individuals who demonstrate dynamic knee valgus motion during athletic tasks is important in order to modify their high-risk movement patterns. This can reduce load on the ACL and PFJ, potentially decreasing the risk of injury. Studies which assess lower limb biomechanics commonly use 3D motion analysis techniques (Blackburn & Padua, 2008; Ford et al., 2003; Hewett et al., 2005). 3D analysis allows clinicians and researchers to quantify all three planes of joint motion during often complex tasks and is postulated as the "gold standard" of motion analysis.

The reliability of 3D analysis for longitudinal studies has been questioned. Kadaba et al. (1989) found that kinematic and kinetic data obtained within the same session were often more reliable than those from different sessions. This trend has also been found during running, pivoting and jumping tasks (Ferber, Davis, Williams, & Laughton, 2002; Ford, Myer, & Hewett, 2007; Queen, Gross, & Liu, 2006; Webster, McClelland, Wittwer, Tecklenburg, & Feller, 2010). Error in marker placement is the greatest influence on between-session reliability (Ferber et al., 2002; Ford et al., 2007; Queen et al., 2006). Measurement accuracy is also prone to error due to skin movement artefact (Cappozzo, Catani, Leardini, Benedetti, & DellaCroce, 1996). It has been recommended that rigid marker arrays be used, rather than single skin mounted markers, as they reduce the effect of skin movement artefact (Manal, McClay, Stanhope, Richards, & Galinat, 2000), although error due to soft tissue artefact still remains, with greatest error evident at the thigh (Cappozzo et al., 1996; Reinschmidt, van den Bogert, Nigg, Lundberg, & Murphy, 1997). However, numerous studies still employ single skin mounted markers which is likely to increase the measurement error of the data collected.

In addition to differences between sessions, some researchers have shown differences in reliability in particular planes of movement. The sagittal plane has the greatest stability across measurements during gait and running (Ferber et al., 2002; Kadaba et al., 1989; Queen et al., 2006). Frontal and transverse planes of movement are believed to be more sensitive to errors

in marker placement (Kadaba et al., 1989), which may explain the tendency for lower between-session reliability values. McGinley et al. (2009) found that during gait analysis the greatest errors were commonly found with hip and knee rotation. Motion in the frontal and transverse planes, in particular dynamic knee valgus, is seen as key to high risk movements associated with ACL and PFJ injury (Hewett et al., 2005; Myer et al., 2010). Therefore the measurement error in these planes may have a significant effect on identification of high-risk athletes with 3D motion analysis.

Perhaps more importantly for identification of high-risk athletes in the field are the financial, spatial and temporal costs of 3D motion analysis. These factors mean it is not practical to use 3D analysis in most clinical settings and particularly for large screening programmes required to help reduce injuries on a wider scale. Therefore, there is a need for a simpler and more cost-effective method of analysis for large-scale use and in the field, which is capable of detecting the high-risk movement patterns linked to ACL and PFJ injury.

The use of 2D video techniques, which employ less expensive, portable and easy to use equipment, may be useful in quantifying frontal plane hip and knee motion during athletic movement (Barber-Westin et al., 2005; Ford et al., 2003; Noyes et al., 2005). It has been shown that qualitative 2D analysis, which involves subjective scoring of the task, has only moderate intra- and inter-rater reliability when assessing frontal plane motion of the lower limb (Chmielewski et al., 2007; Ekegren et al., 2009). In addition, the sensitivity of this subjective method has been questioned. Nearly a third of individuals classified as 'high-risk' according to 3D analysis were not identified using a qualitative scoring system (Ekegren et al., 2009). The lack of reliability and sensitivity of these subjective ratings may be due to differences in rater interpretation or experience. Therefore, the use of an objective measure, such as knee separation distance or FPPA, might increase the reliability of lower limb alignment measurement, allowing for measurement of lower limb alignment across subjects and time.

The knee separation distance method has been used in several studies (Barber-Westin et al., 2005; Barber-Westin et al., 2006; Noyes et al., 2005) although the methods for quantifying the measure have varied. In Noyes et al. (2005) original study, markers were placed on the centre of the patella to assess medial knee motion, whereas some recent studies have placed the marker on the lateral femoral condyle (Barber- Westin et al. 2006, Sigward et al., 2011). Using the femoral condyle method, Sigward et al. (2011) found that knee separation distance

accounted for 52% of the knee valgus angle during a drop jump task, where those with smaller knee separation distances had greater knee valgus angles. However, the femoral condyle method requires a marker to project laterally for it to be visible, whereas the patella method requires a marker simply to be visible on the skin. In the laboratory reflective, spherical markers often used in 3D motion analysis are used, and whilst this is suitable for research environments, such markers may not be available in the clinical environment. Further, the use of knee separation distance is limited to use during bilateral tasks only and does not allow for comparison between limbs. Considering that many ACL injuries occur during single leg landings and many individuals exhibit asymmetry between limbs, these limitations are likely to be significant when attempting to predict ACL injury using this method.

Recently, 2D FPPA has been used to assess dynamic knee valgus during common screening tasks in athletic, injured and general populations (Herrington & Munro, 2010; McLean et al., 2005b; Willson & Davis, 2008b; Willson et al., 2006). Women exhibit increased FPPA compared to men during the single leg squat and drop jump tasks (Herrington & Munro, 2010; Willson et al., 2006) which mirrors findings from 3D studies. 2D FPPA may also be sensitive to changes in dynamic valgus which result from injury or training (Herrington, 2010; Willson et al., 2006). Individuals suffering from PFPS exhibit greater FPPA than uninjured control subjects during the single leg squat task (Willson & Davis, 2008b). Whilst women basketball players showed improvements in FPPA on completion of a four-week jump training programme (Herrington, 2011).

Validity of the FPPA method in relation to 3D has been investigated during single leg squat and running tasks (McLean et al., 2005b; Willson & Davis, 2008b). Willson and Davies (2008b) measured 2D FPPA and 3D lower extremity joint angles of women with and without PFPS during the SLS. They found that 2D FPPA was significantly correlated to 3D hip adduction ($r = 0.32$) and knee external rotation angles ($r = 0.48$), two components of dynamic knee valgus. Interestingly, correlation with knee valgus ($r = 0.21$) was found not to be significant. The association between FPPA during the SLS and 3D joint angles during running and single leg jumping was also investigated. It was noted that increased FPPA during the SLS was also significantly associated with greater 3D hip adduction and knee external rotation during these tasks. This suggests that measurement of FPPA during a single leg squat can help clinicians identify movement patterns during more dynamic activities.

McLean et al. (2005b) assessed the association between FPPA and 3D knee valgus in collegiate basketball men and women during side-step and side-jump activities. In contrast to Willson and Davis (2008b), McLean et al. (2005b) found that FPPA was significantly associated with and accounted for 58-64% of the variance in peak 3D knee valgus angles. The moderate correlations between 2D FPPA and 3D variables in these studies suggest that no single joint motion would be responsible for increases in FPPA. However, similarly to increasing strain on the ACL and PFJ, several combinations of hip and knee motion would result in greater FPPA values. While FPPA was unable to account for 100% of each of the lower limb movements, when considered together, FPPA accounts for a significant proportion of their variance. As such these studies concluded that 2D FPPA may be useful for identification of high-risk athletes and evaluating the value of training and intervention programmes in reducing frontal plane dynamic knee valgus (McLean et al., 2005b; Willson & Davis, 2008b).

The validity of 2D FPPA has not yet been investigated during drop jump or single leg landing tasks. The drop jump task is the only screening task which has been prospectively linked to ACL and PFJ injury (Hewett et al., 2005; Myer et al., 2010). The logistics of measuring FPPA during high-speed cutting manoeuvres in a clinical environment limits the use of this method to assess dynamic knee valgus during this type of task. However, the correlations noted between FPPA during the SLS task and 3D motion in running and jumping tasks (Willson & Davis, 2008b) suggest that measurement of FPPA in common screening tasks would be useful to interpret likely motion during more dynamic movements. The potential of 2D FPPA as a method to identify high-risk individuals may be compromised, in the absence of a prospective study, if the relationship between FPPA and 3D variables associated with injury is not significant.

Furthermore, the reliability of 2D FPPA has not been adequately examined. Only a intraclass correlation coefficient value of 0.88 for within-day reliability of FPPA has been presented (Willson et al., 2006). No study has assessed the intra-tester, inter-tester or between-session reliability of 2D FPPA, or the measurement error values of these tests. Therefore, further investigation of the reliability of 2D FPPA is needed before it can be recommended for use in screening tests. If the reliability and measurement error of this screening method can be established then clinicians will be able to use the tests with confidence, whilst also being able to evaluate individual performance more informatively. Reliability and validity of 2D FPPA will be investigated in chapter three.

2.6.2. Functional Performance Tests

Clinical measures such as knee joint laxity, range of motion, thigh circumference and quadriceps strength have often been used to predict knee function and subsequently inform when an athlete is ready for return to participation (Neeb, Aufdemkampe, Wagener, & Mastenbroek, 1997). However, the relationship between such clinical measures and readiness for return to sport has been refuted (Eastlack, Axe, & Snyder-Mackler, 1999; Lephart et al., 1992).

Barber et al. (1990) realised that for functional limitations of the knee joint to be evaluated, testing which provided an objective measurement whilst simulating sporting activity was required. A number of tests which mimic sporting performance have been devised and investigated in recent years; these have been termed functional performance tests (FPT). A FPT measures joint laxity, muscle strength, agility, pain, proprioception and athlete confidence simultaneously whilst providing an objective and measurable outcome (Barber et al., 1990; Lephart & Henry, 1995; Lephart et al., 1992; Noyes et al., 1991).

FPTs have been used increasingly over recent years in both sport and clinical practice to provide an outcome measure when evaluating athletes returning from injuries. FPTs used to date have included hop for distance tests, star excursion balance test (SEBT), anteromedial lunge, step-down, stairs hopple, vertical jump, carioca's, agility and sprint tests (Barber et al., 1990; Clark, 2001; Delextrat & Cohen, 2008; Goh & Boyle, 1997; Gribble et al., 2004; Herrington et al., 2009; Loudon et al., 2004; Negrete & Brophy, 2000; Noyes et al., 1991; Petschnig et al., 1998; Reid et al., 2007; Risberg & Ekeland, 1994; Rudolph et al., 2000; Semenick, 1990).

FPTs are closed chain in nature and therefore closely assimilate the joint loading forces and kinematics that occur functionally (Lephart & Henry, 1995). Closed chain exercises result in the simultaneous movement of the ankle, knee and hip joints, requiring co-ordinated muscle action to control all segments as occurs during sporting activity (Lephart & Henry, 1995). Furthermore, in the absence of laboratory based techniques such as 3D analysis and force platform measures, FPTs provide a clinical quantification of lower limb function. As a result FPTs are favoured clinically as they mimic the forces experienced by the lower extremity during sporting performance and they require minimal space, time, expense and administration when compared to laboratory based measurements.

Bilateral tests such as the vertical jump, carioca's and agility tests do not allow for comparison between the injured and uninjured limb. In contrast, single limb tests such as the hop tests, single leg vertical jump, stairs hopple and SEBT are able to utilise the uninjured limb as a control for within-subject comparisons, making it easy to quantify function of the injured limb. In addition, these FPTs can identify differences between injured and uninjured limbs following ACL injury (Barber et al., 1990; Goh & Boyle, 1997; Risberg & Ekeland, 1994). The requirement of a set of stairs to complete the stairs hopple test limits it use clinically and in particular during large scale screening. Barber et al (1990) also found that the single leg vertical jump test lacked sensitivity in identifying functional deficits in the injured limb only. This conclusion was reached as over half of the normal population were unable to achieve 90% symmetry in jump height between limbs, whilst only 69% achieved 85% symmetry, suggesting this test may not be suitable for detecting lower limb functional limitations in injured populations.

2.6.2.1. Hop for Distance Tests

Hop for distance tests, where the subject hops as far as possible, are commonly used during rehabilitation from ACL injury (Adams, Logerstedt, Hunter-Giordano, Axe, & Snyder-Mackler, 2012; Clark, 2001; Fitzgerald, Axe, & Snyder-Mackler, 2000b). The hop tests include the single, triple and crossover hop for distance and the six metre timed hop. Hop tests can indicate the willingness of the individual to land on the injured limb, whilst the uninjured limb can also be used as a control for comparison purposes. This can aid assessment of progress throughout rehabilitation and help inform when an athlete is ready to return to competition (Barber et al., 1990; Lephart & Henry, 1995; Noyes et al., 1991).

Recent research has focused mainly on the validity of hop tests with injured athletes. Measures of symmetry and statistical differences between limbs have been evaluated to determine whether hop tests can detect functional deficits in injured limbs. Limb symmetry index (LSI) is one such measure commonly used. LSI is calculated by dividing the distance hopped on the injured limb versus the non-injured limb to give a percentage value. This value indicates the function of the injured limb versus the uninjured limb. An LSI of greater than 85% (Barber et al., 1990) indicates that 'normal' limb symmetry exists and function of the injured limb has been restored. This 85% arbitrary value was decided as the majority of the 'normal' population in Barber et al.'s study had an LSI of greater than 85%. However the validity of this value has not been investigated further and is not always sensitive to deficits in ACL injured participants (Barber et al., 1990; Noyes et al., 1991; Petschnig et al., 1998). For

example, Noyes et al. (1991) found that 42-51% of ACL deficient (ACL-D) patients had a normal (>85%) LSI. Additionally, a potential drawback when calculating LSI is that it is assumed that the opposing limb is 'normal' in terms of the variables that the FPT is measuring. However, if an individual sustains an injury, a period of inactivity or reduced activity will result, which may affect the uninjured limb as much as the injured limb (Ageberg, Zatterstrom, Moritz, & Friden, 2001). Although Barber et al. (1990) found no differences in single hop for distance or six-metre timed hop scores between normal subjects and the uninjured leg of ACL-D patients, showing that this may not always be the case.

A number of studies have shown that hop tests are able to detect deficits between injured and uninjured limbs. Significant differences in hop scores are consistently evident between ACL reconstructed (ACL-R), ACL-D and uninjured limbs (Barber et al., 1990; Goh & Boyle, 1997; Noyes et al., 1991; Petschnig et al., 1998). Barber et al. (1990) found that ACL-D patients hopped on average 25cm less on their injured limb compared to their uninjured limb and normal participants on the single hop test. They also took more than half a second longer to complete the six-metre timed hop test. ACL-R patients at three months follow-up have been shown to have differences between their injured and uninjured limbs as great as 43.7cm on the single hop and 154.9cm on the triple hop (Petschnig et al., 1998). These differences were 22.7cm and 57.5cm respectively in patients who followed a similar rehabilitation programme at one-year follow-up. Furthermore, at one-year, scores on uninjured limbs were not significantly different to those of normal subjects. Improvements in LSI of 15-18% were also seen between the three month and one year follow-up groups. Goh and Boyle (1997) also found participants who were two to four years post ACL-R hopped 25cm further on their uninjured limb on the crossover hop test, and completed the six-metre hop 0.17 seconds quicker. According to the SEM data available within the literature these differences between participants or limbs are also greater than measurement error of the tests.

In addition, hop tests can distinguish between ACL-D individuals identified as copers and non-copers (Eastlack et al., 1999; Rudolph et al., 2000). Copers are defined as those ACL-D individuals who are able to continue playing sport without symptoms of giving-way and they demonstrate similar LSI scores as healthy participants (Eastlack et al., 1999; Rudolph et al., 2000). The presence of copers may explain the low sensitivity values noted in earlier studies (Noyes et al., 1991; Petschnig et al., 1998). Further support for this comes from studies in subjects with chronic ankle instability (CAI). Caffrey et al. (2009) found that participants who did not report giving-way, and would be classified as copers, showed no differences compared

to uninjured controls. In contrast, those who did experience giving-way were significantly worse than uninjured control subjects.

Hop tests have also been used as a performance indicator. The single and triple hop tests have been shown to correlate with an athlete's strength and power (Greenberger & Paterno, 1995; Hamilton, Shultz, Schmitz, & Perrin, 2008; Negrete & Brophy, 2000; Noyes et al., 1991; Nyberg, Granhed, Peterson, Piros, & Svantesson, 2006; Petschnig et al., 1998). In one study the triple hop explained 49-58% of the variance in concentric hamstring and quadriceps peak torque at speeds of 60 and 180°/s and 70% of the variance in vertical jump height in healthy participants (Hamilton et al., 2008). Correlations of 0.48-0.55 have been noted between the triple hop and quadriceps peak torque at 15°/s in ACL-R patients (Petschnig et al., 1998).Correlations between single hop and concentric quadriceps peak torque have ranged from 0.34-0.79 (Greenberger & Paterno, 1995; Nyberg et al., 2006; Petschnig et al., 1998). Proprioception and balance training can also lead to an increase in hop distance (Fitzgerald, Axe, & Snyder-Mackler, 2000a; Greenberger & Paterno, 1995). These studies suggest that hop tests can provide an overview of an athlete's functional ability, which includes their strength, power and balance (Barber et al., 1990; Lephart et al., 1992; Noyes et al., 1991).

Reliability of hop tests has previously been established (Ageberg, Zätterström, & Moritz, 1998; Bandy et al., 1994; Bolgla & Keskula, 1997; Booher, Hench, Worrell, & Stikeleather, 1993; Hopper et al., 2002; Paterno & Greenberger, 1996; Reid et al., 2007; Ross, Langford, & Whelan, 2002). However, the methodology of these studies may be questioned as learning effects which have been reported were not taken into account (Ageberg et al., 1998; Bolgla & Keskula, 1997; Booher et al., 1993; Hopper et al., 2002; Reid et al., 2007). As a result, it is unclear whether the reliability and measurement error values are accurate. Without accurate error measurement values the true significance of the findings to date cannot be determined. Further discussion of the reliability of hop tests will be conducted in chapter four. Table 2.6 provides a summary of the reliability studies undertaken to date.

Although hop tests may not be sensitive to specific limitations, such as strength or balance, they provide a gross measure of an individual's functional ability (Barber et al., 1990; Lephart et al., 1992; Noyes et al., 1991). If hop tests can be shown to be a reliable measure, it would seem plausible to screen healthy individuals for LSI and investigate prospectively whether an abnormal LSI score is a predisposing factor to injury. Reliability of hop tests will be examined in chapter four.

Table 2.6 – Summary of the studies assessing the reliability of the four hop tests.

Authors	Participants	Hop Tests	ICCs	SEM	Notes
Booher et al. (1993)	18 healthy (4m, 14f)	Single, timed	0.97-0.99 - single 0.77 –timed	5.93cm 0.19s	1 practice trial, 2 measured - learning effect evident between trials. No information about participants activity levels
Bandy et al. (1994)	40 healthy men	Single (n=18), triple (n=22), crossover (n=22)	0.93 – single 0.94 – triple 0.90 – crossover	-	2 practice trials and 2 measured, best score taken. No information about participant's activity levels.
Bolgla & Keskula (1997)	20 healthy (5m, 15f)	Single, triple, crossover, timed	0.96– single 0.96 – triple 0.96 – crossover 0.66 - timed	4.56cm 15.44cm 15.95cm 0.13s	3 practice trials, 3 measured, mean taken. Learning effect in single hop only
Ageberg et al. (1998)	75 recreationally active (36m, 39f)	Single	0.96	-	3 measured trials, no information on practice trials – learning effect noted. ICC method unspecified
Ross et al. (2002)	18 US military men	Single, triple, crossover, timed	0.92– single 0.97 – triple 0.93 – crossover 0.92 - timed	4.61cm 11.17cm 17.74cm 0.06s	3 practice, 3 measured trials, learning effects not assessed. Limited to military only.
Injured populations					
Paterno & Greenberger (1996)	20 healthy (7m, 13f) 13 ACL-R (8m, 3f)	Single	0.92-0.96 0.89	-	3 practice trials, 3 measured. Learning effect not measured but also not evident.
Hopper et al. (2002)	19 ACL-R (13m, 6f)	Timed, crossover	0.92-0.98 (raw) 0.81-0.94 (LSI)	-	All participants 12 months post-op. 1 practice, 3 measured, learning effects not assessed. No change in LSI despite change in raw scores.
Reid et al. (2007)	42 ACL-R	Single, triple, crossover, timed	0.92– single 0.88 – triple 0.84 – crossover 0.82 - timed	3.49% 4.32% 5.28% 5.59%	All participants 16 weeks post-op. 1 practice, 2 measured, learning effects not assessed ICC and SEM on LSI only.

M = male; f = female; ACL-R = ACL reconstructed; ICC = Intraclass correlation coefficient; SEM = standard error of measurement.

2.6.2.2. The Star Excursion Balance Test (SEBT)

The SEBT is a test of dynamic postural control which requires participants to maintain a stable base of support whilst completing prescribed reaching tasks in pre-determined directions (Hertel et al., 2000; Winter, Patla, & Frank, 1990). The SEBT is a closed-kinetic chain exercise which mimics the single leg squat exercise and therefore the stance leg requires strength, proprioception, neuromuscular control and adequate range of motion at the hip, knee and ankle joints (Olmsted et al., 2002; Robinson & Gribble, 2008a).

Previous research has suggested that the SEBT is sensitive enough to detect dynamic postural control deficits in patients with CAI, PFPS and an ACL-D limb (Aminaka & Gribble, 2008; Gribble et al., 2004; Herrington et al., 2009; Hertel et al., 2006a; Hubbard, Kramer, Denegar, & Hertel, 2007; Olmsted et al., 2002). In these studies, patients who were injured were shown to have lower SEBT scores compared to their uninjured limb and those of healthy participants. Patients with CAI have demonstrated decreased reach distances on their injured leg in the anterior, antero-medial, medial, posterior and postero-medial directions (Gribble et al., 2004; Hertel et al., 2006a). Aminaka and Gribble (2008) compared anterior reach distances in healthy and PFPS subjects and found that healthy control subjects reached 2.8% further. Herrington et al. (2009) assessed reach distance on all directions of the SEBT in 50 subjects. 25 of these subjects were diagnosed with an ACL rupture and were therefore classified as ACL-D, whilst a further 25 matched subjects made up the control group. Subjects in the ACL-D group showed deficits in the anterior, medial, lateral and postero-medial directions, ranging from 5.4% in the anterior direction to 27.6% in the lateral direction. Furthermore, the authors noted that those with an ACL-D limb exhibited significantly decreased scores on their uninjured limb compared to healthy controls in the medial and lateral reach directions. The authors argued that this may have been a predisposing factor for ACL injury occurrence. However, the lack of significant differences between limbs in the ACL-D subjects suggests that this may have been a result of detraining caused by the injury.

In light of the SEBT's ability to detect functional deficits, the potential for the SEBT to predict future injury risk has been investigated (Plisky et al., 2006). In this study, 235 high-school basketball players (130 boys, 105 girls), were screened using the SEBT prior to the start of the season. A link between SEBT performance and overall lower extremity injury occurrence in these players was evident. Plisky and colleagues found that players with a reach distance difference of greater than 4cm between limbs in the anterior reach direction were 2.5

79

times more likely to sustain an injury. Additionally, girls with 94% LSI were significantly more likely to sustain a lower extremity injury. In this study only the anterior, postero-medial and postero-lateral reach directions were used, although no clear rationale for inclusion of only these directions was presented. Therefore, the potential for other directions which have been shown to detect deficits in injured populations to predict lower limb injury risk was not assessed. Whether different reach directions are able to predict different injuries, as is seen in detection of injury deficits, is worthy of further investigation.

As with the hop tests, it cannot be determined whether the deficits noted between injured and uninjured limbs on the SEBT were truly significant or a result of measurement error associated with the test. For example, it is unclear whether the 4cm difference between limbs noted by Plisky et al. (2006) was outside error measurement associated with the SEBT. Until these values are known these conclusions cannot be drawn.

Inter- and intra-tester reliability of the SEBT has previously been established (Hertel et al., 2000). Although significant learning effects were noted between trials one and six where low ICC values (0.35-0.84) were reported. Reliability for trials seven to twelve, when scores had stabilised, were high (0.81-0.93) suggesting excellent agreement between testers. This led the authors to suggest that six practice trials are undertaken prior to measurement of performance. In Hertel et al's study the SEBT was administered testing in four blocks of three trials on two separate days which is likely to have affected the results. In light of this, Robinson and Gribble (2008) undertook further analysis of the learning effects associated with the SEBT and found that stability in performance was reached after only four trials. This led to the recommendation of four practice trials in all future studies.

Between-session reliability has also been assessed, with ICC values ranging from 0.67-0.93 (Hertel et al., 2000; Kinzey & Armstrong, 1998; Plisky et al., 2006). However, each of these studies used a different protocol and only Hertel et al. (2000) followed the recommended protocol of eitherfour or six practice trials in each direction. For this reason the reliability of the SEBT needs to be revisited. Furthermore, no study has examined the measurement error associated with the SEBT and what percentage change reflects a true improvement in performance.

These studies suggest that the SEBT may be sensitive to post-ACL injury and PFPS deficits and the prediction of future lower limb injury risk, although whether it is sensitive enough to

predict specific injuries such as ACL or PFPS remains to be seen. Additionally, the lack of reliability and error measurement values associated with the SEBT mean the results from these previous studies cannot be truly understood. Examination of the reliability of the SEBT will be undertaken in chapter four.

2.7. Summary

2D motion analysis, hop for distance tests and the SEBT all demonstrate the potential to identify individuals who may be at high risk of sustaining an ACL or PFJ injury. Considering the evidence presented, further investigation and understanding of the potential of these screening tools to identify athletes at high-risk of ACL or PFJ injury is warranted. Gaining further knowledge of the relationship between 2D FPPA and 3D variables associated with dynamic knee valgus is essential for the validation of 2D FPPA as a screening tool. Understanding the reliability and measurement error of such measures is important to establish whether the tests are valid and to enable future studies and clinicians to evaluate any changes in individual or group performance. Assessing the factors which may cause poor performance in these tests, such as strength and range of movement would allow targeted and informed interventions to be implemented to help reduce injury risk. These factors will be investigated in chapter five.

Chapter 3

Reliability and Validity of Two-Dimensional Frontal Plane Projection Angle during Common Athletic Screening Tasks

Acknowledgement

I would like to acknowledge the work of Michael Carolan within the data collection process of this chapter.

3.1. Aim

The aims of this study are to:

1. Establish the intra-tester, inter-tester, within-session and between-session reliability and measurement error of 2D FPPA.
2. Assess the relationship between 2D FPPA and 3D lower limb biomechanics associated with dynamic knee valgus during commonly used lower limb screening tasks.

3.2. Introduction

Motion analysis techniques are widely used within sports medicine research to assess performance and injury risk parameters. Identification of risk factors for ACL and PFJ injury has received much interest, with the demonstration of dynamic knee valgus during common athletic manoeuvres seen as a potentially high-risk movement strategy (Hewett et al., 2005; Myer et al., 2010). Dynamic knee valgus, as discussed in section 2.3.4.1 of chapter two, is a combination of frontal and transverse plane hip, knee and ankle/foot movement. Identification of individuals who demonstrate dynamic knee valgus motion during athletic tasks is therefore important in order to modify these high-risk movement patterns and potentially decrease the risk of injury.

3D motion analysis techniques are widely used in research to quantify lower limb biomechanics during athletic tasks. These techniques afford clinicians and researchers information on all three planes of joint motion during simple and complex tasks. 3D analysis is postulated as the "gold standard" of motion analysis. However, there are several questions regarding its reliability, especially for use in longitudinal study designs (McGinley et al., 2009). As discussed in chapter two, between-session reliability is often lower than within-session reliability across a wide range of tasks (Ferber et al., 2002; Ford et al., 2007; McGinley et al., 2009; Queen et al., 2006). Ford et al. (2007) studied reliability of lower limb

3D angles and moments during the drop jump task and found that between-session ICCs ranged from 0.59-0.92, whereas within-session ICCs ranged from 0.67-0.99. In this study, single skin based markers were used rather than the rigid arrays recommended (Manal et al., 2000) and this is likely to have adversely effected reliability due to skin movement artefact. Additionally, inconsistencies in marker placement between sessions are likely to have a great influence on between-session reliability. Soft tissue artefact has also been cited as a potential source of error, with the greatest influence likely to be at the thigh (Cappozzo et al., 1996; Reinschmidt et al., 1997). This is supported by generally lower ICCs noted for hip angles and moments compared to those at the knee and ankle in the Ford et al. (2007) study.

Frontal and transverse planes of movement are believed to be more sensitive to errors in marker placement, skin movement artefact and soft tissue artefact (Cappozzo et al., 1996; Kadaba et al., 1989; Reinschmidt et al., 1997), which may explain the tendency for lower reliability values in these planes. The greatest errors during gait analysis are often seen with hip and knee rotations (McGinley et al., 2009). Motion in the frontal and transverse planes, in particular dynamic knee valgus, is seen as key to high risk movements associated with ACL and PFJ injury (Hewett et al., 2005; Myer et al., 2010). Therefore the measurement error in these planes may have a significant effect on identification of high-risk athletes with 3D motion analysis.

Of more importance with regards to its use within large-scale screening programmes or for use in the field, are the financial, spatial and temporal costs of 3D motion analysis. These factors mean it is not practical to use 3D analysis in most clinical settings and particularly for large screening programmes required to help reduce injuries on a wider scale. Therefore investigation to find a simpler and more cost-effective method of analysis, which can detect high-risk patterns of movement linked to ACL and PFJ injury, is warranted.

Validity of 2D FPPA

2D video techniques may provide this alternative solution to 3D analysis and were discussed in detail in section 2.6.1 of chapter two. 2D FPPA has been used to assess dynamic knee valgus (Herrington, 2010; Herrington & Munro, 2010; McLean et al., 2005b; Willson & Davis, 2008b; Willson et al., 2006). Characterisation of 3D motion using frontal plane 2D analysis was first explored during cutting manoeuvres by McLean et al. (2005b) and was later defined as FPPA by Willson et al. (2006). These studies assessed the validity of 2D FPPA to characterise select 3D angles of the lower limb during cutting and squatting tasks which were

recorded simultaneously (McLean et al., 2005b; Willson & Davis, 2008b). 2D peak FPPA was shown to account for 58-64% of the variance in peak 3D knee abduction angle between subjects' during side-step and side-jump activities (McLean et al., 2005b). Willson and Davies (2008b) found that 2D FPPA reflected 23-30% of the variance of 3D values during the single leg squat. More interestingly they found that 2D FPPA was significantly correlated with both knee external rotation and hip adduction, two major components of dynamic valgus. The authors of these studies concluded that although 2D analysis is not a substitute for 3D measurements of lower limb kinematics, it is useful for screening FPPA to identify athletes suspected to be at high-risk of ACL of PFJ injury (McLean et al., 2005b; Willson & Davis, 2008b). Individuals who demonstrate excessive 2D FPPA values are thought to demonstrate 3D kinematics which leaves them at high-risk of knee injuries such as ACL tears and PFPS.

It is important that correlations between 2D FPPA and 3D movements which contribute to dynamic knee valgus are evident if FPPA is to identify those at high risk of injury. Whilst a relationship between 2D FPPA and 3D hip and knee angles associated with dynamic knee valgus has been shown for the single leg squat and side-step, whether this relationship exists during other tasks is currently unknown. There has been considerable variety in the tasks used to study ACL and PFJ injury risk, with each task representing different demands.

The drop jump (DJ) task is widely used in research to assess injury risk due to those individuals who demonstrate greater knee valgus motion during the DJ task being at greater risk of ACL and PFJ injury (Hewett et al., 2005; Myer et al., 2010). Therefore correlation between 2D FPPA and 3D variables associated with dynamic knee valgus may add weight for the use of 2D FPPA to help identify potentially high-risk individuals.

The single leg landing (SLL) task may be relevant for assessment as unilateral landings are a more common ACL injury mechanism than bilateral landings (Faude et al., 2005). Research has also shown that individuals demonstrate increased hip adduction and knee valgus during unilateral tasks compared to bilateral tasks (Myklebust et al., 1998; Pappas et al., 2007). The increased demand to decelerate landing forces during the SLL task compared to the DJ task may mean this screening task is more sensitive in identifying those who display dynamic knee valgus, although this has not been investigated.

The single leg squat (SLS) task has previously been used to investigate the link between 2D FPPA and 3D lower limb angles (Willson & Davis, 2008b). The SLS predicts kinematics

demonstrated during running (Whatman et al., 2011) and distinguishes between participants with and without PFPS (Willson & Davis, 2008b). Therefore, the SLS may have potential to identify those at risk of suffering from PFPS. In addition, those who demonstrate increased dynamic valgus during the SLS are likely to exhibit similar dynamic valgus during more complex tasks such as landing and cutting.

Whilst lower limb motion across tasks is often strongly correlated (Harty, DuPont, Chmielewski, & Mizner, 2011), the more dynamic nature of the SLL and DJ tasks compared to the SLS may increase the measurement error associated with the 2D and 3D analysis methods due to greater within-participant variability and soft tissue artefacts. It cannot be taken therefore, that relationships between 2D FPPA and 3D variables previously noted would be present in the SLL and DJ tasks and this relationship requires investigation. Additionally, only the relationship between 2D FPPA and 3D hip and knee angles has previously been investigated. Considering the influence of hip and knee moments in increasing joint load and injury prediction further investigation of this relationship is warranted. The potential of 2D FPPA as a method to identify high-risk individuals may be compromised, in the absence of a prospective study, if the relationship between FPPA and 3D kinetic and kinematic variables associated with dynamic knee valgus is not significant.

Reliability of 2D FPPA

Only ICCs for within-day reliability of FPPA have been presented. Good within-day reliability (ICC=0.88) was reported during the single leg squat task in a sample of collegiate athletes (Willson et al., 2006). However, no study has presented measurement error values or assessed intra-tester, inter-tester, or test-retest reliability of 2D FPPA in any task. Therefore, further investigation of the reliability of 2D FPPA is needed before it can be recommended for use in screening tests. If the reliability and measurement error of this screening method can be established then clinicians will be able to use the tests with confidence whilst also being able to evaluate individual performance more informatively.

3.3. Methods

Participants

Twenty recreationally active participants, ten men (age 22.6 ± 3.1 years, height 177.9 ± 6.0cm, weight 75.8 ± 7.9kg) and ten women (age 21.5 ± 2.3 years, height 170.1 ± 6.1cm, weight 66.2 ± 10.2kg), all of whom were university students, volunteered for the study. Entry criteria for this study are outlined below. The same entry criteria, approval and consent

procedures were used throughout all studies with recreationally active participants (see also chapters 4, 5 and 6). Prior to testing participants were required to self-report if they did not meet any of the following criteria:

- Participants were required to be free from lower extremity injury for at least six months prior to testing, and have no history of lower extremity surgery. Injury was defined as any musculoskeletal complaint which stopped the participant from undertaking their normal exercise routine.

- All participants were aged between 18 and 30 years of age. This age range was selected to represent the young, athletic population to whom the results of the study are most likely to be applied.

- To qualify as recreationally active, participants were required to participate in a minimum of 30 minutes of physical activity three times a week on a regular basis over the past six months, which included recreational and competitive sports.

- Where repeat testing was to take place, participants were asked to wear the same shoes to negate any potential influence on lower extremity biomechanics.

- The study was approved by the University Research and Ethics Committee and all participants gave written informed consent prior to participation.

Protocol

Drop Jump (DJ) task – Figure 3.1

Participants stood with feet shoulder width apart on a 28cm high step, 30cm from the force plates. This height is similar to that used by Hewett et al. (2005) and was used as it has been suggested that the neuromuscular system is unable to attenuate impact forces from heights greater than 30cm (Moran et al., 2009; Moran & Marshall, 2006). Participants were instructed to lean forward and drop from the step as vertically as possible, in an attempt to standardize drop height (Onate, Cortes, Welch, & Van Lunen, 2010). This was monitored by observation during each trial. Participants were required to land with one foot on each of the force plates then immediately perform a maximal vertical jump, finally landing back on the force plates. There were no set instructions regarding arm movement, only for the participants to perform the jump naturally. The initial landing from the step was used for analysis purposes (Herrington & Munro, 2010).

Figure 3.1– the Drop Jump task.

Single Leg Landing (SLL) task – Figure 3.2

As with the drop jump task participants dropped from a 28cm step, again leaning forward and dropping as vertically as possible. Participants were asked to take a unilateral stance on the contralateral limb, step forward and drop onto the force platform corresponding to the landing leg. Participants had to ensure the contralateral leg made no contact with any other surface (Herrington & Munro, 2010). Participants were required to keep their hands on their hips and hold the landing for at least two seconds before stepping off the force plate.

Figure 3.2– the Single Leg Land task.

Single Leg Squat test (SLS) task – Figure 3.3

Participants were asked to take a single leg stance on the force place corresponding to the test limb. Participants were then asked to squat to at least 45° knee flexion and no greater than 60°, over a period of five seconds. Knee flexion angle was checked during practice trials using a standard goniometer (Gaiam-Pro) then observed by the same examiner throughout the trials. There was also an electronic counter for each participant over this five second period in which

the first count initiates the movement, the third indicates the lowest point of the squat and the fifth indicates the end. Trials were only accepted if the participant squatted within the desired degrees of knee flexion and they maintained their balance throughout.

Figure 3.3 – the Single Leg Squat task.

Participants were allowed practice trials prior to each of the three tests until they felt comfortable, this was typically two to three trials. After familiarisation each participant performed three trials of each test. Both legs were tested and analysed for all tasks. Participants were allowed thirty seconds rest between trials and two minutes between tasks. The order in which the tasks were completed was randomised, as was the order in which the legs were tested for the SLS and SLL tasks. To achieve randomisation, two sets of cards were placed face down on a table. The first set of three cards had one of the tasks written on each, whilst the second set of two cards had right or left written on one side. Participants were asked to select from the three task cards to determine which order the task were undertaken. Participants then chose a limb card at the start of both the SLL and SLS tasks. Participants were tested twice on day one (S1), with each test repeated one hour later (S2) to assess within-day reliability of 2D FPPA. Participants were then tested again one week later (S3) at the same time of day to assess between-session reliability of 2D FPPA. The same randomisation was undertaken for each test session. Each test session lasted approximately one hour.

3D analyses

A twelve-camera OQUS (Qualisys, Gothenburg, Sweden) motion analysis system sampling at 100 Hz, with two force platforms (AMTI BP400600, USA) embedded into the floor sampling at 1000Hz, were used to collect the kinematic and kinetic data. Prior to testing reflective markers were attached with self-adhesive tape to the participants' lower limbs at the anterior

superior iliac spines, posterior superior iliac spines, iliac crest, greater trochanters, medial and lateral femoral condyles, medial and lateral malleoli, posterior calcanei, and the head of the first, second and fifth metatarsals. These markers were used to define the anatomical reference frame and centres of rotations of the joints. The markers at the locations of 1st, 2nd and 5th metatarsal heads and calcaneus were assumed to be a rigid body. Five rigid plates, each consisting of four non-collinear markers, were secured to the leg with an adherent spray (Tensospray, BSN Medical, UK) and elastic bandages (Supa-Wrap, Fabriofoam, USA) on the antero-lateral aspect of the thigh, shank and around the pelvis. These rigid bodies were used as tracking markers to track the movement of each segment during the movement trial. The use of a rigid marker set of four non-collinear markers for tracking purposes has previously been shown to be the optimal configuration in comparison to using individual skin markers and other rigid arrays (Manal et al., 2000). Figure 3.4 shows the marker set-up with both anatomical and rigid markers in place. Anatomical markers were removed for data collection leaving only the tracking markers in place, as shown in figure 3.5.
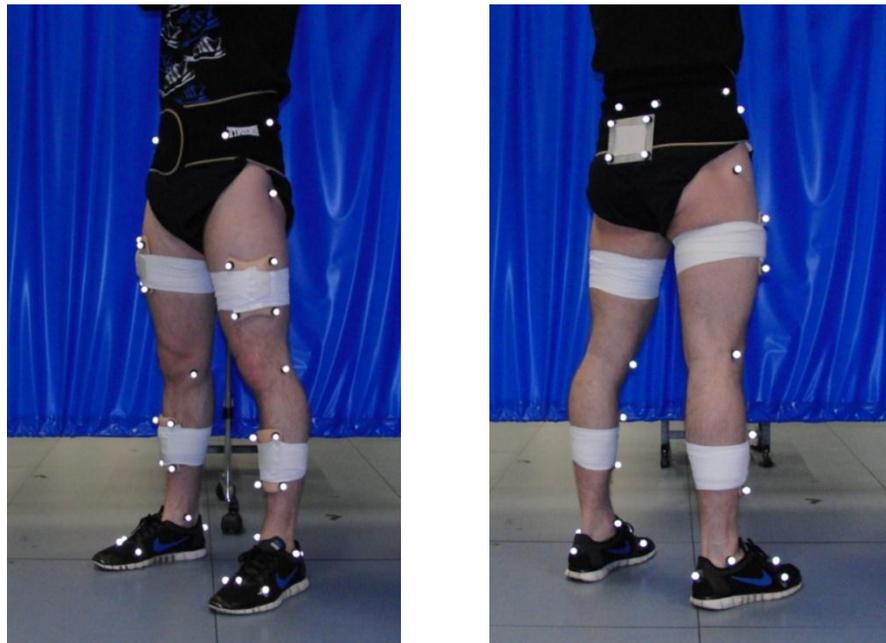
Figure 3.4 - 3D anatomical and rigid marker setup.
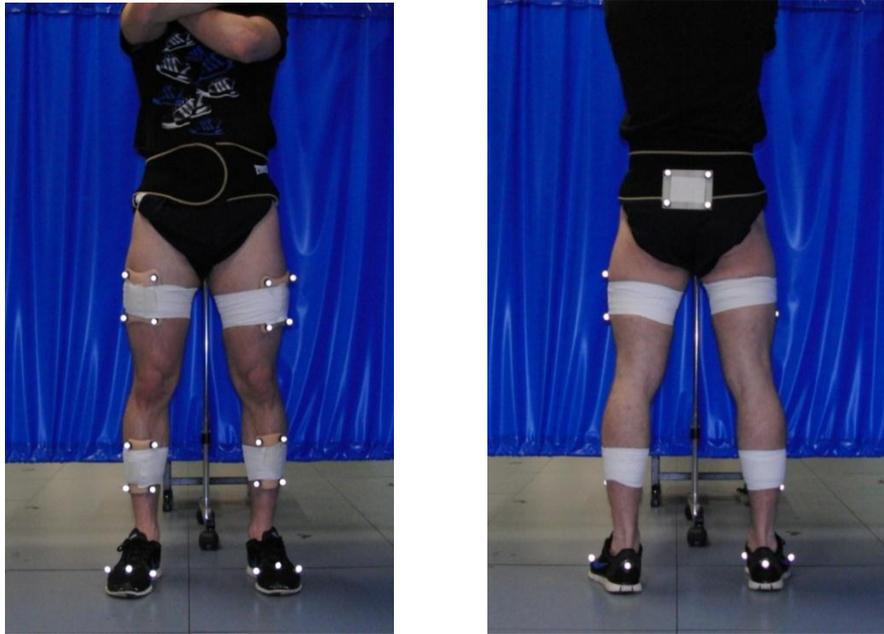
Figure 3.5 - 3D tracking marker setup.

The calibrated anatomical systems technique (CAST) was employed to determine the movement of each segment and anatomical significance during the movement trials (Cappozzo, Catani, Croce, & Leardini, 1995). A static standing trial, where the participant stood on the force plates with all markers in view of the cameras, was taken when all anatomical and tracking markers were attached. This static trial allowed for later identification of the anatomical and tracking markers in the Qualysis Track Manager (version 1.10.282) software prior to extraction to post-processing software. Gaps in kinematic data were interpolated within the Qualysis Track Manager software, those greater than 10 frames were checked manually for errors in marker tracking. A lower extremity kinematic model was created for each participant using this static trial in Visual 3D motion capture software (Version 4.21, C-Motion Inc., Rockville, MD, USA). This model included the pelvis, thigh, shank and foot to quantify motion at the hip, knee, ankle and subtalar joints. A CODA pelvis orientation was used to estimate the position of the hip joint centre. The position of the anatomical markers provided a reference point for the identification of bone movement using only the tracking marker sets during movement trials.

Post-processing calculation of the kinematic and kinetic time series data was conducted using Visual3D motion capture software. Motion and force plate data were filtered using a Butterworth 4th order bi-directional low-pass filter with cut-off frequencies of 12Hz for kinematic data and 25Hz for force plate data. The goal of smoothing data using digital filters is to reduce random noise whilst leaving the signal unaffected. The Butterworth filter is

commonly used in biomechanical research as it has been shown to be effective in removal of random noise in kinematic and kinetic data of human body movement (Winter, Sidwall, & Hobson, 1974). The cut-off frequencies selected were based on work by Yu et al. (1999).

All lower extremity segments were modelled as conical frustra, with inertial parameters estimated from anthropometric data (Dempster, Gabel, & Felts, 1959). Joint kinematics were calculated using an X–Y–Z Euler rotation sequence, where X equals flexion-extension, Y abduction-adduction/varus-valgus and Z internal-external rotation, as depicted in figure 3.6. Joint kinetic data were calculated using three-dimensional inverse dynamics through the Visual 3D software, and the joint moment data were normalized to body mass and presented as external moments.

Initial contact (IC) was defined as when vGRF first exceeded 20N, whilst toe-off (TO) was defined when vGRF first dropped below 20N after IC. DJ data were normalised to 100% of the stance phase (between IC and TO) whilst SLL and SLS data were normalized to 100% of knee flexion phase (between IC and time of maximum knee flexion).

Peak values for hip, knee and ankle angle and moments in the frontal and transverse planes were recorded. Maximum and minimum values of each trial for each person were extracted before a participant specific mean was calculated. By convention hip adduction and internal rotation, knee valgus, tibial internal rotation and subtalar joint complex pronation/eversion were denoted as positive.
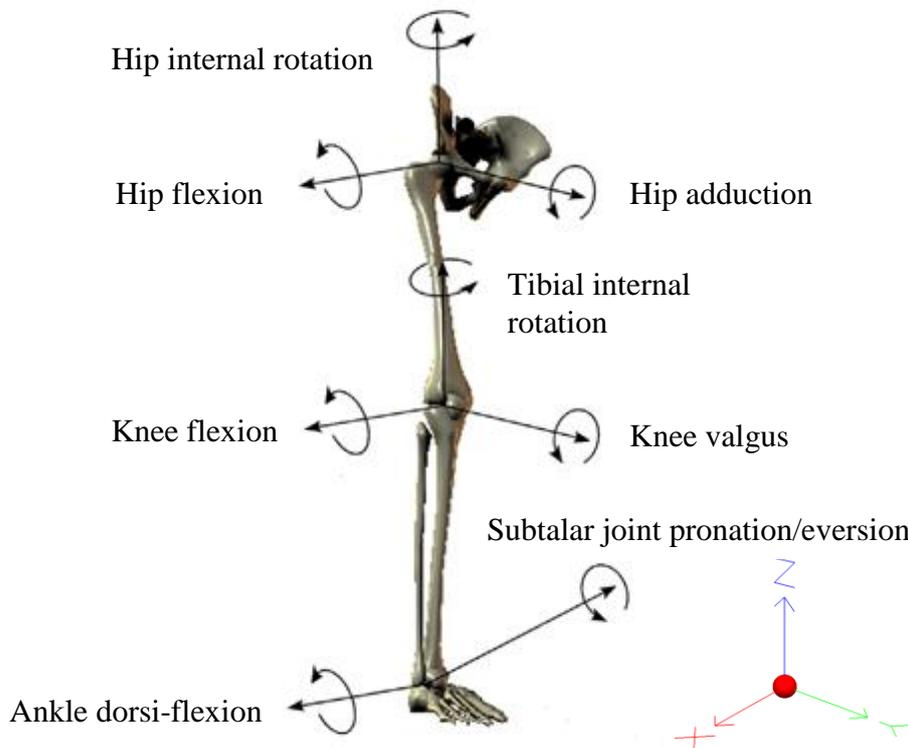
Figure 3.6 – Lower extremity segment and joint rotation denotations. X equals flexion-extension, Y abduction-adduction/varus-valgus and Z internal-external rotation. Hip adduction and internal rotation, knee valgus, tibial internal rotation and subtalar joint complex pronation/eversion were denoted as positive.

2D analyses

A commercially available digital video camera (Sony Handycam DCR-HC37) sampling at 25Hz was wall mounted at a height of 60cm and 10 metres away from the force plates. Digital video footage was recorded at a standard 10x optical zoom throughout each trial in order to standardize the camera position between participants. This video was saved onto a desktop PC for later analysis.

For 2D analysis, markers were placed on the lower extremity of each participant to approximate the radiographic landmarks employed by Willson et al. (2006). Markers were placed at the midpoint of the ankle malleoli for the centre of the ankle joint, midpoint of the femoral condyles to approximate the centre of the knee joint, and on the proximal thigh at the midpoint of the line from the anterior superior iliac spine to the knee marker. Markers were used to determine joint centres as it has been shown to increase intra- and inter-rater reliability in comparison to manual digitisation of joint centres via video (Bartlett, Bussey, & Flyger, 2006). Figure 3.7 shows the placement of these 2D markers. The midpoints were determined using a standard tape measure and all markers were placed by the same experimenter.

Markers were digitised using Quintic Biomechanics software package (9.03 version 17), allowing FPPA of the knee to be obtained. This same procedure for marker placement was carried out in each study where 2D FPPA was measured.

Figure 3.7- 2D marker placement for measurement of Frontal Plane Projection Angle.

Frontal Plane Projection Angle (FPPA)

FPPA of the knee was measured as the angle subtended between the line from the markers on the proximal thigh to the knee joint and the line from the knee joint to the ankle (Willson et al., 2006). FPPA was measured at the frame which corresponded with the point of maximum knee flexion, as shown in figure 3.8. This was determined as the lowest point of the squat and landing tasks. Positive FPPA values reflected knee valgus, excursion of the knee towards the midline of the body so that the knee marker was medial to the line between the ankle and thigh markers. Negative FPPA values reflected knee varus, excursion of the knee away from the midline of the body. Average FPPA from three trials was used for analysis. The same analysis was undertaken to obtain FPPA in all studies in this thesis.
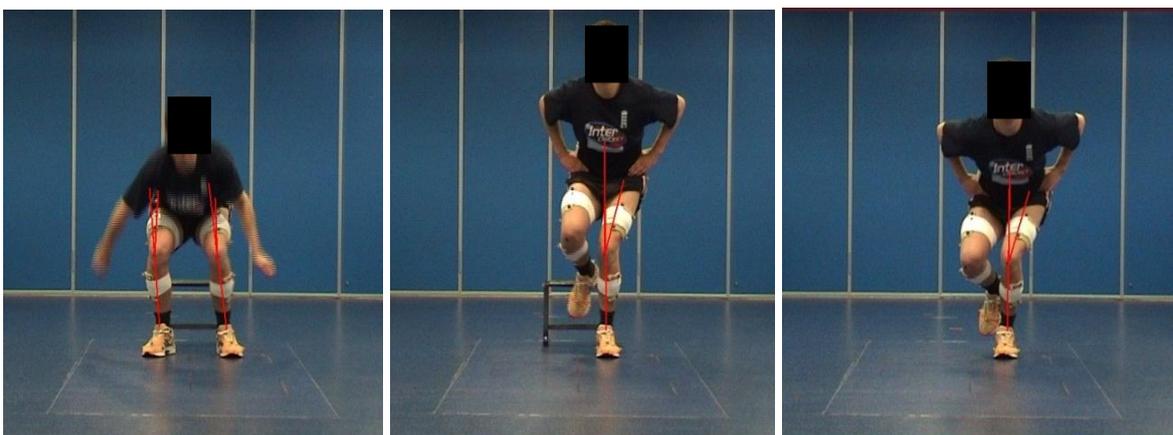
Figure 3.8 - Frontal Plane Projection Angle during drop jump, single leg land and single leg squat tasks.

Statistical Analysis

All statistical analysis was conducted using SPSS for Windows version 16.0 (SPSS Inc., Chicago, IL). Normality for each variable was assessed using the Kolmogorov-Smirnov test. Means and standard deviations for all measured variables are presented.

Reliability of 2D FPPA

For each of the following reliability tests each trial was assessed once and the mean value from three trials for each participant was used. All 2D data was found to be normally distributed. Independent t-tests were carried out to assess differences between men and women and left and right legs. Significance levels were set at $p<0.05$. Where differences were found between genders or limbs reliability analysis was carried out separately

Within-day and between session reliability

Data from S1 and S2 were used to assess within-day reliability. Between-session reliability was assessed using data from S1 and S3. The same experimenter (E1) analysed each video trial.

Intraclass correlation coefficients (ICC) (3,1) (Shrout & Fleiss, 1979) assessed within and between session reliability, from which 95% confidence intervals (CI), standard error of measurement (SEM) and smallest detectable difference (SDD) were calculated to establish random error scores. ICC model (3,1) was chosen as the trial scores were considered to be a random sample of recreational athletes; and scores were the mean of three trials from one experimenter. ICC values were interpreted according to the criteria set by (Coppieters et al., 2002).

Intra-tester reliability

Data from all participants from S1 was used for intra-tester reliability analysis. The same experimenter (E1) who assessed test-retest reliability was assessed for intra-tester reliability. E1 assessed the trials of all participants (T1) before repeating the analysis on the same trials a minimum of one week later (T2). A minimum of a week was chosen as this was deemed to be enough time to avoid recollection of previous video clips and scores, therefore minimising potential bias. ICC (3,1) (Shrout & Fleiss, 1979) and SEM were calculated to assess intra-

tester reliability. ICC model (3,1) was chosen as the mean of three trials from a single rater were used.

Inter-tester reliability

Data from all participants from S1 was used for inter-tester reliability analysis. The first test data (T1) from E1 previously analysed during the intra-tester reliability was used to assess inter-tester reliability. The second experimenter (E2) was given written instructions on how to assess FPPA using the Quintic software. These instructions were based on the description of FPPA outlined in this method and were the same used by E1. Both experimenters were blinded to the others scores to avoid potential bias. ICC (3,2) (Shrout & Fleiss, 1979) and SEM assessed inter-tester reliability. ICC model (3,2) was chosen as the scores of two raters were used to assess reliability between them.

Validity of 2D FPPA

Validity analysis was carried on both limbs and genders collectively using data collected in S1. All data was found to be normally distributed. Correlations between 2D FPPA and 3D variables (hip internal rotation, hip adduction, knee valgus, tibial rotation subtalar joint pronation/eversion angles and moments during the DJ, SLL and SLS) were assessed using Pearson's product correlation coefficients (R). The alpha level was set a-priori as $p < 0.05$. However, this was corrected in order to reduce the likelihood of a type 1 error occurring, to $p < 0.025$. This was determined as relationships between angles and moments for each movement (e.g. hip adduction angle and moment) will be evident, whereas links between individual movements are not clear (hip adduction and tibial rotation). The p-value was corrected by dividing the a-priori value by the number of correlations for each movement to be undertaken (i.e. two). The magnitude of correlations were described as small (0-0.3), moderate (0.3-0.5), large (0.5-0.7) and very large (0.7-1) (Hopkins, Marshall, Batterham, & Hanin, 2009). Power analysis was undertaken where significant correlations were evident using G*Power (version 3.1) (Faul, Erdfelder, Buchner, & Lang, 2009).
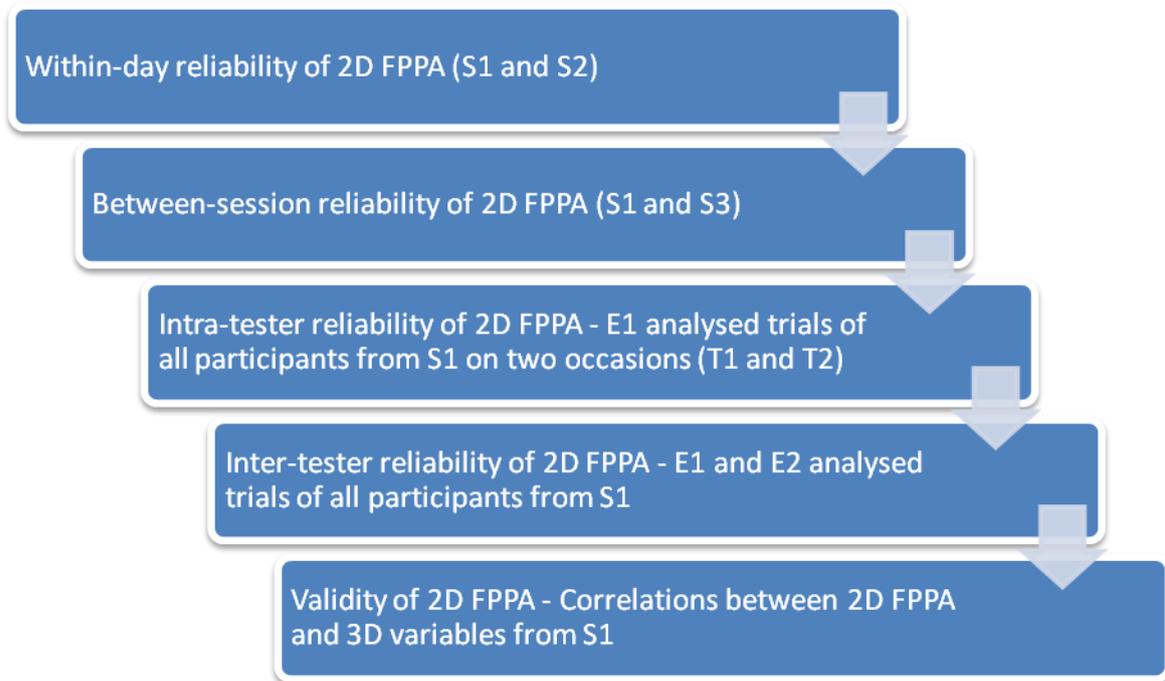
Figure 3.9 – A flow diagram showing statistical analyses undertaken.

3.4. Results

Firstly, all data from S1, S2 and S3 were analysed for differences between gender and limbs. Women demonstrated significantly higher FPPA than men for all tests (DJ $p<0.001$; SLL $p=0.001$; SLS $p=0.017$), therefore reliability data were analysed separately by gender. No differences were found between left and right limbs ($p>0.05$) therefore they were grouped during all further analysis.

Reliability

Within-day and between session reliability

Within-day reliability was shown to be good for all tests, with the exception of SLS in women. ICCs are shown in table 3.1 and ranged from 0.59 to 0.88 for women, the SLS accounting for the lowest, 'fair' score of 0.59. ICCs ranged from 0.79-0.86 for men. Within-day SEM values ranged from 2.8-3.9º and SDDs from 7.7-10.8º.

Between-session reliability was fair to good for all tests and is presented in table 3.2. ICCs ranged from 0.66-0.84 for women, with SLS again having the lowest reliability. ICCs ranged from 0.67-0.84 for men, with fair reliability for the SLL and good for the DJ and SLS. Furthermore SEM and SDD values can also be seen table 3.2, ranging from 3.2-4.1º and 8.9-11.4º respectively.

Table 3.1- Mean and standard deviation (SD)values for session 1 (S1) and session 2 (S2) and within-day intraclass correlation coefficient (ICC), 95% confidence intervals (CI) for ICC, standard error of measurement (SEM), and smallest detectable difference (SDD).

Test	S1 (°)	S2 (°)	ICC	95% CI		SEM (°)	SDD(°)
Men	Mean (SD)	Mean (SD)					
DJ	-6.0 (8.3)	-3.7 (8.8)	0.83	0.72	0.90	3.5	9.8
SLL	4.3 (5.6)	5.1 (6.5)	0.79	0.65	0.87	2.8	7.7
SLS	8.1 (7.9)	8.8 (8.1)	0.86	0.77	0.92	2.9	8.3
Women							
DJ	8.9 (9.2)	9.2 (9.7)	0.88	0.80	0.93	3.3	9.0
SLL	8.1 (6.7)	7.3 (6.9)	0.75	0.58	0.85	3.4	9.5
SLS	11.2 (6.1)	11.4 (6.1)	0.59	0.31	0.75	3.9	10.8

Note: SLS =single leg squat, DJ = drop jump, SLL = single leg land

Table 3.2 – Mean and standard deviation (SD) values for sessions 1 (S1) and 3 (S3), between-day intraclass correlation coefficient (ICC), 95% confidence intervals (CI) for ICC, standard error of measurement (SEM), and smallest detectable difference (SDD).

Test	S1 (°)	S3 (°)	ICC	95% CI		SEM (°)	SDD (°)
Men	Mean (SD)	Mean (SD)					
DJ	-6.0 (8.3)	-6.8 (9.9)	0.84	0.74	0.91	3.6	9.9
SLL	4.3 (5.6)	4.6 (6.2)	0.67	0.45	0.80	3.2	8.9
SLS	8.1 (7.9)	9.1 (7.9)	0.81	0.68	0.89	3.4	9.4
Women							
DJ	8.9 (9.2)	6.3 (11.0)	0.84	0.74	0.91	4.1	11.4
SLL	8.1 (6.7)	6.6 (6.5)	0.75	0.58	0.85	3.5	9.7
SLS	11.2 (6.1)	10.6 (6.1)	0.66	0.43	0.80	3.5	9.7

Note: SLS =single leg squat, DJ = drop jump, SLL = single leg land

Intra-tester reliability

Intra-tester reliability was found to be excellent for all tests and is presented in table 3.3. ICCs ranged from 0.94-0.96 in men and 0.97-0.98 in women. SEM scores ranged from 1-1.9º suggesting that very little measurement error was evident.

Table 3.3 – Mean and standard deviation (SD) values for test 1 (T1) and test 2 (T2), intra-tester intraclass correlation coefficient (ICC), 95% confidence intervals (CI) for ICC, standard error of measurement (SEM).

Test	T1 (°)	T2 (°)	ICC	95% CI		SEM (°)
Men	Mean (SD)	Mean (SD)				
DJ	-5.3 (8.4)	-5.7 (7.8)	0.96	0.93	0.98	1.6
SLL	6.1 (6.7)	6.3 (5.5)	0.95	0.91	0.97	1.4
SLS	10.9 (7.8)	10.7 (7.7)	0.94	0.90	0.97	1.9
Women						
DJ	7.9 (8.8)	8.4 (9.0)	0.98	0.96	0.99	1.3
SLL	8.8 (7.7)	8.7 (7.2)	0.97	0.94	0.98	1.3
SLS	11.7 (7.1)	11.7 (6.9)	0.98	0.97	0.99	1.0

Note: SLS =single leg squat, DJ = drop jump, SLL = single leg land

<u>Inter-tester reliability</u>

Inter-tester reliability was also found to be excellent for all tests and is presented in table 3.4. ICCs ranged from 0.98-0.99 in men and were consistently 0.99 in women. SEM scores ranged from 0.7-1.2° suggesting that reliability between testers was very high and very little measurement error was evident.

Table 3.4 –Mean and standard deviation (SD)values for experimenter 1 (E1) and experimenter 2 (E2), inter-tester intraclass correlation coefficient (ICC), 95% confidence intervals (CI) for ICC, standard error of measurement (SEM).

Test	E1 (°)	E2 (°)	ICC	95% CI		SEM (°)
Men	Mean (SD)	Mean (SD)				
DJ	-5.3 (8.4)	-6.1 (8.8)	0.98	0.96	0.98	1.2
SLL	6.1 (6.7)	6.0 (6.7)	0.99	0.98	0.99	0.7
SLS	10.9 (7.8)	10.8 (7.9)	0.99	0.99	0.99	0.8
Women	Mean (SD)	Mean (SD)				
DJ	7.9 (8.8)	7.7 (9.3)	0.99	0.98	0.99	0.9
SLL	8.8 (7.7)	8.6 (7.4)	0.99	0.99	0.99	0.8
SLS	11.7 (7.1)	11.6 (6.8)	0.99	0.99	0.99	0.7

Note: SLS =single leg squat, DJ = drop jump, SLL = single leg land

<u>Validity</u>

Table 3.5 shows the mean values for each variable in each task, along with the Pearson's correlation coefficient R and p values between each variable and 2D FPPA. Significant correlations are highlighted in bold. Figures 3.10-3.12 show the subsequent R and R^2 values where significant correlations between FPPA and 3D variables were found in each task.

Drop Jump

A number of significant correlations between 2D FPPA and 3D variables were noted. All angles except hip internal rotation demonstrated a significant correlation to FPPA. A large correlation was evident between peak hip adduction angle and FPPA (R=0.62, power = 0.99). A moderate correlation was evident between knee valgus angle and FPPA (R=0.41, power = 0.77). A small negative correlation was evident between tibial internal rotation and angle and FPPA (R= -0.22, power = 0.27) whilst a small positive correlation was seen between subtalar joint pronation/eversion and FPPA (R=0.22, power = 0.27).

Only hip adduction and knee valgus moments demonstrated significant correlations to 2D FPPA. Knee valgus moment showed a moderate correlation to FPPA (R= -0.41, power = 0.77), whilst hip adduction moment showed a small correlation to FPPA (R=0.28, power = 0.42).

Single leg land

Significant correlations were evident between hip adduction, hip internal rotation and knee valgus angles for the SLL task. No correlations were found between 3D moments and 2D FPPA. Peak hip adduction (R=0.47, power = 0.88) and hip internal rotation (R=0.30, power = 0.48) angles showed a moderate relationship with FPPA, whilst knee valgus angle demonstrated a small correlation to FPPA (R=0.20, power = 0.24).

Single leg squat

Peak hip adduction, hip internal rotation, knee valgus and subtalar joint pronation/eversion angles demonstrated significant correlations to 2D FPPA. Moderate correlations were found between hip internal rotation (R=0.34, power = 0.59), subtalar joint pronation/eversion (R=0.31, power = 0.50) and hip adduction (R=0.30, power = 0.83) angles. A small correlation was noted between knee valgus angle and FPPA (R=0.24, power = 0.32). No correlations were evident between 3D moments and FPPA.

Table 3.5 – Means (SD), Pearson's correlations (r) and p values between 2D FPPA and 3D variables for the screening tasks.

	Drop Jump			Single Leg Landing			Single Leg Squat		
	Mean (SD)	R	p	Mean (SD)	R	P	Mean (SD)	R	p
2D FPPA (°)	1.0 (11.0)	-	-	7.0 (6.9)	-	-	10.2 (8.0)	-	-
3D angles									
Hip adduction (°)	**-8.49 (8.19)**	**.62**	**<0.001**	**-3.49 (12.85)**	**.47**	**<0.001**	**4.12 (12.35)**	**.30**	**0.001**
Hip internal rotation (°)	-4.64 (12.64)	.13	0.154	**-5.73 (11.85)**	**.30**	**0.001**	**2.06 (10.25)**	**.34**	**<0.001**
Knee valgus (°)	**-0.58 (11.59)**	**.41**	**<0.001**	**-4.93 (7.77)**	**.20**	**0.02**	**-4.17 (6.71)**	**.24**	**0.009**
Tibial internal rotation (°)	**-19.15 (8.55)**	**-.22**	**0.012**	19.34 (9.92)	.03	0.736	-16.87 (9.13)	-.09	0.329
Subtalar joint (°)	**9.30 (7.21)**	**.22**	**0.014**	-3.43 (5.42)	-.02	0.815	**0.48 (9.60)**	**.31**	**0.001**
3D moments									
Hip adduction moment (Nm·kg^{-1})	**0.04 (0.53)**	**.28**	**0.001**	1.27 (0.32)	.13	0.153	0.84 (0.18)	.07	0.459
Hip internal rotation moment (Nm·kg^{-1})	0.40 (0.38)	.05	0.350	0.88 (0.34)	.07	0.426	0.52 (0.18)	.15	0.121
Knee valgus moment (Nm·kg^{-1})	**-0.09 (0.42)**	**-.40**	**<0.001**	0.70 (0.39)	.20	0.026	0.40 (0.17)	.16	0.114
Tibial internal rotation moment (Nm·kg^{-1})	0.06 (0.28)	-.09	0.329	-0.43 (0.17)	.19	0.03	-.036 (0.12)	-.08	0.431
Subtalar joint moment (Nm·kg^{-1})	-0.13 (0.24)	.08	0.350	-.015 (0.39)	-.12	0.168	0.06 (0.16)	.03	0.732

Nb. Significant correlations are noted in bold
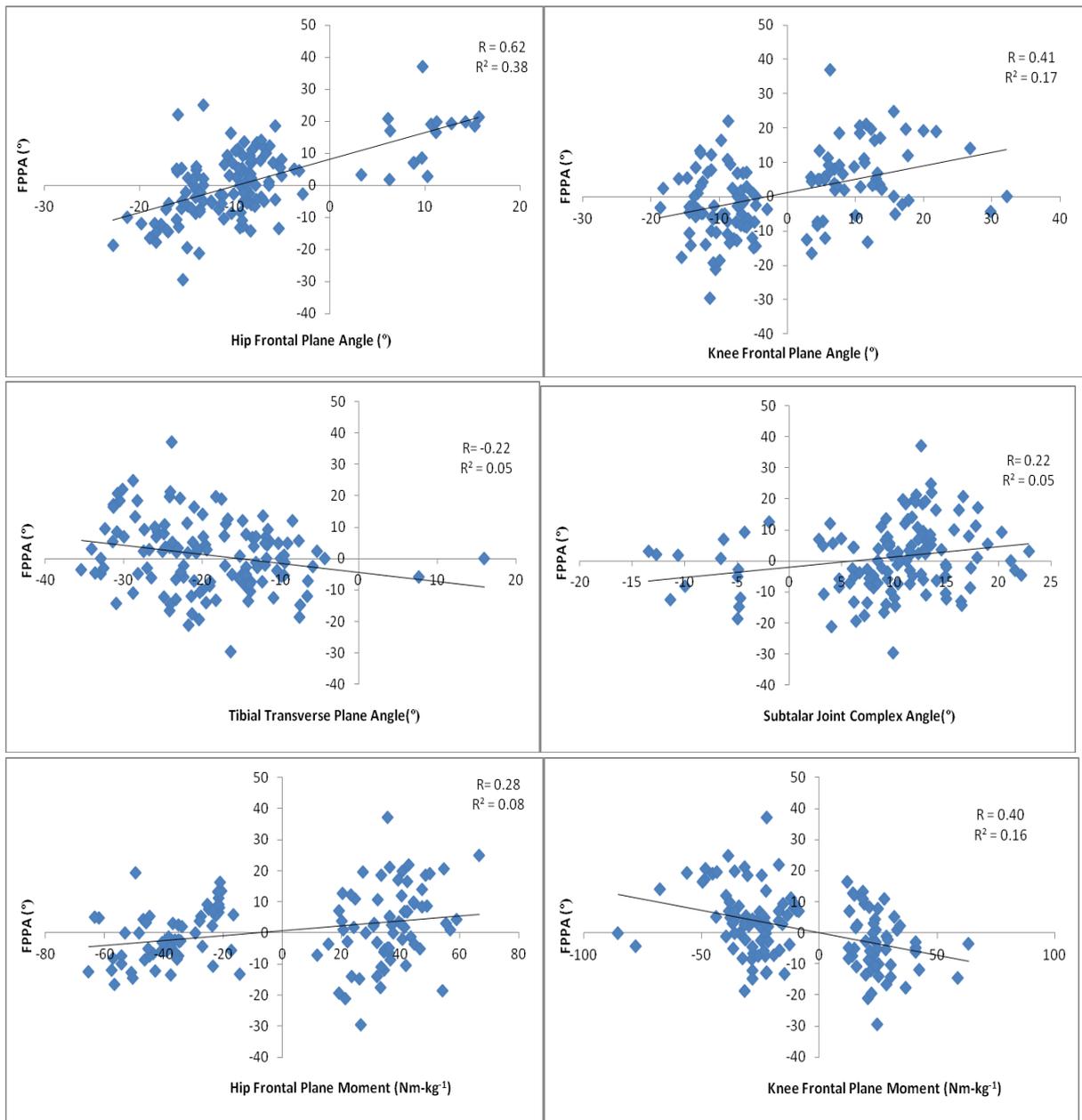
Figure 3.10 – Scatterplot illustrating the significant relationships, including R and R^2 values, between FPPA hip frontal plane angle (top left), knee frontal plane angle (top right), tibial transverse plane angle (middle left), subtalar joint complex angle (middle right), hip frontal plane moment (bottom left) and knee frontal plane moment (bottom right) during the drop jump task.
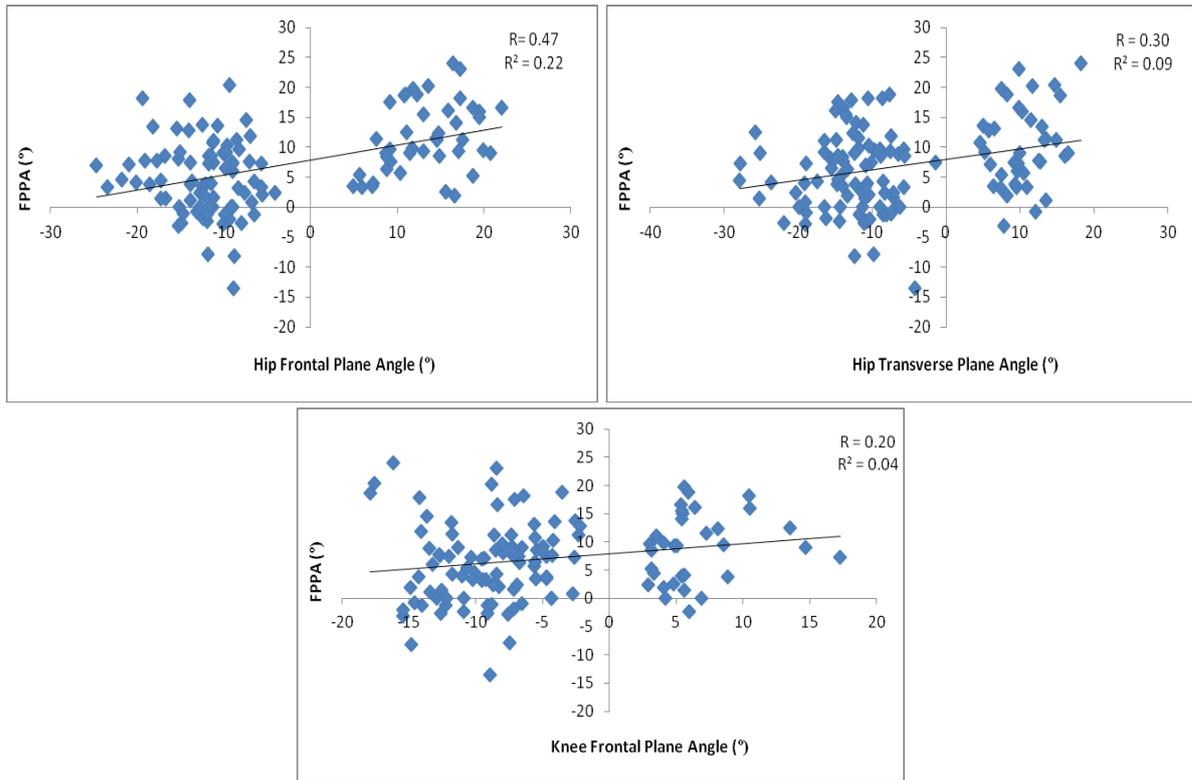
Figure 3.11 – Scatterplot illustrating the significant relationships, including R and R^2 values, between FPPA and hip frontal plane angle (top left), hip transverse plane angle (top right), knee frontal plane angle (bottom) in the single leg land task.
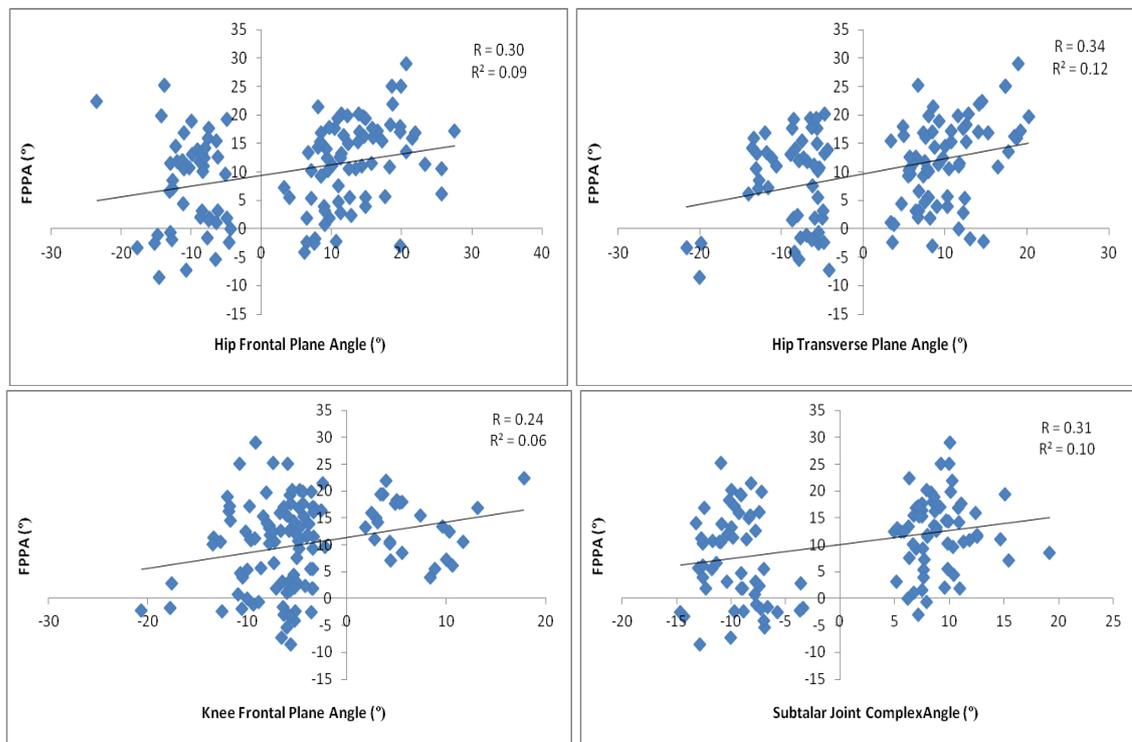
Figure 3.12 – Scatterplot illustrating the significant relationships, including R and R^2 values, between FPPA and hip frontal plane angle (top left), hip transverse plane angle (top right), knee frontal plane angle (bottom left) and subtalar joint complex angle (bottom right) in the single leg squat task.
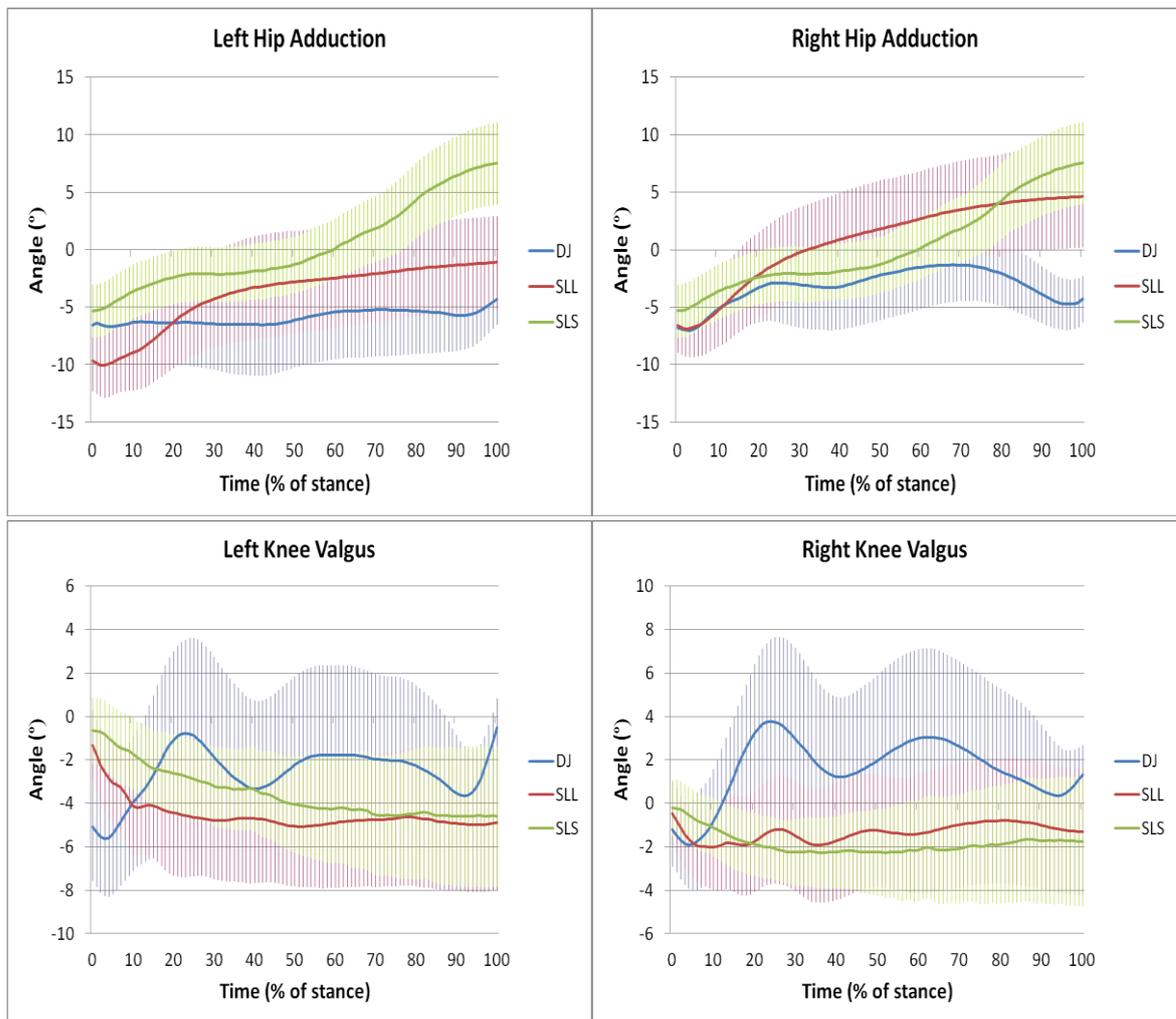
Figure 3.13- Ensemble averages for frontal plane angles at the hip and knee during the drop jump (DJ), single leg land (SLL) and single leg squat (SLS) tasks.
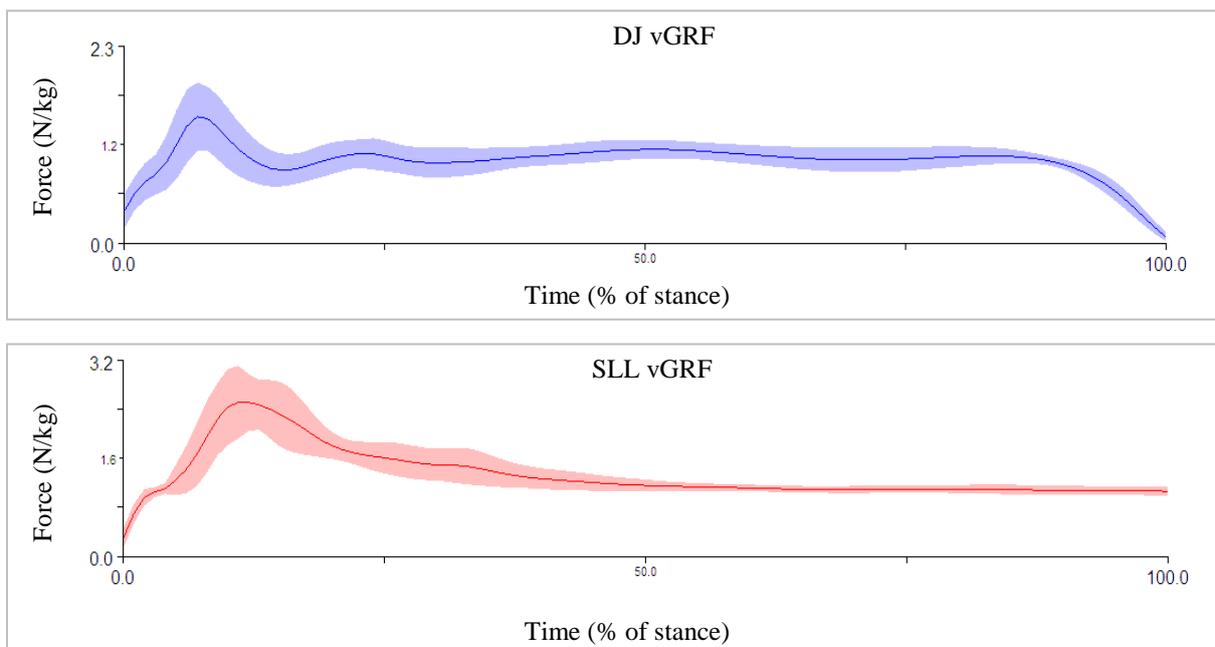
Figure 3.14 – Example force-time graphs for vertical ground reaction forces in the drop jump (blue) and single leg land (red) tasks.

Figure 3.13 shows time normalised curves for the frontal plane angles of the hip and knee. In the SLL and SLS tasks, hip adduction angle increases throughout stance, leading to hip adduction angle being greatest at the point of maximum knee flexion. In comparison, hip adduction during the DJ is more consistent throughout stance, particularly on the left limb.

Participants maintained an abducted hip position throughout the DJ. In contrast, knee valgus angles demonstrate more fluctuation throughout the stance phase. At IC, participants were in a varus knee position, and this increased briefly during the early phase of the weight acceptance. As vGRF reached its peak (figure 3.14) participants progressed towards a knee valgus position. Knee valgus peaked at around 20% of stance, which correlates with the point of maximum knee flexion during the DJ, at the transition between eccentric force acceptance and concentric force production (propulsion) phases.

In the SLL, participants were in an abducted hip position at IC, with hip adduction then increasing by around 5° during the initial weight acceptance phase (first 15 to 20% of stance) on both limbs and this is the steepest area of the curve indicating the greatest rate of change in angle. Hip abduction is maintained throughout stance on the left limb, whereas participants moved into an adducted position on the right limb.

The pattern of hip adduction is almost identical between limbs on the SLS task. Participants began in an abducted position and progressed to an adducted position as knee flexion increased. In contrast, participants began the squat in a relatively neutral position frontal plane position at the knee and progressed to a more varus position as knee flexion increased.

3.5. Discussion

The aims of this study were twofold:
1. Establish the intra-tester, inter-tester, test-retest reliability and measurement error of 2D FPPA during the DJ, SLL and SLS tasks.
2. Assess the relationship between 2D FPPA and 3D lower limb biomechanics associated with dynamic knee valgus during commonly used lower limb screening tasks.

<u>Reliability</u>
In the main, ICC values were good to excellent across all types of reliability, suggesting that 2D analysis of FPPA is reliable.

Knowledge of intra-tester reliability allows for a greater understanding about the source of error of a measurement. The random error associated with a measure can be reduced if the experimenter's measures are consistent. ICCs ranged from 0.94 to 0.98 indicating that intra-tester reliability was excellent. In addition, the low SEM values presented show that there is minimal contribution of experimenter error to the overall error of the measure. Any error above 1.0-1.9º (table 3.3) is due to systematic bias or other within subject variation. Had the intra-tester ICC values been lower and SEM values higher, test-retest reliability would have been reduced.

In addition to the excellent intra-tester reliability scores demonstrated, inter-tester reliability was also found to be excellent. ICCs were all 0.98-0.99 with associated low SEM values (0.7-1.2º). Therefore, it can be concluded that the measure is stable between different examiners, meaning it will minimise the overall measurement error of the test. It is interesting to note that inter-rater reliability was higher than intra-rater reliability. This may be due to the different versions of the ICC calculation used, although the nature of the ICC calculation mean that it can be affected by variability across scores, where decreased variability (less heterogenous data) may result in a lower ICC value (Atkinson & Nevill, 1998). The excellent intra-tester and inter-tester reliability scores, coupled with low SEM values show that the experimenter measurement error associated with 2D FPPA is small.

Systematic bias is often the result of fatigue or learning effects. To control for this, practice trials were undertaken so participants were familiarised with each task, the order in which tasks were undertaken was randomised, and sufficient rest periods were allowed between trials to avoid fatigue. Therefore, whilst the presence of systematic bias cannot be ruled out as this was not assessed, random variation within individuals' performance is most likely to account for the error found in each test. Particularly when the low SEM values for both intra-rater and inter-rater reliability are considered.

As expected, within-day reliability was greater than between-session reliability. This is likely due to greater errors in marker placement between days than within and the potential for greater variation in individual performance. The only exception to this was in the DJ task in men, although the subsequent SEM and SDD scores were greater between-session. This was due to greater standard deviation seen in S3, indicating that variation in performance across individuals was greater in this session than during S1 and S2. Willson et al. (2006) reported within-day reliability ICC of 0.88 for SLS FPPA in collegiate athletes, which is greater than

the 0.59 reported for recreational women and similar to the 0.86 reported in recreational men in the current study. This may in part be due to the greater range of scores seen in the combined men and women dataset in the Willson study. In contrast, it may be that the collegiate athletes were able to maintain more consistency in their performance of the SLS than recreational athletes used in the current study.

The SDD statistic gives an indication of the minimal change in score between tests that can be regarded as statistically significant (Kropmans et al., 1999) and is expressed in the same units as the original measurement. If the SDD values for a specific test are known, then changes between test sessions can be evaluated to determine whether any changes are due to true changes in individual performance or measurement error (Fletcher & Bandy, 2008). This is particularly important when assessing the effect of interventions on performance. For example, if a female athlete's 2D FPPA during the DJ was measured before and after an intervention period, an improvement of at least 9.7º would be required to say that the intervention had a significant effect, over and above measurement error.

Validity

Dynamic knee valgus includes hip adduction, hip internal rotation, knee valgus, tibial external rotation and subtalar joint complex pronation/eversion. It was expected that increases in 2D FPPA would be associated with increases in each of the 3D variables. Overall, the study hypothesis was supported and 2D FPPA significantly correlated to 3D measures which contribute to dynamic knee valgus. More specifically, 2D FPPA correlated to hip adduction and knee valgus angles across all tasks. Hip internal rotation and subtalar joint complex angles correlated to FPPA in two out of three tasks, whilst tibial external rotation correlated to FPPA in the DJ task. Correlations between 3D moments and 2D FPPA were less common, with only hip adduction and knee valgus moments demonstrating small and moderate correlations respectively during the DJ task.

Hip adduction showed moderate to large correlation across all three tasks, and the greatest correlation to FPPA in the DJ and SLL tasks, where 38% and 22% of the variance in hip adduction respectively could be explained by FPPA. This is perhaps not surprising considering the frontal plane nature of the 2D FPPA measure. Willson and Davis (2008b) reported a similar correlation between hip adduction and FPPA during the SLS task in women (r=0.32). Although this means that FPPA can only account for around 9% of the variance in hip adduction during the SLS task, Willson and Davis (2008b) also noted that participants

who exhibited increased FPPA during the SLS demonstrated increased hip adduction during running and single leg jumps. The results of the current study support this in that correlation between hip adduction and FPPA was evident during all tasks, and in fact were greater in the more dynamic SLL and DJ tasks. This implies that individuals who demonstrate greater FPPA during the SLS task will exhibit increases in hip adduction during other dynamic tasks. This is an important consideration as PFPS patients tend to demonstrate increased hip adduction (McKenzie et al., 2010a; Willson & Davis, 2008a; Willson & Davis, 2008b), whilst hip adduction is consistently evident during ACL injury episodes (Boden et al., 2009; Krosshaug et al., 2007a; Olsen et al., 2004).

It has been theorised that increased hip adduction is likely to lead to increases in knee valgus (Powers, 2003). This study showed small to moderate correlations between FPPA and knee valgus angles in each of the three tasks. The fact that hip adduction and knee valgus both correlated to FPPA during all tasks may provide some evidence of a link between the two motions, although this link needs to be formally investigated using correlations. It may also underline the potential influence of hip strength on dynamic knee valgus. Knee valgus motion during the DJ task predicts ACL and PFJ injury risk (Hewett et al., 2005; Myer et al., 2010; Stefanyshyn et al., 2006) and causes increased lateral patella translation during the SLS (Noehren et al., 2012). Therefore the correlations between FPPA and knee valgus demonstrated in both the current and previous studies are important for the validity of FPPA as an injury risk screening tool.

Willson and Davis (2008b) reported a correlation of 0.21 between knee valgus and FPPA, although this was deemed to be an insignificant relationship. A similar, but statistically significant, correlation (R=0.24) between knee valgus and FPPA was found in the current study. The dominant limb only of twenty subjects was examined in the Willson and Davis study, whereas both limbs of twenty subjects were examined in the current study, which may account for the difference in significant findings despite similar correlations. In the current study moderate (R=0.41) and small (R=0.20) correlations were also found between knee valgus and FPPA in the DJ and SLL tasks respectively. Significant correlations between knee valgus and FPPA have previously been noted during the side-step and side-jump tasks (McLean et al., 2005b). This provides further evidence that FPPA relates to knee valgus motion in a number of tasks. FPPA was found to account for 58-64% of the variance in knee valgus in the McLean et al. (2005b) study. In the current study, FPPA accounted for 17% of the variance in knee valgus at best, suggesting that FPPA alone cannot determine the degree

of knee valgus in these tasks, but does give some indication. There were two main differences in the methods of the current study and those of McLean et al. (2005b). Firstly, in the current study joint centres were marked during data collection, whereas joint centres were manually estimated during the digitisation process by McLean et al (2005b). Joint centre estimation without markers has been shown to be less reliable than using markers (Bartlett et al., 2006) and this may have introduced bias in the McLean et al. (2005b) study which led to overestimation of FPPA. Additionally, McLean et al. (2005b) used peak FPPA as opposed to FPPA at maximum knee flexion used in the current and previous studies on FPPA. No study to date has investigated whether there are differences between peak FPPA and FPPA measured at maximum knee flexion. Although peak FPPA is likely to be more representative of peak 3D joint angles and therefore greater correlation between variables, this would effectively make the use of FPPA in the field impossible, due to the amount of time required to digitise each trial.

Increases in hip internal rotation can negatively influence patella alignment and PFJ forces (Lee et al., 2003; Powers et al., 2010; Tennant et al., 2001; Tiberio, 1987). PFPS patients consistently demonstrate greater hip internal rotation motion compared to healthy participants (McKenzie et al., 2010a; Powers et al., 2010; Souza & Powers, 2009a; Souza & Powers, 2009b). In this study, hip internal rotation angle showed moderate correlations to FPPA during the SLS and SLL tasks, although none were evident during the DJ task. This was in contrast with Willson and Davis (2008b) who found an inverse relationship between hip internal rotation and FPPA. The authors did note that this may be explained by the posterior pelvic rotation participants exhibited on the opposing side. They argued that this pelvic rotation resulted in a net hip external rotation angle, a finding also reported by Zeller et al. (2003). Hip external rotation was not evident during the SLS task in the current study, and may explain the positive relationship between hip internal rotation and FPPA, which Willson and Davis hypothesised in their study. Participants did however, exhibit net hip external rotation during the DJ and SLL tasks, although net hip internal rotation moments were also evident in these tasks.

Noehren et al. (Noehren et al., 2012) reported that a valgus aligned squat resulted in increased external rotation of the tibia. Tibial external rotation also causes increased lateral patella translation and contact pressure (Lee et al., 2003; Noehren et al., 2012; Shultz et al., 2012) and ACL load (Berns et al., 1992; Markolf et al., 1995). This study did not support the findings of Noehren et al. (2012) as correlation between tibial external rotation and FPPA

were not found in the SLS, despite FPPA being greatest during this task. The authors also reported that the knee joint external rotation seen was likely a result of increased hip internal rotation during the closed chain squat exercise, a statement echoed by Willson and Davis (2008b). However, the results of the current study do not support this notion as correlations between hip internal rotation and FPPA, and tibial external rotation and FPPA, were not found within the same tasks. Additionally, there is no clearly observable pattern between peak hip internal rotation and tibial external rotation across the three tasks. For example, hip external rotation angles were evident in both the DJ and SLL tasks, whereas tibial internal rotation was seen in the SLL task and external rotation in the DJ task.

Increasing foot pronation has been linked to increases in lateral PFJ load via increasing tibial internal rotation and subsequent increasing of internal femoral rotation (Lee et al., 2003; Tiberio, 1987). Small to moderate correlations between subtalar angles and FPPA during the SLS and DJ tasks were evident in the current study. However, little consistency was shown with increases in hip and tibial internal rotation, which does not support the notion of a link between pronation and tibial internal rotation proposed by Tiberio (1987). Links between pronation and ACL and PFJ injury are currently unclear, therefore the small correlations demonstrated may not be surprising. The results do suggest that pronation may play a role in increasing dynamic knee valgus and therefore potentially increasing injury risk.

The results of this study show that 2D FPPA during the DJ task was moderately correlated to peak knee valgus angles and moments. Increases in peak knee valgus angles and moments during the DJ screening task predict ACL and PFJ injury in women (Hewett et al., 2005; Myer et al., 2010). Furthermore 2D FPPA showed moderate to large correlations to hip adduction angles and moments and small correlations to knee external rotation and subtalar joint complex angles. The combinations of these correlated motions are likely to cause an increase in ACL and PFJ loads, and therefore those individuals who demonstrate high FPPA values can be thought to utilise movements detrimental to the ACL and PFJ, which is likely to increase the risk of injury to these structures.

Unilateral landings are a more common ACL injury mechanism than bilateral landings (Faude et al., 2005), whilst individuals demonstrate increased hip adduction and knee valgus during unilateral tasks (Faude et al., 2005; Myklebust et al., 1998; Pappas et al., 2007). This suggests that the SLL task may be a more sensitive injury risk prediction tool than the DJ task, although prospective studies to confirm this are lacking. Increases in FPPA showed moderate

correlation to increases in peak hip adduction and hip internal rotation angle and small correlation with knee valgus angle. Once again, those who demonstrate high FPPA in the SLL task will be increasing the deleterious loads to the ACL and PFJ.

The SLS task is commonly used to assess dynamic lower limb function (Sahrmann, 2002; Zeller et al., 2003) particularly of those with PFJ injury (Willson & Davis, 2008b). Recent evidence has shown that frontal and transverse plane hip and knee joint kinematics demonstrated during the SLS task strongly correlate to those demonstrated during running (Whatman et al., 2011). Additionally, greater FPPA during the SLS task has been shown to directly associate with hip adduction and knee external rotation during running and single leg jumping (Willson & Davis, 2008b), although no correlation was shown between FPPA and knee valgus during these tasks. The results of the current study showed small to moderate correlations between FPPA and hip adduction, hip internal rotation, knee valgus and subtalar joint complex angles during the SLS task. These correlations were similar to those seen previously during the SLS for the hip adduction and knee valgus angles, but lower than correlations to knee external rotation angles (Willson & Davis, 2008b). Individuals who demonstrate increases in FPPA during the SLS may be assumed to demonstrate 3D kinematics during running which may increase PFJ loading and therefore their likelihood to sustain PFJ injury.

The results of this study showed that, in the main, correlations were small to moderate, although hip adduction showed large correlation to FPPA in the DJ task. This suggests that increases in 2D FPPA are not due to single joint motion but that it incorporates hip adduction, hip internal rotation, knee valgus, tibial external rotation and subtalar joint complex pronation/eversion movements. Different combinations of these movements are likely to increase FPPA and each has the potential to increase ACL and PFJ load and therefore increase injury risk (Hewett et al., 2005; Lee et al., 2003; Markolf et al., 1995; Myer et al., 2010). Despite some differences in the tasks analysed and the methods of collection of 3D data such as number of cameras used, positioning and use of skin based tracking markers or cluster sets, and data filtering methods and frequencies, between the current study and those conducted previously, each have shown similar correlations between FPPA and the 3D variables measured. This suggests that these correlations are common and are likely to hold true on a number of tasks. These previous studies have shown that FPPA accounts for 58-64% of the variance in peak 3D knee valgus during side-step and side-jump activities and 23-30% of hip adduction and knee external rotation during SLS (McLean et al., 2005b; Willson & Davis,

2008b). As such, 2D FPPA is unable to quantify each of these movements independently in the way that 3D motion analysis can. However, individuals who exhibit increases in 2D FPPA during dynamic tasks should be suspected of demonstrating similar increases in 3D joint motions which may leave them at increased risk of ACL and PFJ injury. If 2D FPPA is to be used in the field to identify high-risk individuals and evaluate the effect of interventions, further investigation of the reliability of this measure is needed. These results suggest that 2D FPPA may be used in future research, clinical and large-scale screening projects to assess the lower extremity dynamic valgus in the absence of more sophisticated 3D motion analysis with confidence.

Normative 2D FPPA values for the DJ and SLL tasks have been reported previously (Herrington & Munro, 2010). The authors of the study suggesting that "average" performance resulted in values of 7-13º and 5-12º for the DJ and SLL tasks respectively in women and 3-8º and 1-9º in men respectively. Although, (Herrington, 2011) reported that national league women basketball and volleyball players demonstrated FPPA values of 13-24º and 8-14º in the DJ and SLL tasks respectively. It was suggested that participants who exhibit valgus FPPA values in excess of the normative values may be demonstrating kinematics which are detrimental and may increase the risk of patellofemoral joint and/or ACL injury. These results from the current study compare well to these values, with men's and women's mean DJ values of -5.5º and 8.2º and SLL values of 4.7º and 7.3º. Many of the male participants presented with varus angles during the DJ task, which may account for the 8º difference from the normative values and whilst participants in both studies were recreationally active this does not account for the type of activity they participate in and the affect this may have on their lower limb control.

Willson and colleagues have reported FPPA values for the SLS lower than those seen in the current study. FPPA of approximately 0º and 4º for men and women collegiate athletes respectively and 3º in recreational women (Willson et al., 2006) (Willson & Davis, 2008b) were found. It is clear that FPPA varies across tasks and individuals. Further study on other populations is required as a result, as it is likely to show differences in normative data, although the use of different populations is unlikely to affect the reliability of the measure itself. The participants recruited in this study and those to date have all been similar; recreationally active men and women. Therefore it is unclear whether the results would be applicable to other populations. However, this specific target population has been used due to the prevalence of PFPS and ACL injury in this group.

Limitations of the current study include the fact that 3D motion analysis conducted using cluster markers are susceptible to error caused by soft tissue artefact, with frontal and transverse plane motion most susceptible to such errors during high-velocity movements (Cappozzo et al., 1996; McGinley et al., 2009). This potential error in measurement may affect the correlation to frontal plane motion measured using 2D FPPA. It could be argued that FPPA is prone to this same error due to the use of skin based markers. However, the fact the correlations found were similar to previous studies suggests that they are consistent.

3.6. Conclusion

2D FPPA has been shown to be reliable both within and between sessions, and within and between raters. FPPA was also shown to significantly correlate to 3D measures of frontal and transverse plane hip, knee and ankle motion during the DJ, SLL and SLS screening tasks. Whilst 2D FPPA is not suitable for quantification of subtle 3D joint motions it may provide clinicians with a useful tool for identifying those who demonstrate dynamic knee valgus and may therefore be at increased risk of ACL and PFJ injury. Having established the reliability, measurement error and validity of the use of 2D FPPA for assessing dynamic knee valgus, prospective injury risk and intervention studies should employ this method to screen participants' lower limb mechanics. 2D assessment of these tests provides a simple, inexpensive and reliable alternative for clinicians' and with further validation may be useful for large scale injury risk screening. Correlations between 2D FPPA and 3D measures were greatest during the DJ task and therefore it is recommended that this task would be the most useful clinically. The magnitude of correlations between 2D FPPA and 3D measures in the SLL and SLS tasks were similar, however reliability was greater during the SLL task. Therefore it is recommended that the SLL task is used when assessing unilateral control.

The results indicate that 2D FPPA provides a reliable and valid measure of gross lower limb kinematics in the absence of 3D measurements. Although minimum knee flexion angle was controlled in the SLS task, it is unclear whether increased knee flexion angles effect the amount of dynamic knee valgus measured and further investigation of this possible confounding factor is needed. Another limitation of this study is the population that was used. All participants were healthy, recreationally active University students. It is unclear whether 2D FPPA may be influenced by age or by activity levels, therefore these results may not be applicable to elite athletes, injured or adolescent and older age groups. Further research is needed in these groups.

Chapter 4
Reliability of the Hop for distance and Star Excursion Balance Tests

4.1. Aim

The aim of the chapter is to assess the reliability of selected screening tools which can be used in the field to assess lower limb function (hop for distance tests and the SEBT).

4.2. Introduction

Screening tools which can be used in the field to assess lower limb function were discussed in chapter two. The hop for distance tests and the SEBT demonstrate the potential to identify those at high-risk of ACL and PFJ injury and also to evaluate the efficacy of interventions designed to reduce injury risk. As discussed earlier, the reliability, validity and clinical utility of such tests are important for consideration of their use in the field.

A number of factors can influence the reliability of a test. These can be broadly grouped into random error and systematic bias. Random error is the 'noise' in a measurement, typically seen as within-subject variation, inconsistencies in the measurement protocol or the examiner's measurements (Atkinson & Nevill, 1998; Hopkins, 2000; Tyson, 2007). Systematic bias refers to a trend for measures to be different due to learning effects or fatigue (Atkinson & Nevill, 1998; Batterham & George, 2003).

Learning effects are often present in the performance of novel movement tasks. This is observed as a continued improvement across trials and has been identified in both the SEBT and hop for distance tests (Hertel et al., 2000; Hopper et al., 2002). Robinson and Gribble (2008b) investigated the learning effects of the SEBT and found that four practice trials were adequate for stability of the measure. However, the learning effects of the hop for distance test have not been established. If the learning effect of a test is not taken into account, the results may not be an accurate reflection of the participant's maximum ability. It is important to establish the number of trials needed before scores begin to stabilise, at which point it can be assumed the learning effect is negated, for the test to be valid. Furthermore, accounting for this learning effect will help to reduce systematic bias and reduce measurement error (Atkinson & Nevill, 1998).

First, current evidence for the reliability of each of the screening tools was examined, and evidence gaps identified. In light of this, further investigation of the reliability of hop for

distance tests and the SEBT was undertaken. Finally, a conclusion to these three studies is presented:

- Hop for distance tests (4.3)
- SEBT (4.4)
- Conclusion (5.5).

4.3. Reliability of the hop for distance tests

4.3.1. Introduction

The relationship between clinical measures of knee joint function and readiness for return to sport has been refuted (Barber et al., 1990; Eastlack et al., 1999; Lephart et al., 1992). Barber et al. (1990) observed that for functional limitations of the knee joint to be evaluated, testing which provided an objective measurement whilst simulating sporting activity was required. A number of FPTs which mimic sporting performance have been devised and investigated in recent years. FPTs, such as the hop for distance tests (Barber et al., 1990; Clark, 2001; Semenick, 1990), are closed chain in nature and therefore assimilate more closely the joint loading forces and kinematics that occur functionally (Lephart et al., 1992). The hop tests include the single, triple and crossover hops for distance, and the six metre timed hop. As discussed in chapter two, the hop tests provide an indication of limb function and may have the potential to predict injury risk, therefore the reliability of these tests needs to be determined.

Test-retest reliability of hop tests has been investigated and, with the exception of the timed hop for distance, consistently shown to be high (Ageberg et al., 1998; Bandy et al., 1994; Bolgla & Keskula, 1997; Booher et al., 1993; Hopper et al., 2002; Paterno & Greenberger, 1996; Reid et al., 2007; Ross et al., 2002). Test-retest ICC values of 0.92-0.97 for healthy participants and 0.84-0.98 for ACL-D subjects have been reported for the single, triple and crossover hop for distance tests (Ageberg et al., 1998; Bandy et al., 1994; Bolgla & Keskula, 1997; Booher et al., 1993; Hopper et al., 2002; Paterno & Greenberger, 1996; Reid et al., 2007; Ross et al., 2002). The six metre timed hop commonly shows the lowest reliability scores (Bolgla & Keskula, 1997; Booher et al., 1993). For example, Bolgla and Keskula (1997) reported an ICC value of 0.66 for the timed hop, compared to 0.96 for the single, triple and crossover hop for distance tests. The low reliability scores may be due to the use of a stopwatch in these studies, which is likely to increase measurement error of the test. The use

of timing gates, which eliminates human error, resulted in improved reliability, with ICC scores of 0.95-0.96 (Hopper et al., 2002).

The limb symmetry index is an indication of the function of one limb versus another. Test-retest reliability of LSI scores in each hop test has also been shown to be high (ICC 0.81-0.94) in injured participants (Hopper et al., 2002; Paterno & Greenberger, 1996; Reid et al., 2007), lending weight to its use during rehabilitation. However, the reliability of LSI in healthy participants has not been studied, this is important considering that LSI is the measure proposed to determine those who may be at greater risk of injury and further investigation is therefore warranted.

Authors have reported the presence of learning effects in some studies (Ageberg et al., 1998; Bolgla & Keskula, 1997; Booher et al., 1993; Hopper et al., 2002; Reid et al., 2007), which may make the reliability values of previous studies invalid. Only one study has investigated the learning effects observed between trials (Bolgla & Keskula, 1997). The results suggested that three practice trials was adequate for the triple, crossover and timed hops, whilst four trials may be needed for the single hop. The authors concluded that further investigation of learning effects associated with the hop tests was required.

The effect of gender on distance hopped has also been investigated. Barber et al. (1990) found that men hop significantly further than women, although there are no differences between LSI scores (Gaunt & Curd, 2001). Despite the findings of Barber et al. (1990) studies have often used a mix of men and women (Ageberg et al., 1998; Bolgla & Keskula, 1997; Booher et al., 1993; Hopper et al., 2002; Reid et al., 2007). Moreover, the studies did not assess whether differences were evident between the sexes. These potential differences may skew subsequent data analysis and reliability scores.

The findings of studies reporting reliability to date may be called in to question as learning effects and sex differences were not accounted for. Although the reliability of the hop tests has been investigated previously, learning effects and reliability have not been adequately assessed. Additionally, no study has taken into account the reported differences between men and women (Barber et al., 1990) and clearly delineated between the two groups. Furthermore, few studies have reported the SEM values of the hop tests. As discussed previously in section 2.6, knowledge of the SEM is important to assess changes in test performance.

Raw scores are commonly reported in the literature and this is appropriate when comparing a participant's score against themselves on the same limb. However, it would seem sensible to assume that an individual with longer legs would be able to hop further. Indeed, significant correlations between subjects height and the distance hopped on the single and crossover hop tests have been previously shown (Gaunt & Curd, 2001; Kramer, Nusca, Fowler, & Webster-Bogaert, 1992). In these studies, taller participants were found to hop further. This is a factor that has not been considered in the literature and it would be reasonable to assume that a difference in leg length would also affect hop distance. Furthermore, this would allow for more accurate comparison of scores between limbs within-subjects. Therefore, anthropometric factors, such as leg length, may affect hop distances and should be taken into account when comparing between limbs and between participants or groups. Normalising for leg length would potentially reduce between-subject variability and allow for more accurate comparison between individuals.

4.3.2. Aim

Therefore the aims of this study were to:

a) Establish whether gender differences are apparent for each test and for LSI;

b) Assess the presence of learning effects;

c) Establish a standardized protocol and then assess the between-session reliability and associated measurement error of this protocol for the single hop for distance, triple hop for distance, crossover hop for distance and six-metre timed hop; and

d) Establish the reliability and measurement error of LSI in healthy participants.

4.3.3. Methods

Participants

Twenty-two participants, eleven men (age 22.8 ± 3.1 years, height 179.8 ± 4.0cm, weight 79.6 ± 10.0kg) and eleven women (age 22.3 ± 3.7 years, height 167.7 ± 6.2cm, weight 59.2 ± 6.9kg) all of whom were university students, volunteered for the study. The same entry criteria, approval and consent procedures were used as previously outlined in chapter three (section 3.3).

Procedures

Participants were tested at the same time of day on three separate occasions, each separated by one week. All participants were asked not to participate in strenuous exercise in the 24 hours prior to testing. Participants were also asked to wear the same training shoes on each

occasion so as to control for the effect of different designs of shoe and support they provide on individual performance. Each participant's leg lengths were measured on the first test occasion. Leg length was measured from the anterior superior iliac spine to the distal tip of 0074he medial malleolus using a standard tape measure while participants lay supine (Gribble & Hertel, 2003). Limb dominance was determined by asking participants which limb they would predominantly use to kick a ball. Limb dominance was required for calculation of LSI scores.

Hop tests

The single hop for distance, triple hop for distance, crossover hop for distance and six-metre timed hop tests were originally described by (Noyes et al., 1991). A six-metre long, 15cm wide line was marked on the floor, along the middle of which was a standard tape measure, perpendicular to the starting line. To record time for the six metre timed hop two sets of electronic timing gates (Fitness Technology Inc., Aus) were placed on tripods at a height of 0.75 metres (to approximate hip height), three metres apart, at the start and finish lines of the six-metre course. The setup for each hop test is shown in figure 4.1.

Participants performed six trials of each hop test, with all trials being measured. Both limbs were tested and no restrictions were given to participants regarding the use of arm movement. A rest period of 30 seconds was given between trials and two minutes between each of the four hop tests (Reid et al., 2007). The order of testing was randomised for participant. Each hop test began with the great toe of the testing leg on the marked start line and the distance hopped was measured to the rear of the foot upon final landing. Participants were required to maintain the final landing in the single, triple and crossover hop tests for a minimum of two seconds. Unsuccessful hops were classified as a loss of balance, an extra hop on landing or touching down of either the contralateral lower extremity or the upper extremity.

For the single hop, participants were required to hop as far forwards as possible along the line of the tape measure and land on the same limb. The triple hop involved participants performing three consecutive maximal hops along the line of the tape measure. During the cross over hop participants maximally hopped forward three times, alternately crossing the 15cm wide line. In the six-metre timed hop participants hopped forward as quickly as possible from the start line through the timing gates at the end of the six-metre course. Time was measured from when the participant passed through the first timing gate and stopped when they passed through the second.

Leg length was used to normalise hop distances by dividing the distance reached by leg length, then multiplying by 100. The result is presented as a percentage value. Normalisation did not occur for timed hop scores. LSI was calculated by dividing the normalised distance hopped on the dominant limb by the normalised distance hopped on the non-dominant limb, and multiplying the result by 100, giving a percentage value.
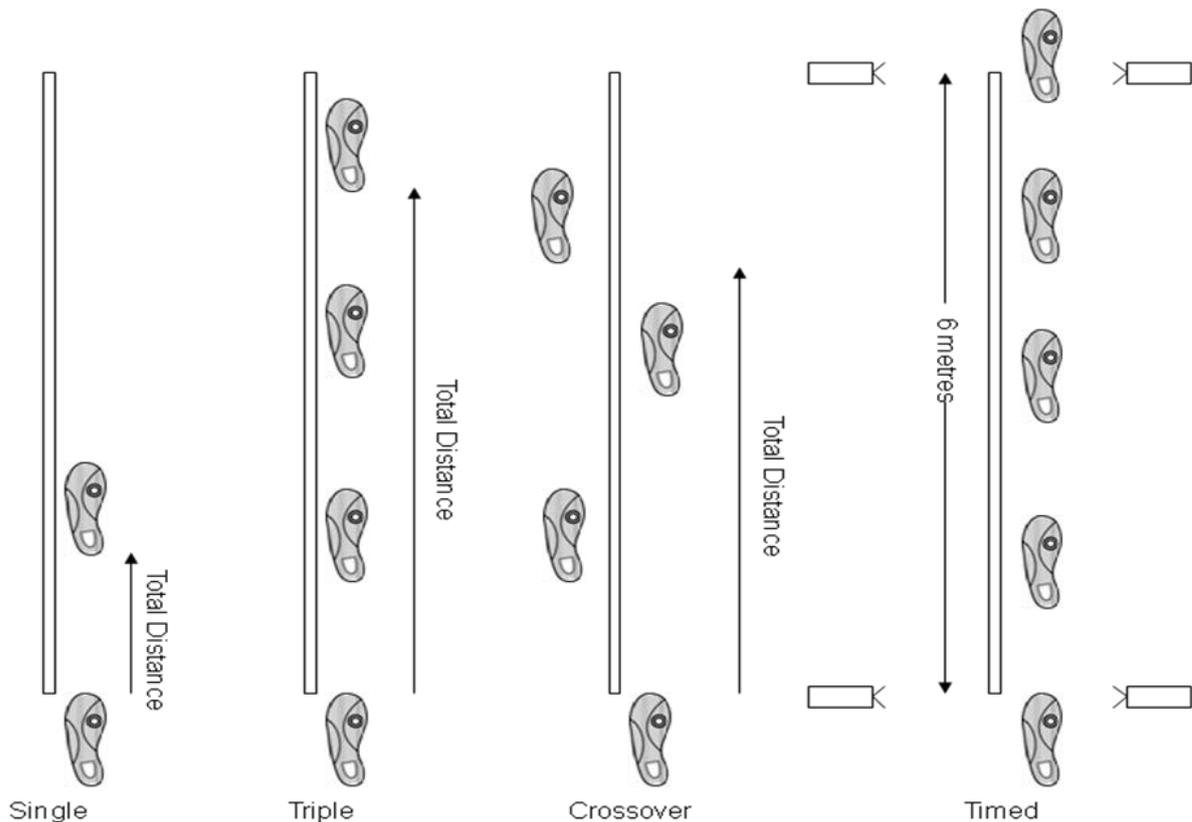
Figure 4.1. The single, triple and crossover hop for distance and timed hop tests.

Statistical Analysis

All statistical analysis was conducted using SPSS for Windows version 16.0 (SPSS Inc., Chicago, IL). Statistical analysis was undertaken on both raw and normalised scores. Normality for each variable was assessed using the Kolmogorov-Smirnov test. LSI values for single, crossover and timed hops were found not to be normally distributed. All other data was found to be normally distributed. Means and standard deviations for all measured variables are presented.

Independent t-tests were carried out to assess differences between men and women for normally distributed data. Mann-Whitney U Tests were carried out for the single, crossover and timed hop LSI data.

Separate one-way repeated-measures analysis of variance (ANOVA) were then carried out on week one normalised scores to assess learning effects, with Bonferroni correction applied in instances where significant differences were found.

ICC (3,1) (Rankin & Stokes, 1998) assessed between session reliability for raw and normalised hop scores, from which 95% CI of ICC, SEM and SDD were calculated to establish random error scores. A one-way repeated measures ANOVA was conducted on the normalised values to assess differences between scores for each week, with effect sizes determined where significant differences were found. Effect sizes were determined using the Cohen δ method (Thomas et al., 2005), which defines 0.2, 0.5 and 0.8 as small, medium and large respectively.

ICC (3,1) was also used to assess between-session reliability of the LSI scores, from which 95% CI of ICC and SEM were calculated. ICC model (3,1) was chosen as the trial scores were considered to be a sample which cannot be regarded as representative of the wider population, only those of recreational athletes; and scores were the mean of three trials from one experimenter. ICC values were interpreted according to the criteria set by (Coppieters et al., 2002). A one-way repeated measures ANOVA assessed the differences between triple hop LSI scores for each week. A Friedman test was conducted to assess differences between single, crossover and timed hop LSI scores across weeks. Alpha levels were set at 0.05 for all tests.

4.3.4. Results

Firstly, the results showed that men hopped significantly further than women in all hop tests ($p<0.001$), therefore genders were separated for all further analysis of raw and normalised scores. Effect sizes were high for all tests ranging from 1.08-2.59. No differences in LSI values were found between men and women and therefore they were grouped for all further analysis of LSI. Effect sizes were small for the single (0.26), triple (0.03) and crossover hop test (0.16), and medium for the timed hop (0.55). These values are presented in table 4.1.

Learning effects

The results showed that learning effects were present in the majority of tests in both men and women, where scores improved across trials. Only the timed hop in men had no significant changes in performance across trials. Table 4.2 shows the means and standard deviations for all tests and indicates where significant differences between trials were found.

In the majority of tests, significant improvements were found from trial one, only in the timed hop was this not evident. Significant differences were found between trials four and six in the crossover hop in men, indicating that four practice trials are required. Differences were also found between trials three and six in the triple hop in women, indicating three practice trials are needed. Bolgla and Keskula (1997) indicated that three practice trials were required, which is supported by the results of the current study except for the case of the crossover hop in men.

Between-session reliability

After establishing how many trials were needed for scores to stabilize, subsequent trials were used for reliability analysis. Therefore trials four to six were used in all tests barring the crossover hop in men, where trials five to six were used to calculate ICC, 95% CI, SEM and SDD values. These values are presented in tables 4.3 (normalised values) and 4.4 (raw scores).

The hop tests showed good to excellent between-session reliability for both normalised and raw scores (ICC 0.76-0.92), with the exception of the timed hop in men which showed adequate reliability (ICC=0.60). Significant differences were noted in scores between sessions, indicating that performance improved from weeks one to three. However effect sizes were small, ranging from 0.13-0.43, suggesting that the differences found were small.

Table 4.5 presents the reliability analysis for the LSI scores. No significant differences were found between weeks in any of the hop tests. ICC values ranged from 0.56 to 0.78. According to the criteria outlined by Coppieters et al. (2002) the triple and crossover hops showed good reliability, whilst the single and timed hops demonstrated fair reliability. Subsequent SEM values range from 2.5-4.2%, indicating that measurement error was low.

Table 4.1 – Mean (SD), p-value and effect sizes for hop test scores in men and women

Test	Men	Women	p-value	Effect Size
Single Hop (cm)	163.7 (19.3)	129.5 (16.2)	<0.001	1.91
Single Hop (%)	176.9 (22.4)	148.1 (18.4)	<0.001	1.41
Single Hop LSI (%)	103.6 (13.7)	100.7 (8.3)	0.568	0.26
Triple Hop (cm)	537.1 (51.8)	421.4 (36.2)	<0.001	2.59
Triple Hop (%)	577.1 (64.6)	482.9 (41.2)	<0.001	1.74
Triple Hop LSI (%)	100.4 (5.3)	100.6 (7.5)	0.921	0.03
Crossover Hop (cm)	482.3 (54.5)	394.9 (42.9)	<0.001	1.78
Crossover Hop (%)	518.9 (65.2)	457.5 (47.4)	0.001	1.08
Crossover Hop LSI (%)	100.6 (7.7)	101.7 (6.1)	0.720	0.16
Timed Hop (s)	1.76 (0.13)	2.05 (0.19)	<0.001	1.78
Timed Hop LSI (%)	99.1 (4.8)	102.1 (6.1)	0.218	0.55

*Table 4.2 – Week one mean ± standard deviation values for all trials of the four hop tests for men and women (Values are percentage of leg length * 100, except for timed hop).*

| | Trial Number | | | | | |
Test	1	2	3	4	5	6
Men (n=11)						
Single hop (%)	161.9 ± 27.6	171.5 ± 27.2*	176.6 ± 23.9*	179.1 ± 24.4*	181.86 ± 21.47*#	185.3 ± 18.9*#
Triple hop (%)	569.5 ± 68.7	573.8 ± 64.3	583.9 ± 68.9	577.6 ± 69.6	582.78 ± 68.44	580.8 ± 61.9
Crossover hop (%)	491.7 ± 78.8	520.2 ± 77.9	510.7 ± 68.2	516.6 ± 67.2	531.41 ± 64.48*	543.8 ± 59.6*§¥
Timed hop (s)	1.84 ± 0.21	1.79 ± 0.18	1.75 ± 0.11	1.78 ± 0.14	1.79 ± 0.151	1.78 ± 0.13
Women (n=11)						
Single hop (%)	139.9 ± 18.1	143.3 ± 21.7	148.8 ± 17.9*	149.3 ± 19.4*	151.7 ± 22.0*	153.2 ± 18.9*#
Triple hop (%)	460.6 ± 51.8	473.6 ± 48.7	478.0 ± 44.8	486.3 ± 40.1*	490.2 ± 44.9*	496.6 ± 42.6*#§
Crossover hop (%)	436.6 ± 54.3	442.1 ± 60.6	444.8 ± 62.8	450.4 ± 52.2	463.2 ± 51.1*	468.3 ± 53.9*#
Timed hop (s)	2.14 ± 0.16	2.14 ± 0.20	2.18 ± 0.26	2.12 ± 0.18	2.06 ± 0.17#§	2.07 ± 0.18

Significant difference from trial 1 (p<0.05) - *
Significant difference from trial 2 (p<0.05) - #
Significant difference from trial 3 (p<0.05) - §
Significant difference from trial 4 (p<0.05) - ¥

*Table 4.3 - Mean, standard deviation (SD), intraclass correlation coefficient (ICC), 95% confidence intervals (CI) for ICC, standard error of measurement (SEM), and smallest detectable difference (SDD)values for the four hop tests (After practice trials. All values presented as percentage of leg length * 100 except timed hop).*

Test	Week 1	Week 2	Week 3	ICC	95% CI		SEM	SDD
Men								
Single hop (%)	183.2 (21.6)	188.8 (14.6)*	194.8 (13.7)*#	0.80	0.71	0.87	7.9	21.8
Triple hop (%)	579.8 (65.6)	578.9 (57.5)	595.6 (58.2)*#	0.92	0.89	0.95	17.2	47.6
Crossover hop (%)	535.7 (61.4)	557.7 (41.3)*	570.2 (60.4)*	0.86	0.78	0.92	21.2	58.7
Timed hop (s)	1.78 (0.14)	1.76 (0.13)	1.73 (0.12)*	0.60	0.40	0.74	0.08	0.23
Women								
Single hop (%)	150.9 (19.8)	158.7 (17.2)*	161.9 (14.1)*	0.80	0.70	0.87	7.9	21.9
Triple hop (%)	492.9 (41.8)	506.9 (44.1)*	516.0 (64.6)*	0.80	0.69	0.87	23.2	64.3
Crossover hop (%)	460.6 (52.2)	483.7 (54.5)*	482.9 (58.3)*	0.89	0.83	0.93	18.5	51.2
Timed hop (s)	2.08 (0.18)	2.03 (0.17)*	2.09 (0.22)#	0.85	0.78	0.90	0.07	0.19

Significant difference from week 1 (p<0.05) - *

Significant difference from week 2 (p<0.05) - #

Table 4.4 - Mean, standard deviation (SD), intraclass correlation coefficient (ICC), 95% confidence intervals (CI) for ICC, standard error of measurement (SEM), and smallest detectable difference (SDD) values for the four hop tests (After practice trials. All values presented are raw scores).

Test	Mean	SD	ICC	95% CI		SEM	SDD
Men							
Single hop (cm)	175.4	15.3	0.76	0.63	0.84	7.5	20.8
Triple hop (cm)	543.5	47.3	0.88	0.82	0.92	16.4	54.4
Crossover hop (cm)	516.0	46.9	0.80	0.67	0.88	21.0	57.4
Women							
Single hop (cm)	137.9	15.5	0.79	0.68	0.86	7.1	19.7
Triple hop (cm)	442.0	42.5	0.76	0.63	0.84	20.8	57.8
Crossover hop	416.7	46.0	0.86	0.81	0.92	17.2	47.6

Table 4.5 – Limb symmetry index (LSI) mean, standard deviation (SD), intraclass correlation coefficient (ICC), 95% confidence intervals (CI) for ICC and standard error of measurement (SEM) values for the four hop tests.

Test	Week 1	Week 2	Week 3	ICC	95% CI		SEM
Single hop (%)	99.6 (8.3)	100.0 (5.9)	100.8 (4.9)	0.56	0.10	0.80	4.2
Triple hop (%)	99.5 (6.3)	98.5 (5.2)	99.3 (4.1)	0.78	0.54	0.90	2.5
Crossover hop (%)	99.9 (4.9)	99.8 (6.5)	99.6 (5.0)	0.76	0.51	0.89	2.7
Timed hop (%)	100.2 (6.2)	98.6 (4.3)	99.6 (5.3)	0.56	0.11	0.80	3.5

4.3.5. Discussion

The aims of this study were to:

a) Establish whether gender differences are apparent for each test and for LSI,

b) Assess the presence of learning effects,

c) Establish the between-session reliability and associated measurement error of this protocol for the single hop for distance, triple hop for distance, crossover hop for distance and six-metre timed hop,

d) Establish the reliability and measurement error of LSI in healthy participants.

The use of FPTs has become increasingly popular as a mode of assessment during rehabilitation and training programmes. However, it is important that these tests are reliable and that the results of the tests can be interpreted appropriately. Therefore information regarding whether practice trials are needed due to learning effects and the development of a reliable, standardized protocol which takes this into account is highly important for practitioners.

The results showed that men performed better than women in all tests, echoing the findings of Barber et al. (1990). This was demonstrated by significantly greater raw and normalised hop distances and lower timed hop scores. As a result, learning effects and reliability were analysed separately for men and women to reflect these differences. It is recommended that future studies also take the differences in performance between men and women into account. However, when calculating and comparing LSI scores, there were no differences between men and women, therefore separation of sexes when calculating or comparing LSI scores is

not required. These findings support those of Gaunt and Curd (2001) who found no differences in LSI between sexes in high-school athletes.

Both raw and normalised scores are presented in this study. Only raw scores have been reported in the literature to date, and while they are appropriate for comparing an individual's scores against themselves, they may not be appropriate when comparing across groups or between individuals. Previous studies have shown that taller individual's hop further on the single and crossover hop tests (Gaunt & Curd, 2001; Kramer et al., 1992). It would seem reasonable to assume that a difference in leg length would also affect hop distance and therefore normalising hop distance scores using leg length would potentially reduce between-subject variability and allow for more accurate comparison between individuals. Furthermore, this would allow for more accurate comparison of scores between limbs within-subjects.

The results of the current study indicate that learning effects are present in the administration of the hop for distance tests. Bolgla and Keskula (1997) previously described learning effects during hop test administration. They indicated that three practice trials should be included for all hop tests, but may not be adequate. In the current study it was noted that three practice trials were required in the single and triple hop for distance and the timed hop tests in all participants. However, learning effects were different between genders for the crossover hop, with men needing more familiarization than women. The significant difference between trials four and six in the crossover hop in men, indicate that four practice trials are required on this test, whilst only three are needed for women. In order for the results of these tests to be reliable when used with participants it is important for the correct number of practice trials to be included to allow participants the chance to familiarize. In turn, this will give more consistent and reliable results which better reflect an individual's performance.

It was also noted that a significant improvement in normalised scores were found between weeks one and three in all tests, except the timed hop in women. However, no significant performance improvements were noted between weeks one and two. Men's single and triple hop for distance scores also improved from week two to three. These findings suggest that familiarisation may actually take more than a single session in some cases. However, this may also be due to a training effect in the participants, whereby neural or muscular adaptations lead to improved performance, particularly in the study population where plyometric training may be a novel training method. Additionally, training interventions most often last a minimum of four weeks; after which significant improvements in hop test scores

have been found (Herrington, 2010). Therefore it is unlikely that hop testing would take place weekly over a three week period but rather that participants would be tested at the start and end of an intervention period.

Reliability is an important aspect of performance testing; if a test is not reliable we are unable to conclude anything from the results it produces. Test-retest reliability of all the hop tests in the current study, except the timed hop for men, was good or excellent. Raw ICC scores ranged from 0.76-0.88. These results reflect those of previous studies which have reported ICC values of between 0.66-0.99 (Ageberg et al., 1998; Bandy et al., 1994; Bolgla & Keskula, 1997; Booher et al., 1993; Paterno & Greenberger, 1996; Reid et al., 2007; Ross et al., 2002). ICC for the timed hop in men was 0.60 in the current study, which is very similar to the score of 0.66 reported by Bolgla and Keskula (Bolgla & Keskula, 1997). ICC scores for the single, triple and crossover hop tests, including those from the current study, range from 0.80-0.99, indicating that the hop for distance tests are reliable. The low reliability scores for the timed hop call into question whether this particular test should be included in injury and rehabilitation screening.

Interestingly, normalised ICC scores (0.80-0.92) were higher than raw scores (0.76-0.88). Although SEM values were lower for raw scores. It is unclear why the ICC values were different as they can be affected by a number of factors. The SEM was lower in the raw scores due to lower standard deviations observed. We also found that significant differences in normalised mean scores were present between sessions. Mean scores demonstrated a tendency to increase across sessions, with sessions three often having the best score. However, the effect sizes were small and changes observed were well within the SDD values presented. Therefore the changes are likely due to measurement error rather than performance improvements.

Only two studies have calculated SEM values for raw hop test scores (Bolgla & Keskula, 1997; Booher et al., 1993). In each of these studies the number of men and women were unequal and participant activity levels were not disclosed making direct comparison to the current study difficult. A comparison of SEM values for raw scores is presented in table 4.6. SEM values for the single hop in both of these studies were lower than in the current study, whereas timed hop values were higher. Differences in SEM values were more than likely due to higher ICC values noted for hop for distance tests in these studies. Whereas the lower SD

in the timed hop in the current study, which may be due to increased accuracy of timing gates, accounts for the lower SEM compared to previous studies.

Table 4.6 – Comparison of standard error of measurement scores between studies.

Study	Participants	Single hop (cm)	Triple hop (cm)	Crossover hop (cm)	Timed hop (s)
Current study results	Recreational men (n=11)	7.5	16.4	21.0	0.08
	Recreational women (n=11)	7.1	20.8	17.1	0.07
Booher et al. (1993)	Men (n=4) and women (n=14)	3.50	-	-	0.19
Bolgla & Keskula (1997)	Men (n=5) and women (n=15)	4.56	15.44	15.95	0.13

Note: men's and women's scores were collated for Booher et al's and Bolgla and Keskula's studies.

The mean raw scores for the four hop tests in the current study also compare well with previous studies (Ageberg et al., 1998; Bolgla & Keskula, 1997; Booher et al., 1993). However, direct comparison is again difficult due to different populations and mix of men and women. The results of the current study compare favourably to those conducted on patients with previous ACL injury (Barber et al., 1990; Goh & Boyle, 1997; Hopper et al., 2002; Reid et al., 2007). In these cases we compared the results of the current study to those of the uninjured limb, although once again direct comparison can only be made with one of these studies. The higher scores found in the recreational athletes in the current study compared to those of the uninjured limb of individuals in previous studies may suggest that these particular individuals possess functional deficiencies which caused them to be at greater risk of ACL injury. However, the decreased performance could also be a bilateral deficit resulting from the injury itself.

Between-session reliability of LSI scores was also investigated in this study, with fair to good ICC values found. The timed hop showed the lowest reliability value (ICC=0.56) and the triple hop the highest (0.78). Despite the relatively low ICC scores, no statistically significant differences were found between weeks, suggesting that the LSI values were stable across the three week study period. Furthermore, the greatest change in LSI was 1.5%, found between weeks one and two in the timed hop test. All changes were considerably lower than the SEM

values quoted for each test. As mentioned previously, less heterogenous data may result in a lower ICC value (Atkinson & Nevill, 1998), and this may in part explain the relatively low between-session reliability found for LSI. This decreased variability is demonstrated by that fact that all participants in the current study achieved an LSI of greater than 90%. In comparison, Gaunt and Curd (2001) found that only 89% of the 201 high school athletes they tested achieved an LSI of 85%, furthermore 4% failed to achieve 80% LSI.

The LSI SEM scores presented allow clinicians to make a more informed decision with regards to an individual's score, for example the true LSI score on the single hop test lies within 4.2% of the observed value. SDD values were not calculated for the hop tests as the LSI value is inherently influenced by the opposing leg, therefore any changes seen may actually be due to changes in the opposing limb rather than the limb of interest. Changes in individual performance should be evaluated using the SDD values presented for the raw scores.

4.4. Reliability of the Star Excursion Balance Test

4.4.1. Introduction

The SEBT is an FPT which assesses dynamic postural control (Hertel et al., 2000; Kinzey & Armstrong, 1998). The SEBT is a closed-kinetic chain exercise which mimics the single leg squat exercise and therefore the stance leg requires strength, proprioception, neuromuscular control and adequate range of motion at the hip, knee and ankle joints (Olmsted et al., 2002; Robinson & Gribble, 2008a). As discussed in section 2.6.2.2 of chapter two, the SEBT is able to detect deficits in dynamic postural control in patients with CAI, an ACL-D limb and PFPS (Aminaka & Gribble, 2008; Gribble et al., 2004; Herrington et al., 2009; Hertel et al., 2006a; Hubbard et al., 2007; Olmsted et al., 2002). In addition, the SEBT has shown the potential to predict lower limb injury (Plisky et al., 2006). As a FPT the SEBT offers a simple, low-cost alternative to more sophisticated laboratory assessments for use in clinical settings.

One problem often cited is the time-consuming protocol for the SEBT. Participants perform six practice trials in each direction before undertaking a further three measured trials (Hertel et al., 2000). This number of trials was suggested as Hertel et al. (2000) observed significant learning effects occurred across trials one to six during testing, with scores stabilising and longest excursion distance occurring from trials seven onwards. Furthermore, higher reliability scores were noted for trials seven to twelve compared to trials one through six. However, the authors administered the twelve trials in four blocks on two separate days, which is likely to have affected performance between trials. Participants were also allowed to use their arms freely, which does not reflect the most commonly used SEBT protocol of hands remaining on hips. Both of these factors may increase the amount of time needed to learn the task (Robinson & Gribble, 2008b).

Considering this, Robinson and Gribble (2008b) studied maximum normalised excursion distances and angular displacement of the hip and knee across nine trials. The results showed that only the lateral reach direction needed more than four trials before stability in excursion distance was achieved, and in that case it was achieved on the fifth trial. Angular displacement also stabilised after four trials in most cases, with only knee flexion in the anterolateral direction, and hip flexion in the posterolateral direction taking more than four trials. The authors concluded that the number of practice trials needed could be reduced from six to four, therefore streamlining the SEBT protocol. Combined with previous findings which support the use of specific reach directions for assessment of certain injuries, SEBT

administration could be greatly simplified, with fewer practice trials and fewer reach directions tested. However, further research and justification is needed in this area.

Normalisation of SEBT reach distances using leg length was first recommended by Gribble and Hertel (2003) . They found that both height and leg length was related to performance, but that leg length had a stronger relationship. Furthermore, they found that men performed significantly better than women when raw scores were examined, however when scores were normalised to leg length, these differences were eradicated. Further study of differences between genders has been conducted. Sabin, Ebersole, Martindale, Price, and Broglio (2010) found no differences in performance between men and women in the anterior and medial reach directions in both recreationally active participants and collegiate basketball players. Differences were found in the posterior reach direction, although these differences were not evident when averaged across the three reach directions. This outlines the importance of normalising SEBT excursion distances, and the need for confirmation that differences do not exist between men and women. In addition, no studies to date have examined whether sex differences in LSI exist in the SEBT.

High intra- and inter-tester reliability of the SEBT has previously been reported (Hertel et al., 2000; Kinzey & Armstrong, 1998). Only one study has evaluated between-session reliability of the SEBT with normalised scores, with ICC values ranging from 0.89-0.93 (Plisky et al., 2006). However, only three reach distances; anterior, posteromedial and posterolateral, were evaluated. Therefore, further study of between-session reliability of all reach directions is warranted. Perhaps most importantly, no study has investigated the measurement error associated with the SEBT and what percentage change reflects a true improvement in performance. This information is important to evaluate previous and future research, especially intervention studies, and also for practitioners who use the SEBT to evaluate individual performance during training or rehabilitation. Without measurement error values, changes in performance cannot be evaluated properly as it is not known whether these changes may be attributed to measurement errors or from the intervention.

4.4.2. Aim

Therefore the aims of the current study are to:

a) Establish whether gender differences are apparent for normalised scores and for LSI in the SEBT,

b) Assess the learning effects associated with the SEBT to determine the number of practice trials needed;

c) Establish the between- session reliability and associated measurement error using a standardised protocol; and

d) Establish the reliability and measurement error of LSI in healthy participants.

4.4.3. Methods

Participants

Twenty-two participants, eleven men (age 22.8 ± 3.1 years, height 179.8 ± 4.0cm, weight 79.6 ± 10.0kg) and eleven women (age 22.3 ± 3.7 years, height 167.7 ± 6.2cm, weight 59.2 ± 6.9kg) all of whom were university students, volunteered for the study. The same entry criteria, approval and consent procedures were used as previously outlined in chapter 3 (section 3.3).

Procedures

Leg length was measured from the anterior superior iliac spine to the distal tip of the medial malleolus using a standard tape measure while participants lay supine. Leg length was used to normalise excursion distances by dividing the distance reached by leg length then multiplying by 100 (Gribble & Hertel, 2003).

Participants were tested on three occasions, each separated by one week. Participants were tested at the same time of day on each occasion (Gribble, Tucker, & White, 2007). The SEBT was performed as described by Robinson and Gribble (2008b). Participants stood in the middle of a grid laid on the floor with 8 lines extending at 45° angles from the centre of the grid, each of which is labelled according to the direction of excursion in relation to the standing limb.

Participants undertook the testing barefoot, with foot position controlled by aligning the heel with the centre of the grid and great toe with the anteriorly projected line. Participants were asked to maintain a single-limb stance on the test limb whilst reaching the opposite limb to touch as far as possible along the chosen line with the most distal part of their foot. The foot

was only allowed to touch lightly so as not to aid balance. The participant then returned to bilateral stance. The point at which the participant touched was marked by the examiner and measured manually using a measuring tape. The same investigator measured all participants, and marks were erased after each trial. Figure 4.2 (A, B and C) show the anterior, lateral and posterior reach directions respectively.

For a trial to be successful the participants hands had to remain on their hips, the reach limb could not provide support upon touching down, the heel of the stance limb had to remain in its position in the centre of the grid and not lift from the ground and balance had to be maintained.

All reach directions were tested for each participant. Reach direction and stance limb order were randomised using the same method described in section 4.3.3. Each participant performed seven consecutive trials in each direction with one limb before switching to the other limb, with one minute recovery allowed between each direction. LSI was calculated for each reach direction by dividing the normalised distance reached on the dominant limb by the normalised distance reached on the non-dominant limb, and multiplying the result by 100, giving a percentage value.
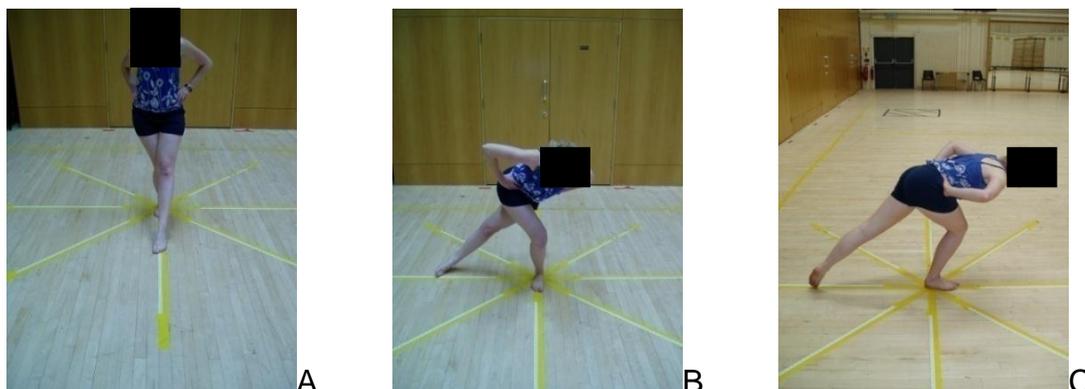
Figure 4.2 - (A) Anterior reach direction, (B) lateral reach direction and (C) posterior reach directions of the Star Excursion Balance Test.

Statistical Analysis

All statistical analysis was conducted using SPSS for Windows version 16.0 (SPSS Inc., Chicago, IL). Normality for each variable was assessed using the Kolmogorov-Smirnov test. All data was normally distributed except for LSI in the lateral reach direction.

Independent t-tests assessed differences between men and women and between limbs for reach distances in each direction. Independent t-tests also assessed the differences in LSI between men and women. A Mann-Whitney U test was carried out when comparing LSI between limbs for the lateral reach direction. Separate one-way repeated-measures ANOVA were then carried out on week one scores to assess learning effects, with Bonferroni correction applied where significant differences were found.

ICC (3,1) (Rankin & Stokes, 1998) assessed between session reliability, from which 95% CI of ICC, SEM (Thomas et al., 2005) and SDD (Kropmans et al., 1999) were calculated to establish random error scores. ICC model (3,1) was chosen as the trial scores were considered to be a sample which cannot be regarded as representative of the wider population, only those of recreational athletes; and scores were the mean of three trials from one experimenter. A one-way repeated measures ANOVA was conducted on the normalised values to assess differences between scores for each week, with effect sizes determined where significant differences were found. Effect sizes were determined using the Cohen δ method (Thomas et al., 2005), which defines 0.2, 0.5 and 0.8 as small, medium and large respectively.

ICC (3,1) was also used to assess between-session reliability of the LSI scores, from which 95% CI of ICC and SEM were calculated. Separate one-way repeated measures ANOVA assessed the differences between weeks for all normally distributed data. A Friedman test was conducted to assess differences between lateral reach direction LSI scores across weeks. ICC values were interpreted according to the criteria set by (Coppieters et al., 2002). Alpha levels were set at 0.05 for all tests.

4.4.4. Results

No significant differences were found between men and women (table 4.7) or limbs for all reach directions, they were therefore grouped for all analysis. Table 4.8 shows the mean and standard deviations for normalised (to leg length) maximum excursion distances across trials one to seven. All directions except postero-lateral showed a significant increase in normalised excursion distance across trials. The shortest excursion distance occurred in trial one across all directions, with the greatest excursion distance occurring in trial seven for all but the medial reach direction. Normalised excursion distances stabilised by trial four in all directions, shown by the decrease in excursion distance between trials four and five. Additionally, there were no significant differences noted between trials four and seven in any direction.

Trials 5-7 were used for reliability analysis. ICCs ranged from 0.84-0.92, SEM values from 2.2-2.9%, and SDD values from 6.1-8.2%. Table 4.9 shows the mean, SEM, SDD and ICC values for trials 5-7 for all directions for normalised excursion distances. Significant differences between weeks were also evident, although the direction of these changes was not consistent. Excursion distances decreased from week one to week three in the three anterior reach directions, no changes were noted in the medial and posterior-medial reach directions, whilst significant improvements occurred between weeks one and three in the lateral, posterior and posterior-lateral reach directions. All significant changes across weeks were within the SEM value quoted for that direction, except for the lateral reach direction. Additionally, effect sizes were low (0.19-0.31) suggesting the differences between the means were small and overlap between weeks was actually high. The mean, SEM and SDD values for raw scores are also shown in table 4.10 where SEM values ranged from 1.9-2.5cm and SDD values from 5.4-7.0cm.

Table 4.11 shows the reliability analysis for LSI scores. The only significant difference was noted between week two and three in the anterior reach direction, no differences were found between weeks in any other reach direction. Anterior LSI significantly reduced by 2.7% from week two to week three. Despite a lack of significant differences between weeks ICC values indicated reliability across weeks was fair. SEM values ranged from 2.9-6.1%. Interestingly, the only direction in which a significant difference was found between weeks demonstrated the greatest reliability and lowest SEM score.

Table 4.7 – Mean (SD) and p-values for SEBT reach direction in men and women

Test	Men	Women	p-value
Anterior	93.5 (5.8)	92.3 (5.0)	0.492
Anterior-medial	94.4 (6.6)	91.8 (5.0)	0.163
Anterior-lateral	79.1 (7.4)	77.7 (7.6)	0.565
Medial	92.4 (10.1)	87.8 (6.3)	0.076
Lateral	78.9 (10.6)	76.8 (8.3)	0.460
Posterior	77.7 (13.1)	83.2 (8.6)	0.110
Posterior-medial	89.0 (13.1)	85.8 (5.7)	0.223
Posterior-lateral	84.5 (10.5)	79.7 (8.3)	0.098

Table 4.8 - Mean ± standard deviations for normalised maximum excursion distance (excursion distance/ leg length x 100) (N=22).

Direction	Trial Number						
	1	2	3	4	5	6	7
Anterior	91.0 ± 6.0	92.1 ± 6.1	93.1 ± 6.3*	93.7 ± 5.6*#	92.7 ± 5.6	93.6 ± 6.1*	94.1 ± 6.4*
Anterior-medial	91.1 ± 6.3	92.7 ± 6.0*	93.5 ± 6.4*	94.6 ± 6.5*#§	93.3 ± 5.5*	94.8 ± 5.8*#	95.0 ± 6.0*#¶
Anterior-lateral	76.0 ± 8.0	77.5 ± 7.9	78.2 ± 7.8*	78.8 ± 7.9*	78.1 ± 8.0	79.8 ± 7.6*¶	80.4 ± 8.0*#§¶
Medial	87.8 ± 8.3	90.4 ± 8.8*	91.5 ± 8.5*	92.4 ± 8.9*#	90.4 ± 9.6	90.9 ± 8.7*	92.2 ± 8.7*¶‡
Lateral	73.0 ± 9.7	75.9 ± 10.5*	77.4 ± 9.8*	79.0 ± 9.9*#	78.2 ± 9.3*	79.1 ± 8.9*#	80.5 ± 9.6*#¶
Posterior	83.7 ± 11.7	85.1 ± 12.0*	86.2 ± 11.4*	87.3 ± 11.7*#¶	84.9 ± 12.4	87.0 ± 11.1*¶	87.4 ± 10.7*#¶
Posterior-medial	85.7 ± 8.6	86.9 ± 8.8	87.8 ± 9.5*	88.4 ± 8.9*	87.6 ± 8.9	89.0 ± 9.4*	89.1 ± 8.3*#
Posterior-lateral	80.3 ± 10.6	81.5 ± 10.4	81.9 ± 12.3	82.8 ± 9.9	81.4 ± 9.9	82.8 ± 9.6	83.4 ± 9.4

* significant difference from trial 1 (p<0.05)
# significant difference from trial 2 (p<0.05)
§ significant difference from trial 3 (p<0.05)
¥ significant difference from trial 4 (p<0.05)
¶ significant difference from trial 5 (p<0.05)
‡ significant difference from trial 6 (p<0.05)

Table 4.9 - Mean, standard deviation (SD), intraclass correlation coefficient (ICC), 95% confidence intervals (CI) for ICC, standard error of measurement (SEM), and smallest detectable difference (SDD) values for normalised trials 5-7 of all reach directions.

Test	Week 1 (%)	Week 2 (%)	Week 3 (%)	ICC	95% CI		SEM (%)	SDD (%)
Anterior	93.4 (5.9)	92.8 (6.2)	92.0 (6.4)*	0.84	0.78	0.88	2.5	6.9
Anterior-medial	94.1 (5.8)	93.4 (5.7)	92.8 (5.6)*	0.85	0.80	0.89	2.2	6.1
Anterior-lateral	79.4 (7.8)	78.5 (7.2)	77.9 (8.1)*	0.87	0.82	0.90	2.8	7.7
Medial	91.6 (8.6)	92.4 (6.3)	91.9 (6.3)	0.86	0.82	0.90	2.7	7.4
Lateral	78.8 (9.0)	80.7 (8.8)*	81.7 (9.7)*	0.91	0.88	0.94	2.8	7.7
Posterior	86.4 (11.4)	87.2 (9.4)	88.4 (8.7)*#	0.92	0.89	0.94	2.8	7.7
Posterior-medial	88.4 (8.8)	89.8 (7.0)	89.5 (7.7)	0.86	0.81	0.90	2.9	8.2
Posterior-lateral	82.5 (9.6)	83.9 (9.2)	84.7 (9.0)*	0.92	0.89	0.94	2.6	7.1

Significant difference from week 1 (p<0.05) - *

Significant difference from week 2 (p<0.05) - #

Table 4.10 - Mean, standard deviation (SD), intraclass correlation coefficient (ICC), 95% confidence intervals (CI) for ICC, standard error of measurement (SEM), and smallest detectable difference (SDD) values for raw trials 5-7 of all reach directions.

Test	Mean (cm)	SD (cm)	ICC	SEM (cm)	SDD (cm)
Anterior	83.9	5.9	0.88	2.0	5.7
Anterior-medial	84.7	5.9	0.89	1.9	5.4
Anterior-lateral	71.2	7.2	0.89	2.4	6.7
Medial	83.4	7.4	0.90	2.3	6.5
Lateral	72.9	9.1	0.93	2.4	6.7
Posterior	79.2	10.1	0.94	2.5	6.9
Posterior-medial	80.9	8.0	0.90	2.5	7.0
Posterior-lateral	75.9	9.4	0.94	2.3	6.4

Table 4.11- Limb symmetry index (LSI) mean, standard deviation (SD), intraclass correlation coefficient (ICC), 95% confidence intervals (CI) for ICC and standard error of measurement (SEM) values for all reach directions.

Test	Week 1 (%)	Week 2 (%)	Week 3 (%)	ICC	95% CI		SEM (%)
Anterior	99.5 (5.3)	100.5 (4.0)	97.8 (2.7)[#]	0.50	-0.02	0.78	2.9
Anterior-medial	100.4 (5.3)	100.2 (4.1)	100.3 (4.6)	0.53	0.05	0.79	3.2
Anterior-lateral	100.8 (6.8)	101.9 (5.0)	100.4 (3.9)	0.55	0.08	0.80	3.6
Medial	99.5 (6.7)	99.6 (6.1)	99.7 (4.7)	0.39	-0.25	0.73	4.7
Lateral	100.2 (5.8)	101.1 (7.8)	102.2 (5.0)	0.51	0.01	0.78	4.4
Posterior	101.6 (8.3)	102.7 (6.9)	103.0 (5.2)	0.51	0.01	0.78	4.7
Posterior-medial	100.9 (8.4)	101.5 (7.0)	102.3 (6.7)	0.30	-0.43	0.67	6.1
Posterior-lateral	99.1 (6.1)	98.1 (6.7)	97.7 (4.9)	0.54	0.67	0.80	3.9

Significant difference from week 2 (p<0.05) - [#]

4.4.5. Discussion

The aims of the current study were to:

a) Establish whether gender differences are apparent for each test and for LSI,

b) Assess the learning effects associated with the SEBT to determine the number of practice trials needed;

c) Establish the between-session reliability and associated measurement error using a standardised protocol; and

d) Establish the reliability and measurement error of LSI in healthy participants.

According to the results of this study, there were no differences between men and women for normalised excursion distances, providing support for previous studies by Gribble and Hertel (2003) and Sabin et al. (2010). These findings underline the importance of normalising reach distance scores when comparing between individuals and indicate that men and women need not be separated in future studies when normalisation is used. Additionally, no differences were found between men and women for LSI scores, therefore LSI can be compared across individuals.

Previously, Robinson and Gribble (2008b) found that both excursion distance scores and joint angular displacement stabilised within four trials, which prompted them to recommend only four practice trials were needed rather than the six previously recommended by Hertel et al. (2000). The findings of this study support those of Robinson and Gribble (2008b) whereby excursion distances stabilised after four trials. This was characterised by a decrease in excursion distance between trials four and five, and a lack of difference between trials four and seven, in all reach directions. Therefore SEBT administration could be simplified from performing six practice trials as previously recommended (Hertel et al., 2000).

Using this protocol reliability scores were high, with ICCs ranging from 0.84-0.92. These values were similar to those from previous research where ICCs ranged from 0.78 to 0.96 (Hertel et al., 2000; Plisky et al., 2006). In Hertel et al.'s (2000) study a significant learning effect was found on day one, where trials four to six were significantly higher than trials one to three, which resulted in the lower ICC of 0.78. The ICCs for day two, trials seven to twelve where no learning effect was evident increased to a minimum of 0.82. Plisky et al. (2006) followed the four practice trial protocol and found test-retest reliability to be 0.89-0.93. Considering that ICCs for the current study ranged from 0.84-0.92 the simplified protocol of four practice trials achieves the same reliability as using six practice trials. This provides further support for the use of the simplified protocol.

SEM values presented give clinicians reference data to decide within what range an individual's true score will lie. For example, in the current study normalised SEM values range from 2.2-2.9%, suggesting that an individual's true score would lie within this range. Only one study has presented SEM values between-session reliability, these values were for raw scores. Direct comparison to the current study cannot be made due to differing protocols. However, the SEM values noted in this study (1.9-2.5cm) compare favourably to those of Kinzey and Armstrong (1998) (3.43-4.78cm), providing further evidence that the four practice trial protocol is reliable.

The SDD values suggest that this is the minimum amount of change needed to exist between two independently obtained SEBT performance scores for the change to be significant (Kropmans et al., 1999). Therefore, according to the current study's normalised SDD values, for a true change in performance in the anterior direction to be observed an individual would have to improve by 6.8% between tests.

This knowledge of measurement error is important for the use of outcome measures during rehabilitation as it gives clinicians and patients an indication of when a rehabilitation protocol is meeting its aims. Both raw and normalised mean, SEM and SDD scores are presented (tables 4.7 and 4.8). Normalising excursion distances is appropriate when comparing scores between individuals, however if only comparing a re-test score for one individual, such as in clinical environments, raw scores can be used.

Previous research has suggested that the SEBT is sensitive enough to detect dynamic postural control deficits in patients with CAI and an ACL-deficient (ACL-D) limb (Gribble et al., 2004; Herrington et al., 2009; Hertel et al., 2006a; Olmsted et al., 2002). In these studies, patients who were injured were shown to have lower SEBT scores compared to their uninjured limb and those of healthy participants. In particular the anterior-medial, medial and posterior-medial reach directions were shown to detect functional deficits in participants with CAI (Hertel et al., 2006a). Herrington et al. (2009) found that ACL-D patients showed functional deficits in the anterior, medial, lateral and posterior-medial reach directions.

In light of the error measurement values presented in the current study the significant differences which have previously been highlighted between participants actually fall within this study's measurement error and therefore cannot be deemed to be clinically meaningful. For example, Olmsted et al. (2002) state that a significant difference was found between participants with and without CAI, and also between the injured and uninjured limb of those with CAI. The overall difference in raw reach distances between groups in that study was no more than 4.2cm. This falls below the range of 5-7cm raw SDD scores observed in the current study and suggests that the differences were within measurement error. Similar results are demonstrated in other studies on the effect of CAI on SEBT performance, where the reported significant differences fall within measurement error boundaries in some directions (Gribble et al., 2004; Hertel et al., 2006a).

Additionally, Herrington et al. (2009) found that ACL-D patients showed functional deficits in the anterior, medial, lateral and posterior-medial reach directions. Further analysis shows that only the lateral and medial directions in that study fall outside of the measurement error values presented here and can therefore be classed as truly significant. The original conclusions of the CAI studies (Hertel et al., 2006a) that not all reach directions need to be tested in this population may not be true as the differences they found were within measurement error. Although ACL-D patients may only need to be tested in the medial and

lateral directions in order to detect deficits (Herrington et al., 2009). Further study of this area is required to clarify previous findings and to further establish the sensitivity of each reach directions to specific injuries.

Although it is unclear whether the SEBT is able to detect functional deficits between injured and uninjured populations, it may be possible to detect deficits in healthy athletes and therefore predict future potential injury risk (Plisky et al., 2006). Raw SEM in the anterior reach direction was 2cm in the current study, meaning that the 4cm difference in reach distance in the anterior direction between left and right limbs quoted to predict lower limb injury is above measurement error, thus lending support to the potential for SEBT to predict injury risk. Whether this holds true for prediction of specific injuries, such as ACL or PFPS, requires further investigation.

No study has investigated the reliability of LSI in the SEBT. The results of the current study found that, despite a lack of significant differences in LSI scores between weeks, moderate ICC values indicate that LSI was only fairly reliable for the SEBT. As mentioned previously in this chapter, ICC scores can be negatively affected by data with decreased variability, which would be indicated by a lack of statistically significant difference between weeks in all but one reach direction. In particular, the medial reach direction has a relatively low ICC score of 0.39, despite only a 0.2% difference between scores from weeks one to three.

A significant reduction in LSI was found in the anterior reach direction from week two to week three. This change (2.7%) was the greatest seen between weeks in any directions and was actually with the calculated SEM value of the measure, and could therefore be considered to lie within measurement error of the test. Considering this, it would seem that the variability of the LSI scores across the weeks was actually very low, indicating that the measure was reliable.

The main limitation of this study is that the SEM and SDDs calculated were from data taken from participants who were healthy, recreationally active University students. How this may reflect individuals who are undergoing injury rehabilitation or older age groups is unclear and further research should be conducted in this area.

It can be concluded that a standardised protocol of four practice trials followed by three measured trials for SEBT administration should be adopted. The high test-retest reliability

coupled with the low error scores found suggests that the SEBT is suitable for use in clinical practice and further research. Clinicians and researchers now have normalised and raw score reference data to help them evaluate whether changes in an individual's performance during rehabilitation is a true reflection of progress or due to measurement error.

4.5. Conclusion

In this chapter, several areas of hop tests and SEBT have been investigated. Firstly, it was found that gender differences are evident in the hop for distance and timed hop tests, where men performed better than women, and therefore they should be analysed separately in future studies and in the field. These differences were not evident when assessing LSI scores and therefore they can be analysed together. Differences between men and women were not found in the SEBT for both normalised excursion distances and LSI values, therefore they can be analysed together in future.

Learning effects have previously been reported in both the hop tests and the SEBT. The results of this chapter show that three practice trials are needed in the hop tests, with the exception of the crossover hop for distance in men where four practice trials are required. Four practice trials are required prior to measurement of excursion distances in the SEBT.

Reliability and measurement error of the hop for distance tests and the SEBT have been fully established in this chapter. Both the hop tests and the SEBT are reliable for use in the field and in future research. Using the SEM and SDD values presented in this chapter, clinicians and researchers can now make informed decisions on whether changes in performance are due to random error or true changes in individual performance.

Reliability of the LSI was found to be fair to good, as indicated by ICC scores. However, the lack of significant differences and variability of scores between weeks indicate that LSI is a useful tool for research and evaluation of injured individuals. As discussed in chapter two, the ability of FPTs such as the hop for distance tests and the SEBT to detect functional deficits has been determined. Poor scores on the SEBT has also been associated with occurrence of lower limb injury (Plisky et al., 2006). Whether these tests can specifically detect functional deficits which may predict future ACL or PFJ injury is unknown and further investigation is warranted. The measurement error values identified in this study will allow for greater understanding of changes in FPT performance resulting from interventions or injury.

Chapter 5

Factors contributing to dynamic knee valgus

5.1. Aim

Having established the reliability and validity of 2D FPPA in chapter three, and considered the reliability of FPTs in chapter four, the aim of this chapter is to assess which factors contribute to dynamic knee valgus, measured via frontal plane projection angle (FPPA).

5.2. Introduction

As discussed in chapters two and three, dynamic knee valgus, as measured via FPPA, may help to identify those at risk of ACL injury and PFPS. Modification of movement strategies which are regarded as high-risk for ACL injury and PFPS is important in order to reduce injury occurrence. Despite the frequent use of the drop jump and single leg drop landing for clinical screening, little is known about which factors contribute to dynamic knee valgus during these tasks. In particular, there are no studies to date which have assessed the factors which contribute to FPPA. In this thesis, FPPA has been shown to be a valid and reliable measure of dynamic valgus for use in the clinical environment. These contributory factors need identifying, to enable targeted prevention strategies and injury rate reduction. Figure 5.1 shows some of the likely contributing factors to dynamic valgus that have previously been identified in the literature as outlined in chapter two and figure 2.16.
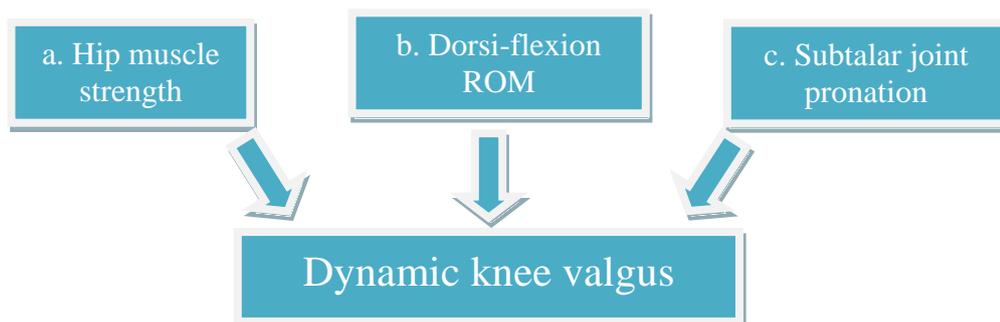
Figure 5.1. Contributing factors to dynamic knee valgus.

a) Hip muscle strength:

As previously discussed in chapter two, section 2.3.4.3, a number of studies have investigated the link between hip muscle strength and lower limb kinetics and kinematics. It has been suggested that weakness of the hip abductors and external rotators may lead to increased hip adduction and internal rotation, two key contributors to dynamic valgus (Hewett et al., 2005;

Zeller et al., 2003). The fact that women often demonstrate significantly lower strength and display greater hip adduction and internal rotation motion than men, provides further support for this theory (Beutler et al., 2009; Claiborne et al., 2006; Jacobs et al., 2007; Leetun et al., 2004; Willson et al., 2006). However, studies have not always confirmed this (Beutler et al., 2009; Jacobs et al., 2007; Sigward et al., 2008; Willson & Davis, 2009). One reason may be that most studies examined isometric hip strength in a lying position, which does not reflect the action of the hip musculature during functional activities. Assessment of concentric/eccentric muscle function or isometric function in a weight-bearing position is more representative of normal function and thus may be more valid. Assessment of isometric hip abductor muscle strength has been conducted in previous studies (Carcia et al., 2005; Carcia & Martin, 2007).

Additionally, the majority of studies in the literature have used a handheld dynamometer to test isometric hip strength. A study by Kawaguchi and Babcock (2010) found significant correlations in isometric hip adduction (r=0.83) and hip extension (r=0.42) strength measured using a handheld dynamometer and an isokinetic dynamometer. The authors concluded that the handheld dynamometer was therefore a valid measure of isometric hip muscle strength. However, 31-82% of the variance in isometric hip strength scores on the isokinetic dynamometer was unexplained by the handheld dynamometer, suggesting a lack of agreement between the measures. It appears that the recommended use of an immovable strap to restrain the dynamometer (Katoh & Yamasaki, 2009; Wikholm & Bohannon, 1991) was not followed in the Kawaguchi and Babcock (2010) study, which may have negatively influenced the results. However, measurement of isometric hip strength using a fixed dynamometer is likely to improve the reliability and validity of the measurement.

b) Dorsi-flexion range of movement:

Decreased flexibility of the gastrocnemius and/or soleus muscles cause decreased ankle dorsi-flexion range of motion (ROM). This may lead to compensatory foot pronation to achieve the required dorsi-flexion ROM at the ankle during gait and other activities (Piva et al., 2005; Witvrouw et al., 2000). In one prospective study, high-school physical education students who developed PFPS had 3º less flexibility of the gastrocnemius muscle than those who did not (Witvrouw et al., 2000). Furthermore, PFPS patients demonstrate significantly decreased length of gastrocnemius and soleus compared to healthy controls (Piva et al., 2005). When combined with hip abduction strength, they were able to discriminate between those with and without PFPS in 87% of cases (Piva et al., 2005). These findings suggest that decreased dorsi-

flexion ROM, as a result of decreased flexibility of the gatrocnemius and soleus muscles, may play a part in development of PFPS, via increasing dynamic knee valgus.

Additionally, decreased dorsi-flexion ROM is correlated to increased GRF (Fong, Blackburn, Norcross, McGrath, & Padua, 2011b; Self & Paine, 2001), which is associated with greater knee valgus motion (Hewett et al., 2005). A decreased available dorsi-flexion ROM is also correlated to increased valgus (Sigward et al., 2008). In this study, dorsi-flexion ROM measured at 30º knee flexion accounted for 11% of the variance in frontal plane knee angle. Additionally, Hagins, Pappas, Kremenic, Orishimo, and Rundle (2007) found that knee valgus increased by 1.4º when participants landed on an inclined surface which reduced the amount of dorsi-flexion which could be achieved. Overall, this suggests that a decrease in dorsi-flexion ROM will lead to compensatory movements that increase ACL and PFJ loads.

c) Subtalar joint pronation:

Women have been shown to demonstrate greater pronation than men (Kernozek et al., 2005; Zeller et al., 2003), whilst pronation has been postulated to affect femoral rotation (Nawoczenski et al., 1998; Tiberio, 1987), potentially increasing lateral PFJ contact pressures (Lee et al., 1994; Lee et al., 2003). The contribution of pronation to PFJ injury was discussed in section 2.3.4.1.e in chapter two with conflicting results noted. Boling et al. (2009b) found that participants who demonstrated greater pronation were more likely to suffer from PFPS. Further, small to moderate significant correlations between FPPA and subtalar joint complex pronation/eversion were also found in chapter three. Considering this, it follows that an increase in pronation would likely lead to an increase in FPPA and as a result, an increase in potential injury risk.

Navicular drop is a measure of the difference in height of the navicular tuberosity when the subtalar joint is in neutral and during weight-bearing (Sell, Verity, Worrell, Pease, & Wigglesworth, 1994b). Navicular drop is the most valid and reliable tool for assessing dynamic subtalar joint pronation available to clinicians (Cornwall & McPoil, 1999; Sell, Verity, Worrell, Pease, & Wigglesworth, 1994a; Williams & McClay, 2000). In addition, navicular drop has been prospectively linked to occurrence of PFPS (Boling et al., 2009b), whilst ACL injured patients also demonstrate greater navicular drop than their uninjured counterparts (Allen & Glasoe, 2000). Navicular drop measures therefore provide a useful clinical tool. No study has specifically assessed the contribution of pronation, measured using navicular drop, to dynamic knee valgus.

In light of the review of literature the purpose of this chapter was to investigate whether isometric hip muscle strength measured using a fixed dynamometer, dorsi-flexion range of movement and navicular drop contribute to dynamic knee valgus, as measured via 2D FPPA, during the DJ and SLL. The DJ and SLL tasks were chosen as they both demonstrated relationship with 3D measures of dynamic knee valgus and were the most reliable tests as shown in chapter three.

5.3. Methods

Participants

Sixty seven recreationally active University students, 31 men (age 20.5 ± 3.6 years, height 1.78 ± 0.08m, weight 78.6 ± 13.8kg) and 36 women (age 21.5 ± 3.7 years, height 1.67 ± 0.07m, weight 64.9 ± 9.7kg) volunteered to take part in the study. The same entry criteria, approval and consent procedures were used as outlined in chapter three (section 3.3).

Protocol

Each participant undertook the following tests in this order, on the same day:

- 2D FPPA analysis
- Isometric hip strength testing
- Dorsi-flexion ROM
- Navicular drop

Subject height and weights were recorded using a combined digital scales and stadiometer (Seca Delta, Seca UK).

2D analysis

Protocol

The same procedure for placement of markers to measure FPPA was used as previously described in chapter three (section 3.3).

Camera setup

A commercially available digital video camera (Casio EX-F1), set in standard mode and sampling at 30Hz, was mounted on a tripod at a height of 50cm, three metres away from the centre of the landing platform. Cameras were levelled using the built-in level on each tripod. The 3-4-5 rule was used to ensure that the camera was placed perpendicular to the plane of

motion to reduce the likelihood of perspective or parallax error. The digital video footage was saved onto a desktop PC for later analysis.

The DJ and SLL tasks were undertaken as described previously in chapter three (section 3.3).

Frontal Plane Projection Angle (FPPA)

Measurement of FPPA was undertaken using the same method as previously described in chapter three (section 3.3).

Isometric hip strength testing

Isometric force production of the hip abductors, external rotators, and a combination of both hip abductors and external rotators was measured using the Biodex System 3 isokinetic dynamometer (Biodex Medical Systems, Shirley, NY). All muscle force values were collected in Newtons and later normalised to each participant's body mass (N/kg). Normalisation to body mass allowed for more accurate comparison across participants and to the literature. The order in which participants completed the three strength tests (ie. Standing hip abduction, standing clam and seated external rotation described below) was randomised using the same method as described in chapter three.

For all tests, participants were required to push as hard as possible into the dynamometer for five seconds. Two practice trials were conducted for familiarisation, followed by three measured trials. Each trial was separated by 30 second rest periods (Beutler et al., 2009; Jacobs et al., 2007; Widler et al., 2009). A 5 minutes rest period was included between each of the three strength tests.

Standing hip abduction (figure 5.2)

Participants performed isometric hip abduction strength testing in a standing position. This position was considered to be more representative of how the muscles function during landing. Standing hip abduction testing has been shown to be valid and reliable (Jacobs & Mattacola, 2005; O'Dwyer, Sainsbury, & O'Sullivan, 2011; Widler et al., 2009). Test-retest reliability ICC for the standing hip abduction was 0.88 (Widler et al., 2009). Gluteus medius activity has also been shown to be high in this test (O'Dwyer et al., 2011; Widler et al., 2009). Participants stood facing the dynamometer head with their hip joint centre adjacent to the axis

of rotation of the dynamometer arm. The height of the dynamometer head was then adjusted to align with the hip joint centre. In some cases participants stood on an aerobic step (Reebok International, Canton, MA) to ensure their hip joint centre was aligned with the axis of rotation. The hip joint centre was defined as the intersection of two lines directed inferiorly from the anterior superior iliac spine and medially from the greater trochanter of the femur (Jacobs & Mattacola, 2005). Participants were asked to take a shoulder width stance, this foot width was then measured to standardise stance width between limbs and tests, to ensure no effect of length-tension relationships on muscle force production. Once in this position, the lever arm of the dynamometer was lowered until it came into contact with the participant's leg, with the pad positioned 5cm above the lateral epicondyle of the femur. This position ensured that no movement of the test limb would occur. Participants were instructed to push laterally into the dynamometer using their thigh, using the hip as the axis of rotation. The test leg was held slightly off the ground in a non-weight bearing fashion. During each maximal effort participants were required to maintain neutral trunk and pelvis alignment. To help achieve this, participants held onto the dynamometer head for stability.

Standing clam (figure 5.3)

Participants performed the isometric clam test in a partial squat position. This test aimed to assess the combined strength of the hip abductors and external rotators, in a position mimicking that of the drop jump landing. Previous studies have shown that a side-lying version of this test recruits both the gluteus maximus and medius muscles (Nyland, Kuzemchek, Parks, & Caborn, 2004) and correlates with 3D knee valgus during a single leg jump landing task (Howard, Fazio, Mattacola, Uhl, & Jacobs, 2011). Participants stood facing the dynamometer head in the same shoulder width stance as during the standing hip adduction tests, and were then instructed to squat to 45° of knee flexion. This was checked using a standard goniometer by the principle investigator prior to each trial. The height of the dynamometer head was then adjusted so that the participant's hip joint centre was adjacent to the axis of rotation of the dynamometer arm. In some cases participants stood on an aerobic step (Reebok International, Canton, MA) to ensure their hip joint centre was aligned with the axis of rotation. Once in this position, the lever arm of the dynamometer was lowered until it came into contact with the participant's leg, with the pad positioned 5cm above the lateral epicondyle of the femur. This position ensured that no movement of the test limb would occur. Participants were instructed to push laterally into the dynamometer using their thigh, using the hip as the axis of rotation as if performing the clam manoeuvre, ensuring that both feet stayed in contact with the ground. During each maximal effort participants were required

to maintain neutral trunk and pelvis alignment. To help achieve this, participants held onto the dynamometer head for stability.

Seated external rotation (figure 5.4)

Participants undertook isometric hip external rotation strength testing in a seated position, with both the hip and knee in 90º of flexion, and the hip in a neutral position in the frontal plane. Johnson and Hoffman (2010) showed that hip external rotation torque does not change with increases in hip flexion, therefore testing at 90° would be valid. The axis of rotation of the dynamometer was aligned with the centre of the knee joint, which was defined as the midpoint of the femoral condyles. The thigh of the test leg was strapped to the seat to ensure that no other hip movement occurred, including contraction of the hip adductors affecting the strength measure. Once in this position, the lever arm of the dynamometer was lowered until it came into contact with the participant's leg, with the pad positioned 5cm above the medial malleolus. Participants were instructed to push into the dynamometer with the knee as the axis of rotation, as if trying to raise the medial malleolus to the ceiling.

Figure 5.2 – Standing isometric hip abduction strength test.

Figure 5.3 – Standing isometric clam strength test.

Figure 5.4 – seated isometric external rotation strength test.

<u>Dorsi-flexion ROM</u>

Weight-bearing ROM assessment of the gastrocnemius and soleus muscles was undertaken using a standard goniometer. Marks were placed on the head of fibula and head of the fifth metatarsal. Dorsi-flexion angle was measured from the head of fibula, to the head of the 5th metatarsal, using the lateral malleolus as the axis of rotation (Fong, Blackburn, Norcross, McGrath, & Padua, 2011a). The stationary arm of the goniometer was placed in line with the fibula head, with the moving arm parallel to the 5th metatarsal. Each measure was taken three times, with the mean value taken and all measurements were taken by the same experimenter.

Firstly, participants were asked to stand on a solid platform, which was raised from the ground, with their feet shoulder width apart whilst the degree of ankle dorsi-flexion was measured. The test leg was positioned at the edge of the bench to allow dorsi-flexion to be measured with the goniometer. This initial measure was regarded as neutral and subsequent dorsi-flexion angles were calculated from this.

The modified lunge version of these dorsi-flexion ROM tests were used and this has been shown to have excellent intra- and inter-tester reliability (Krause, Cloud, Forster, Schrank, & Hollman, 2011). For the gastrocnemius, participants were instructed to step forward and lean onto the contralateral limb, with the tested limb behind, keeping the knee of the test limb straight (figure 5.5). Participants were instructed to lean as far forward as possible whilst keeping the heel of the test limb on the ground, without rotation of the lower leg and keeping the subtalar joint in neutral. Subtalar joint movement was assessed by the principle investigator by palpating the medial and lateral aspects of the talar dome by placing thumb and forefinger anteriorly to the medial and lateral malleolus. Once again, the test limb was positioned at the edge of the bench. The angle measurement was taken once the participant's heel began to rise from the ground (Denegar, Hertel, & Fonseca, 2002).

For the soleus, participants were instructed to step forward and lean onto the contralateral limb, with the tested limb behind. Participants were then asked to bend the knee of the test limb, and maximally flex their ankle by squatting on their test limb (figure 5.6). The same requirements as for successful measurement of gastrocnemius ROM were followed.
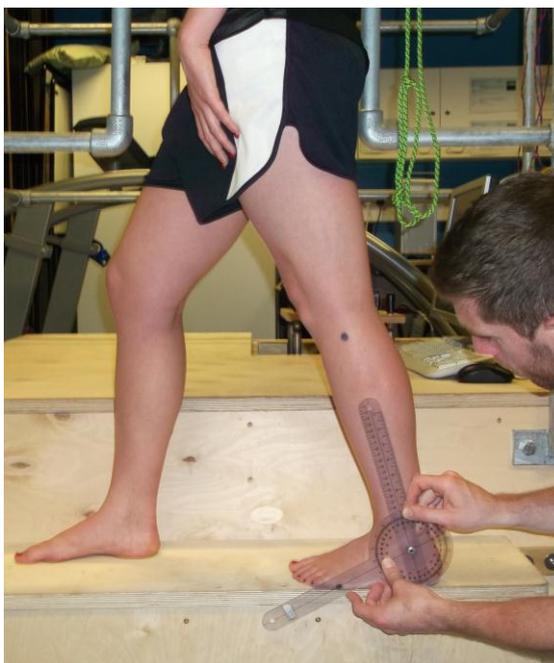
Figure 5.5 – gastrocnemius range of motion test.

Figure 5.6 – soleus range of motion test.

Navicular drop

Measurement of navicular drop was undertaken as originally described by Brody (1982). Good to excellent intra- and inter-tester reliability of this method has also been established (Sell et al., 1994). The navicular tuberosity was palpated and marked prior to measurement of navicular drop, whilst participants lay supine. Whilst seated, the participant was placed into

subtalar joint neutral. A 2x7cm piece of card was placed vertically on the medial side of the foot, just posterior to the navicular. The distance from the floor to the mark on the participant's navicular tuberosity was then marked on the card with a line, as shown in figure 5.7. Participants were then asked to take a bilateral stance. The distance from the floor to the mark on the participant's navicular tuberosity was again measured.

Navicular drop was measured as the difference between the navicular tuberosity height in a seated subtalar joint neutral position and a bilateral standing position. This procedure was repeated three times, with the mean value in millimetres taken. All measurements were taken by a single experimenter.

Figure 5.7 – measurement of navicular drop.

Statistical Analysis

All statistical analysis was conducted using SPSS for Windows version 16.0 (SPSS Inc., Chicago, IL). Means and standard deviations for all measured variables were presented. The independent variables in this study were isometric hip strength (abduction, external rotation and standing clam), ankle dorsi-flexion ROM (knee flexed, knee extended) and navicular drop. The dependent variables of interest were 2D FPPA during the DJ and SLL tasks.

Kolmogorov-Smirnov tests indicated that data was normally distributed. Paired t-tests indicated that no differences existed between left and right limbs in all tests and they were

therefore grouped for all analysis. Men and women were considered together in order for the greatest sample size possible to be considered within the regression analyses.

Forward and Backwards stepwise regression analyses were employed to determine whether the independent variables measured were able to predict FPPA during either the DJ or SLL task. Stepwise regression is based upon statistical criteria whereby variables are only included in the model when they make a statistically significant contribution. This is useful when the regression is being undertaken as an exploratory exercise to determine which variables are useful in the prediction of the dependent variable and there is no prior knowledge of which of the independent variables will have the greatest impact (Montgomery & Peck, 1992; Tabachnick & Fidell, 2007).

Firstly, a forward stepwise regression analysis was undertaken, whereby all variables are excluded at the start and added in one at a time providing they make a significant contribution to the prediction model. Following this a backward deletion regression analysis was undertaken to confirm the findings of the forward regression. In the backward regression, all independent variables were entered into the equation, with variables removed if they no longer significantly contribute to the regression. Pearson's product correlation coefficients between each independent variable and the dependent variable of interest were also generated as part of the regression analyses output. The alpha level was set as $p < 0.05$.

Following this, secondary analysis was undertaken to investigate whether differences in each of the independent variables were evident between those who exhibit high FPPA values and those who are considered normal. High FPPA was determined using a normative paper (Herrington & Munro, 2010), where FPPA greater than 13º for women and 8º men on the DJ task, and 12º for women and 9º for men on the SLL task was considered high. Analysis was undertaken to compare between limbs within subjects where one limb was considered to have high FPPA and the other normal, and also to compare all high FPPA limbs against all those considered as normal. Paired t-tests were conducted for each variable to compare scores and the alpha level was set as $p < 0.05$. Effect sizes were determined using the Cohen δ method (Thomas et al., 2005), which defines 0.2, 0.5 and 0.8 as small, medium and large respectively.

5.4. Results

Means and standard deviations for all measured variables are presented in table 5.1. FPPA was 0.9° in the DJ task and 10.3° in the SLL task. Pearson's correlation coefficients for each independent variable are presented in table 5.2. Significant correlations were evident between isometric hip abduction, hip external rotation and standing clam tests and FPPA during the DJ task. The strongest correlation to DJ FPPA was found with the standing clam (r = -.44) and therefore standing clam entered the forward regression first and was found to be the largest predictor of FPPA (r^2= 0.20). According to the forward regression model no other independent variables significantly contributed to the prediction of DJ FPPA. This was further confirmed by the backward model. When all independent variables were entered into the backward model only 25% of DJ FPPA was explained, however this was not significantly different to standing clam alone.

No significant correlations were found between the independent variables and FPPA in the SLL task. As a result, the regression analyses found that none of the measured independent variables were able to predict FPPA in the SLL task.

Table 5.1. Mean and standard deviation (SD) of all measured variables for recreational men and women.

	Mean (SD)
DJ FPPA (°)	0.9 (12.7)
SLL FPPA (°)	10.3 (7.7)
Standing Abduction (N/kg)	103.9 (24.9)
External rotation (N/kg)	83.2 (25.7)
Standing Clam (N/kg)	125.6 (43.1)
Gastrocnemius ROM (º)	26.5 (5.1)
Soleus ROM (º)	31.1 (6.5)
Navicular drop (mm)	7.8 (3.7)

Table 5.2. Pearson's product correlation coefficients between 2D Frontal Plane Projection Angle in the Drop Jump and Single Leg Land tasks and the independent variables measured.

Test	Drop Jump FPPA		Single Leg land FPPA	
	r	p	r	p
Standing Abduction (N/kg)	-.34	0.002	-.03	0.381
External rotation (N/kg)	-.25	0.016	-.06	0.314
Standing Clam (N/kg)	-.44	<0.001	-.02	0.445
Gastrocnemius ROM (º)	.02	0.422	.02	0.441
Soleus ROM (º)	.02	0.448	-.16	0.064
Navicular drop (mm)	-.08	0.305	-.07	0.329

Tables 5.3-5.6 present the results of secondary analysis comparing individuals with high FPPA against their own uninjured limbs and all other participants. This analysis revealed that significant differences were evident between high FPPA and normal limbs for the DJ task only. Those who exhibited high FPPA also demonstrated significantly greater standing abduction (p=0.006, ES = 0.89) and external rotation (p=0.016, ES=0.74) force than those who demonstrated normal FPPA. No other differences between high FPPA and normal limbs were evident either between all limbs or within subjects.

Table 5.3. Means and standard deviations for each measured variable in high FPPA limbs (n=32) and normal limbs (n=102) in the drop jump task

	High FPPA	Normal
DJ FPPA (°)	16.9 (5.5)	-3.1 (10.9)
Standing Abduction (N/kg)	102.4 (25.1)*	79.8 (25.5)
External rotation (N/kg)	82.8 (33.9)*	62.2 (20.3)
Standing Clam (N/kg)	109.9 (39.5)	100.6 (43.1)
Gastrocnemius ROM (º)	26.1 (5.9)	26.3 (5.1)
Soleus ROM (º)	29.0 (8.1)	31.3 (6.3)
Navicular drop (mm)	6.6 (1.9)	7.9 (3.9)

* significant difference at p<0.05

Table 5.4. Means and standard deviations for each measured variable in high FPPA limbs (n=38) and normal limbs (n=96) in the single leg landing task.

	High FPPA	Normal
SLL FPPA (°)	16.5 (5.3)	4.7 (4.7)
Standing Abduction (N/kg)	106.2 (25.1)	101.7 (24.8)
External rotation (N/kg)	83.1 (25.9)	81.5 (28.1)
Standing Clam (N/kg)	133.2 (43.9)	120.1 (42.3)
Gastrocnemius ROM (º)	26.9 (5.4)	26.1 (4.6)
Soleus ROM (º)	30.6 (6.7)	31.7 (6.3)
Navicular drop (mm)	7.5 (3.7)	7.9 (3.8)

Table 5.5. Means and standard deviations for each measured variable in high FPPA limbs and the opposing limb within-subjects (n=20) in the drop jump task.

	High FPPA	Normal
DJ FPPA (°)	17.4 (5.4)	0.9 (6.7)
Standing Abduction (N/kg)	91.6 (20.3)	88.3 (22.2)
External rotation (N/kg)	69.0 (18.7)	62.9 (17.3)
Standing Clam (N/kg)	123.6 (38.1)	117.6 (38.6)
Gastrocnemius ROM (º)	25.0 (6.4)	29.7 (5.9)
Soleus ROM (º)	31.3 (9.6)	32.4 (7.2)
Navicular drop (mm)	6.2 (1.9)	6.5 (1.6)

Table 5.6. Means and standard deviations for each measured variable in high FPPA limbs and the opposing limb within-subjects (n=21) in the single leg landing task.

	High FPPA	Normal
SLL FPPA (°)	16.2 (6.5)	6.3 (3.4)
Standing Abduction (N/kg)	93.1 (24.7)	93.5 (27.7)
External rotation (N/kg)	81.5 (21.3)	86.8 (26.7)
Standing Clam (N/kg)	179.3 (25.9)	158.9 (26.6)
Gastrocnemius ROM (º)	25.4 (6.1)	26.4 (6.8)
Soleus ROM (º)	27.8 (8.3)	29.4 (6.5)
Navicular drop (mm)	7.4 (2.6)	7.4 (1.4)

5.5. Discussion

The aim of this study was to investigate which factors contribute to FPPA during the DJ and SLL tasks. To this end, participants undertook a number of tests which have previously been linked to dynamic knee valgus. Overall, only a limited number of variables measured demonstrated significant correlations to FPPA. There were no correlations between these variables and FPPA in the SLL task.

Of the six measures evaluated in this study which were theorised to be potential contributors to FPPA, only three demonstrated significant correlation to FPPA during the DJ task only. Standing hip abduction, hip external rotation and the standing clam isometric strength tests all significantly correlated to DJ FPPA. However, only the standing clam was identified as a significant predictor of FPPA in the regression analysis, accounting for 20% of the variance in FPPA. A decrease in standing clam strength was correlated with an increase in FPPA. No other variables contributed significantly to the regression model.

The side-lying clam exercise is commonly used in rehabilitation with the goal of increasing hip abductor and external rotator strength and has been shown to recruit the gluteus maximus and medius muscles (DiStefano, Blackburn, Marshall, & Padua, 2009; McBeth, Earl-Boehm, Cobb, & Huddleston, 2012; Nyland et al., 2004) which are the primary external rotator and abductor of the hip respectively (Neumann, 2010). The side-laying clam also moderately correlates with 3D knee valgus during a single leg jump landing task (Howard et al., 2011). The standing clam test was used in this study to simulate the weight-bearing function of the hip musculature during the DJ and SLL tasks at hip and knee flexion angles achieved during these screening tasks. Although EMG was not used to assess muscle activation, the fact that normalised force values were greater for the clam exercise than other hip muscle tests suggests that some co-activation of the hip abductor and external rotator muscles was evident. Considering this possible co-contraction, it is not surprising that force was greatest in the clam exercise and the strongest correlation with FPPA was found with the standing clam rather than either the hip abduction or external rotation tests alone. In addition, exploratory analysis revealed that a regression model including both hip abduction and external rotation strength was only able to explain 13% of the variance in FPPA during the DJ task. Despite the significant individual correlations between DJ FPPA and hip abduction and external rotation strength, neither of these measures was able to significantly contribute to the regression model due to collinearity between variables. Collinearity indicates that there is correlation between variables, which is indicated with the standing clam, hip abduction and external rotation tests.

Hip abduction and external rotation showed correlations of 0.68 and 0.13 with the standing clam respectively, accounting for almost fifty percent of the variance in standing clam scores. This suggests that the standing clam measure alone would be more useful than assessing hip abduction and external rotation.

Although it is unclear whether the standing version of the clam test used in the current study would recruit the hip musculature in the same way as reported in the side-lying position, weight-bearing exercises such as the single leg squat and lateral band walk have been shown to recruit the gluteus maximus and gluteus medius muscles to a greater extent than the side-lying clam (DiStefano et al., 2009). The standing clam test was undertaken in a similar position and required similar initial movement of the test limb to the lateral band walk task used by DiStefano et al. (2009), which resulted in high gluteus medius activity. However, the point of resistance in the lateral band walks was just proximal to participants' ankles, which generates a longer lever arm likely to increase muscle activation compared to point of resistance at the distal thigh in the standing clam test.

It has been proposed that the function of the hip rotator muscles may change based on the degree of hip flexion exhibited during a task. Delp, Hess, Hungerford, and Jones (1999) showed that the internal rotation moment arm of both the gluteus medius and gluteus maximus muscles increases as hip flexion increases, although the gluteus maximus retained an overall external rotation moment arm. This is an important consideration as hip flexion is evident during both the DJ and SLL tasks. However, whilst this suggests that the internal rotation torque production potential is increased when the hip is flexed; an actual amount of torque produced is not provided. As such, Johnson and Hoffman (2010) found that there was no change in isometric external rotation torque, tested using a fixed dynamometer, with varying degrees of hip flexion, whereas internal rotation torque increased with increased hip flexion. Additionally, internal rotation torque was approximately 10% greater than external rotation torque at 90° hip flexion, whereas there was no difference at 40°. An imbalance between internal rotation and external rotation torques could result in increased internal rotation excursion when the hip is flexed. However, it is unlikely that significant differences between internal and external rotation torques due to hip flexion excursion would affect athletes as hip flexion angles of 20° to 50° have been reported across several tasks (Decker et al., 2003; Jacobs et al., 2007; Lawrence et al., 2008; McLean et al., 2004a).

Dynamic hip abduction strength has previously been linked with frontal plane motion of the knee (Claiborne et al., 2006; Jacobs & Mattacola, 2005), whereas links with isometric hip abduction strength are not as clear but have been shown (Beutler et al., 2009; Lawrence et al., 2008; Sigward et al., 2008; Willson et al., 2006). One possible reason for the lack of association with isometric hip strength in some studies may be the nature of the measurement. Isometric hip abduction strength is commonly measured in a side-lying position to allow for isolation of the muscle to be achieved. However, this does not reflect how the muscle works during dynamic tasks. Widler et al. (2009) suggested that side-lying hip abduction has greater construct validity for testing maximal unilateral contraction due to the bilateral deficit principle. This principle states that there will be a decrease in force exerted by a single limb during a maximal bilateral contraction, due to reduced muscle activation, than is observed during a unilateral contraction (Ohtsuki, 1983). Therefore it could be argued that to truly test a muscle's maximal force, a unilateral effort, during which a minimal amount of activation of the contralateral muscle occurs, would be necessary. However, most muscles do not work in isolation, and in tasks such as the DJ, bilateral activation of the hip abductors would occur. Testing of the hip abductors in a standing position causes greater activation of the contralateral hip abductors (Widler et al., 2009). Consequently, testing of the hip abductors during a standing position as used in this study is likely to be more representative of how this muscle group works during bilateral functional tasks and is reflected in significant correlations noted with DJ FPPA. However, the lack of correlation between standing hip strength measures and FPPA during the SLL task, coupled with significant correlations between side-lying clam and knee valgus during a single leg jumping exercise found previously (Howard et al., 2011), may suggest that a side-lying test would be more representative of hip strength for unilateral tasks.

Furthermore, most studies have assessed isometric strength using a handheld dynamometer, whereas measurement of isometric hip strength using a fixed dynamometer is likely to improve the reliability and validity of the measurement. To this end, standing hip abduction strength was moderately negatively correlated with FPPA during the DJ task, whereas no correlation was evident with the SLL task. Considering that significant correlations were evident between 3D hip adduction angle and moments and FPPA in the DJ task it is not surprising that increases in hip abduction strength demonstrate a significant correlation with decreases in FPPA. However, a correlation between hip abduction strength and FPPA in the SLL task would also be expected since a correlation between 3D hip adduction and FPPA was found in chapter three.

Sigward et al. (2008) found that isometric hip strength measured using a handheld dynamometer in a side-lying position, did not correlate with frontal plane knee excursion during the DJ task. In direct contrast, the results of the current study found that standing isometric hip abduction and the standing clam tests were significantly correlated to FPPA during the DJ task. These results provide support for the use of a weight-bearing strength test measured using a fixed dynamometer when assessing isometric hip strength in relation to FPPA during the DJ task.

During maximal isometric contractions, such as those used in isometric strength testing, muscle activation will be at its greatest (Coburn et al., 2005). Peak activation of the gluteus medius and gluteus maximus muscles has been shown to be between 69-79%, and 69-98% of maximal isometric voluntary contraction (MVIC) respectively during a single leg landing from a 30cm and 45cm box (Zazulak et al., 2005). In contrast, Carcia and Martin (2007) found that gluteus medius muscle activity during a drop jump task was 111% to 121% of MVIC. Although direct comparison cannot be made between these studies due to different methods of establishing MVIC – Carcia and Martin (2007) measured using standing hip abduction whereas Zazulak et al. (2005) measured MVIC in side-lying - this demonstrates that hip muscle activation may differ during dynamic tasks and in some cases may not be as high as during the isometric strength tests. This may help explain the lack of a significant relationship between hip muscle strength and FPPA during the SLL task in the current study, and provide further evidence for the relationship in the DJ task. This also highlights how hip muscle strength may be more important in some tasks such as the DJ, than others and therefore further exploration with respect to a wider range of tasks is warranted.

Hip external rotation strength was not correlated to FPPA during the SLL task, supporting previous findings (Beutler et al., 2009; Sigward et al., 2008). In contrast, women with greater hip external rotation strength have been shown to exhibit lower hip adduction and knee valgus moments during a SLL task (Lawrence et al., 2008). Whilst Lawrence et al. (2008) did not present correlations between the variables measured, the results implied that those with greater hip external rotation strength would demonstrate lower frontal plane loading at the knee. Although direct comparisons cannot be made between the current study and that of Lawrence et al's., significant correlations between FPPA and knee valgus moments presented in chapter three of this thesis, led to the expectation of a correlation between hip external rotation strength and FPPA. Participants in the Lawrence study dropped from 40cm as

opposed to the 28cm used in this study and the increased demand this is likely to place upon the hip musculature may have led to the association with frontal plane loading demonstrated.

Previous research has suggested that decreased ankle dorsi-flexion ROM and increased subtalar joint pronation can lead to increases in frontal plane knee motion during dynamic tasks (Hagins et al., 2007; Sigward et al., 2008) and the development of PFPS (Boling et al., 2009b; Witvrouw et al., 2000). ROM of both the gastrocnemius and soleus muscles was measured in the current study to ensure that the contribution of each to dorsi-flexion ROM was assessed. Additionally, dorsi-flexion ROM in a weight-bearing position was measured to attempt to make the test more specific to function of the joint during dynamic tasks. Navicular drop was used as it has been cited as the most valid and reliable measure of subtalar joint pronation (Cornwall & McPoil, 1999; Sell et al., 1994a; Williams & McClay, 2000). Despite these reported links, no correlations were evident between gastrocnemius ROM, soleus ROM or navicular drop and FPPA in either the DJ or SLL task.

Participants in the current study demonstrated a mean navicular drop of 7.8mm, which was similar to that of uninjured participants (8.1mm) and lower than those of ACL-injured participants (10.5mm) previously found (Allen & Glasoe, 2000). Boling et al. (2009b) found that individuals who later developed PFPS had a navicular drop of 8.1mm, compared to 7.2mm in those who did not. The clinical relevance of the 1mm difference between injured and uninjured participants in the Boling et al. study is questionable and likely to be within measurement error of the test. Allen and Glasoe utilised an electromechanical digitiser to measure navicular height, which measures the change of position of the navicular. It is unclear whether this has any bearing on the accuracy of the measurement as the examiner is required to place the probe directly below the navicular, therefore the measurement still relies on the experimenters ability to palpate the navicular in the same way as measurement of navicular drop in the current study. The lack of correlation between navicular drop and FPPA in this study may be due to the navicular drop values exhibited by the participants not being excessive. Further, the fact that participants wore footwear during the DJ and SLL tasks may have influenced the variability of the measurement. If participants wore trainers which aimed to control pronation, they may have exhibited less pronation than measured during the barefoot navicular drop test, which would have led to decreased pronation during the screening tasks and a subsequent lack of correlation.

A previous study by Sigward et al. (2008) found that ankle dorsi-flexion ROM explained 11% of the variance in 3D knee separation distance. In this study, dorsi-flexion was measured passively with the knee at 30° flexion and was found only to be 3.5° which is significantly different to values reported in other studies. Gastrocnemius and soleus ROM values in the current study were similar to those of uninjured participants and greater than individuals with PFPS noted previously (Piva et al., 2005). However, gastrocnemius ROM was at least 5° lower than participants who subsequently suffered PFPS measured in a similar weight-bearing stance as the current study (Witvrouw et al., 2000). Although Piva et al. (2005) measured ROM passively they attempted to control subtalar joint motion, as did the current study, and it is unclear whether this was the case in the Witvrouw et al. (2000) study. Therefore these results cannot be directly compared to either study. As was the case in the navicular drop test, it may be that participants did not demonstrate significantly reduced dorsi-flexion ROM to cause an increase in pronation or effect FPPA. The lack of correlations between FPPA and dorsi-flexion ROM and navicular drop may also be explained by the results of chapter three where small correlations were found between pronation and FPPA in the DJ task, and no relationship was evident in the SLL task.

Secondary analysis revealed that in the main there were no differences in the independent variables between high FPPA and normal limbs. The only exception being in the DJ task where high FPPA limbs exhibited greater hip abduction and external rotation strength than normal limbs, which was unexpected. Perhaps more surprising was the lack of difference between standing clam strength, particularly considering this was the strongest predictor of DJ FPPA. The overall lack of differences between high FPPA and normal limbs was not surprising in the cases of dorsi-flexion ROM and navicular drop due to the lack of correlation shown between these variables and FPPA in both the DJ and SLL tasks. Limb asymmetry is commonly cited in the literature as a possible risk factor for injury. However, these results suggest that despite differences between limbs in FPPA, similar differences between limbs in hip strength, ankle ROM or navicular drop were not evident, maybe due to the fact that these measures were unable to significantly predict the magnitude of FPPA in this study. Greater information may be gathered by conducting regression analyses on those individuals with high FPPA only. Regression analysis could not be performed for those with high FPPA only in the current study due to the small sample size (Tabachnick & Fidell, 2007).

Questions could be raised about the use of isometric muscle contraction to measure muscle strength capability in relation to dynamic tasks. Whilst this is potentially clinically useful, it is

not reflective of how the muscle works functionally and it may be that the dynamic nature of the muscle contraction requires a similar test of the muscles. Therefore the isometric strength value will not provide an accurate reflection of the muscles' contribution during dynamic tasks. This is supported by research which has shown that isokinetic assessment of muscle function is able to predict athletic performance more accurately than isometric assessment (Anderson et al., 1991). This may explain why concentric and eccentric hip abduction strength correlated to frontal plane knee motion but this is not always evident for isometric strength (Beutler et al., 2009; Claiborne et al., 2006; Jacobs & Mattacola, 2005; Sigward et al., 2008). Additionally, muscle activation levels can be affected by training status and gender (Chimera, Swanik, Swanik, & Straub, 2004; Zazulak et al., 2005). Therefore assessment of muscle strength during concentric and eccentric contractions may provide more useful information from a research perspective. However, this may not be useful in a clinical situation where measurement of dynamic muscle strength is not possible and the fact remains that PFPS patients exhibit significant isometric hip muscle strength weakness (Prins & van der Wurff, 2009). Additionally, measurement of rate of force development of the gluteal muscles during the isometric contractions would give a more accurate reflection of muscle function during the dynamic tasks. This may show a different relationship with FPPA in the DJ and SLL tasks and should be investigated in future research.

The limitations of regression analysis should also be considered in the current study. The sample size of this study was relatively small for stepwise regression analysis (Tabachnick & Fidell, 2007) and therefore the results should be interpreted with some caution. Although previous studies (Sigward et al., 2008) using stepwise regression analysis have been conducted with smaller numbers than those in the current study. Regression analysis also assumes that independent variables are measured without any error, this is clearly an impossible assumption to meet; therefore it is important to ensure that the independent variables used are reliable. This is underlined by the fact that outliers can have a large impact on the regression and it is recommended that they are either removed or rescored (Montgomery & Peck, 1992; Tabachnick & Fidell, 2007). Initial screening of data is therefore important when considering the use of regression analysis. No outliers were identified in the screening of data in the current study and therefore this is unlikely to have affected the outcomes.

5.6. Conclusion

FPPA during the DJ task was found to be partially attributed to standing clam strength, whereas ankle dorsi-flexion ROM and navicular drop were found not to significantly predict FPPA in this task. Therefore combined hip abduction/external rotation strength should be assessed in those individuals who exhibit high FPPA during the DJ task. Hip strength as measured in this study, dorsi-flexion ROM and navicular drop were unable to predict FPPA in the SLL task.

The overall lack of correlations between the measured variables and FPPA may be due to the range of FPPA scores in the subject sample and further study of subjects with high FPPA should be undertaken. Although when participants with high FPPA were extracted from the dataset and compared to those with normal FPPA values, no differences were found. However, regression analysis to further investigate this high valgus population could not be undertaken on this subset due to a small sample size. It is important to note that only 20% of the variance in the DJ task could be accounted for by the measures assessed in this study, suggesting that other factors such as learnt motor patterns or dynamic muscle strength may contribute to FPPA during screening tasks.

The results suggest that the standing clam test alone should be used to assess hip muscle strength in relation to the DJ task, as opposed to using both the hip abduction and external rotation strength tests separately. However, it may be more applicable to measure hip abduction or combined abduction/external rotation (clam) strength in a side-lying position in relation to unilateral tasks.

Chapter 6

The Use of Feedback to Modify Movement Patterns during Common Screening Tasks

6.1. Aim

The aim of this chapter is to assess the effect of video and verbal feedback on reducing FPPA during the DJ and SLL tasks.

6.2. Introduction

Knowledge of optimal technique is important for reducing injury risk. As discussed earlier in chapter two, section 2.5.3 of the literature review, feedback is a fundamental tool for learning and performing of motor skills and has been shown to improve landing strategies across a number of studies. The use of simple verbal feedback decreases GRFs and knee valgus angles and moments during landing tasks (Cowling et al., 2003; McNair et al., 2000; Mizner et al., 2008; Prapavessis & McNair, 1999). Furthermore, the use of video to supplement verbal instructions given to participants can decrease GRF and improve frontal and sagittal plane landing mechanics during both simple and more complex sporting movements (Cronin et al., 2008; Herman et al., 2009; Onate et al., 2005; Onate et al., 2001). A combination of analysis of self and analysis of an expert has been shown to be the most effective type of video feedback for reducing GRF and increasing knee flexion displacement during vertical jump landing (Onate et al., 2005). These improvements were also retained one week later, suggesting motor patterns may have changed and the improvements would endure, therefore decreasing injury risk in the long-term (Onate et al., 2005).

Herman et al. (2009) found that augmented feedback, based on the Onate (2005) expert and self-combination protocol, resulted in decreased GRFs and increased knee flexion and hip abduction angles. However, no changes were noted in other variables relating to dynamic knee valgus, such as hip internal rotation, knee valgus or tibial rotation angles. No other studies based on Onate et al.'s (2005) protocol have evaluated such measures. In addition, the Onate protocol is based on criteria which have been theorised to reduce injury risk. Greater improvements may be seen using feedback criteria based on identification of high-risk movement patterns such as the Landing Error Scoring System (LESS) (Padua et al., 2009).

The LESS is a movement assessment tool which takes into account frontal and sagittal plane motion of the trunk, hip, knee and ankle (Padua et al., 2009). Higher scores on the LESS,

which indicates poor movement patterns, correlate to 3D movement patterns which potentially increase injury risk (Padua et al., 2009). For example, those with high (poor) LESS scores demonstrate increased hip adduction and knee valgus angles and moments. Therefore, the use of a scoring system such as the LESS as a basis for feedback is likely to improve FPPA scores during landing tasks.

In chapter three of this thesis, it was shown that FPPA correlates with hip adduction, hip internal rotation, knee valgus, tibial external rotation and foot pronation during the DJ and SLL tasks. This indicates that individuals who exhibit high FPPA also demonstrate movement patterns which place increased stress on the ACL and PFJ, increasing risk of injury. Therefore, this study aims to combine the expert and self-combination feedback protocol used by Onate (2005) with the LESS to determine whether this will reduce FPPA during the DJ and SLL tasks.

6.3. Methods

Participants

Two groups were recruited for this study, an intervention (feedback) group and a control (no feedback) group. Firstly an intervention group of twenty recreationally active participants, eight men (age 24.3 ± 4.7 years, height 178.1 ± 6.8cm, weight 81.1 ± 7.7kg) and twelve women (age 22.6 ± 3.8 years, height 166.9 ± 6.3cm, weight 67.2 ± 10.9kg), all of whom were university students, volunteered for the study.

Secondly, a control group consisting of eight recreationally active participants, four men (age 23.0 ± 4.2 years, height 181.3 ± 7.19cm, weight 76.5 ± 12.4kg) and four women (age 20.0 ± 4.0 years, height 164.9 ± 2.7cm, weight 57.8 ± 9.2kg) all of whom were university students, volunteered for the study.

The same entry criteria, approval and consent procedures were used as previously outlined in chapter three (section 3.3).

Protocol

Prior to testing, markers were placed on the lower extremity of each participant as described chapter three (section 3.3) for assessment of 2D FPPA.

The DJ and SLL tasks were undertaken as described in chapter three (section 3.3).

Feedback Group protocol

Participants completed the DJ and SLL tasks in a random order to minimise any potential cross-over effects. Each participant first completed baseline testing, during which they performed three test trials of the selected task. Participants then undertook the feedback session, followed by post-feedback testing, which included a further three test trials. This process was then repeated for the second task. Both legs were tested and analysed during the DJ task, whereas one leg was randomly chosen and tested for the SLL task.

After completion of baseline testing participants underwent a video-assisted summary feedback programme based on the 'expert plus self' combination used by Onate et al. (2005). The expert model was trained in proper landing technique by the principal investigator; This landing was based on the criteria for the highest possible score on the LESS (Padua et al., 2009). This included the model demonstrating:

- at initial contact: trunk and hip flexion, a minimum of 30° knee flexion, no evidence of knee valgus or sideways trunk lean, both feet simultaneously contacting with toes first;
- after initial contact: further trunk and hip flexion, a minimum of a further 45° knee flexion, no evidence of knee valgus, feet shoulder width apart with no more than 30° rotation and overall impression of a soft landing.

Participants first viewed two trials of the expert video, followed by their own three trials. In each case the sagittal plane video was viewed first. Each trial was viewed twice, first at normal speed and second in slow motion, controlled by the principal investigator. To help review the technique on display in each trial, participants were required to complete a checklist. The checklist was based on the best possible score on the LESS and expert technique to provide a focus on technique parameters that would bring a performance improvement (appendix 1). The principal investigator explained the criteria and reviewed the video with the participant to ensure their understanding. This included identification of errors in their performance and how each could be improved. Where participants already performed a specific criterion correctly they were instructed to maintain this technique, for example if

there was no evidence of knee valgus they were instructed to maintain this rather than to land with further knee varus.

Each feedback session lasted five minutes on average. Immediately following the feedback session participants performed a further three trials of the landing task. No further feedback was given to participants whilst they were completing the landing tasks.

Control Group Protocol

Participants completed the DJ and SLL tasks in a random order to minimise any potential cross-over effects. Each participant first completed baseline testing, during which they performed three test trials of the selected task. Participants then sat quietly for five minutes, followed by repeat testing, which included a further three test trials. This process was then repeated for the second task. A five minute rest period was included as this reflected the average time it took to give feedback in the intervention group. During the five minute rest period participants were given no feedback on their performance and were unable to view or communicate with any other participants undertaking the study. As with the feedback group both legs were tested and analysed during the DJ task, whereas one leg was randomly chosen and tested for the SLL task.

Frontal Plane Projection Angle (FPPA)

FPPA of the knee was measured as previously described in chapter three (section 3.3).

Camera and force plate setup and data analysis

Three tripod mounted digital video cameras (Casio EX-F1) set in standard mode and sampling at 30Hz, recorded frontal and sagittal plane views of each landing tasks. Each camera was mounted at a height of 50cm, three metres away from the centre of the force plate. Cameras were levelled using the built-in level on each tripod. The 3-4-5 rule was used to ensure that the camera was placed perpendicular to the plane of motion to reduce the likelihood of perspective or parallax error. Each camera was linked via USB-2 cable to one of three laptops (Toshiba Satellite Pro A200). Each video was automatically captured and saved on the computer's hard drive using EX-F1 controller (Casio version 1.0.0.1) software. This allowed immediate playback of the trials during the feedback protocol. One force platform (AMTI BP600900, USA) embedded into the floor sampling at 1200Hz, collected ground reaction force data using the Qualysis Track Manager software (version 1.10.282). Force plate data was filtered using a Butterworth 4th order bi-directional low-pass filter at 25Hz using

Visual3D software (Version 4.21, C-Motion Inc., Rockville, MD, USA). The cut-off frequencies selected were based on work by Yu et al. (1999). Peak vertical ground reaction force data, defined as the maximum value during the initial landing phase of the jump, were normalized to the participants' bodyweight (BW).

Secondary analysis included the assessment of contact time and jump height during the DJ task. Contact time during the initial landing phase was calculated to assess whether changes in technique resulted in a change in contact time. The point of initial contact of the first landing, take-off and initial contact of the second landing during the drop were determined manually within the Qualysis Track Manager software. Contact time during the initial landing was calculated by subtracting the time of initial contact of the first jump from the time of take-off.

Jump height was calculated in order to assess the potential effect of technique changes on performance during the DJ task. Jump height was calculated using the flight time method (Moir, 2008). This was calculated using the following equation:

$$\text{Jump height (m)} = 1/2g \, (t/2)^2$$

Where $g = 9.81 m/s^2$, t = time in air

Time in the air was calculated by subtracting the time of take-off from the time of initial contact of the second landing.

Statistical Analysis

All statistical analysis was conducted using SPSS for Windows version 16.0 (SPSS Inc., Chicago, IL). Means and standard deviations for all measured variables were presented. Data was assessed for normality used a Kolmogorov-Smirnov test and was found to be normally distributed.

<u>Drop Jump</u>

Paired t-tests were carried out to determine whether changes in dependent variables occurred from baseline to post-feedback/repeat test. Alpha level was set a-priori as $p=0.05$, corrected p-value was set at $p=0.013$ to minimise the likelihood of a type 1 error occurring. This p-value was determined as four t-tests (FPPA, GRF, contact time and jump height) were being carried out per group (feedback and control) and these two groups were unrelated.

Paired t-tests were carried out to determine whether changes in dependent variables occurred from pre-feedback to post-feedback. Corrected p-value was set at p=0.025, this was adjusted from p<0.05 to minimise the likelihood of a type 1 error occurring. This p-value was determined as two t-tests were being carried out per group and these groups were unrelated.

Effect sizes were determined using the Cohen δ method (Thomas et al., 2005), which defines 0.2, 0.5 and 0.8 as small, medium and large respectively.

6.4. Results

Drop Jump

Baseline and post-feedback/ repeat test means and standard deviation values for FPPA, vGRF, contact time and jump height for DJ are presented in table 6.1. After feedback there was a significant decrease in FPPA and jump height, and a significant increase in contact time. FPPA reduced by 23.9º, jump height by 0.03 metres and contact time increased by 0.13 seconds. Effect sizes for the change in FPPA and contact time were large, whilst effect size for change in jump height was small. No changes were seen in the control group from pre to post feedback in any of the measured variables.

Table 6.1 - Frontal plane projection angle (FPPA), ground reaction force (GRF), contact time and jump height means and standard deviations (SD) for baseline and post feedback/repeat test in the feedback and control groups for the drop jump (DJ) task.

Feedback	Baseline	Post-feedback	*P* Value	Effect size
FPPA (º)	4.0 ± 10.7	-19.9 ± 18.9	<0.001*	1.04
GRF (%BW)	2.73 ± 0.35	2.55 ± 0.34	0.033	0.52
Contact Time (s)	0.50 ± 0.11	0.63 ± 0.12	<0.001*	1.13
Jump Height (m)	0.27 ± 0.08	0.24 ± 0.07	<0.001*	0.39
Control	Baseline	Repeat test	*P* Value	Effect size
FPPA (º)	7.5 ± 8.3	6.6 ± 9.6	0.433	0.10
GRF (%BW)	2.44 ± 0.39	2.42 ± 0.53	0.783	0.04
Contact Time (s)	0.45 ± 0.06	0.45 ± 0.06	0.935	0
Jump Height (m)	0.25 ± 0.07	0.25 ± 0.06	1.000	0

*denotes significance at p<0.013

<u>Single Leg Landing</u>

Baseline and post- feedback/repeat test means and standard deviation values for FPPA and vGRF for the SLL are presented in table 6.2. In the intervention group, post feedback FPPA reduced by 5.2º compared to baseline in the SLL task. Post feedback GRF significantly reduced by 0.25BW compared to baseline feedback. No changes were seen in the control group from baseline to repeat test in any of the measured variables.

Table 6.2 - Frontal plane projection angle (FPPA) and ground reaction force (GRF) means and standard deviations (SD) for baseline and post feedback/repeat test in the feedback and control groups and the single leg landing (SLL) task.

Feedback	Baseline	Post-feedback	*P* Value	Effect size
FPPA (º)	8.7 ± 7.4	3.5 ± 8.1	0.023*	0.67
GRF (%BW)	3.02 ± 0.39	2.77 ± 0.39	0.025*	0.64
Control	Baseline	Repeat test	*P* Value	Effect size
FPPA (º)	8.2 ± 4.2	7.6 ± 4.4	0.591	0.14
GRF (%BW)	2.51 ± 0.38	2.49 ± 0.44	0.702	0.05

*denotes significance at p≤0.025

Figures 6.1 and 6.2 show the change in FPPA from baseline to post feedback in participants in the intervention group who demonstrated FPPA higher than the normal range quoted by Herrington and Munro (2010). Men and women who exhibited FPPA of greater than 8º and 13º respectively in the DJ and 9º and 12º respectively in the SLL task were included in these figures. The figures clearly show that in all cases where participants exhibited high FPPA, this was reduced as result of the feedback protocol. The magnitude of these changes differed between individuals and between tasks.
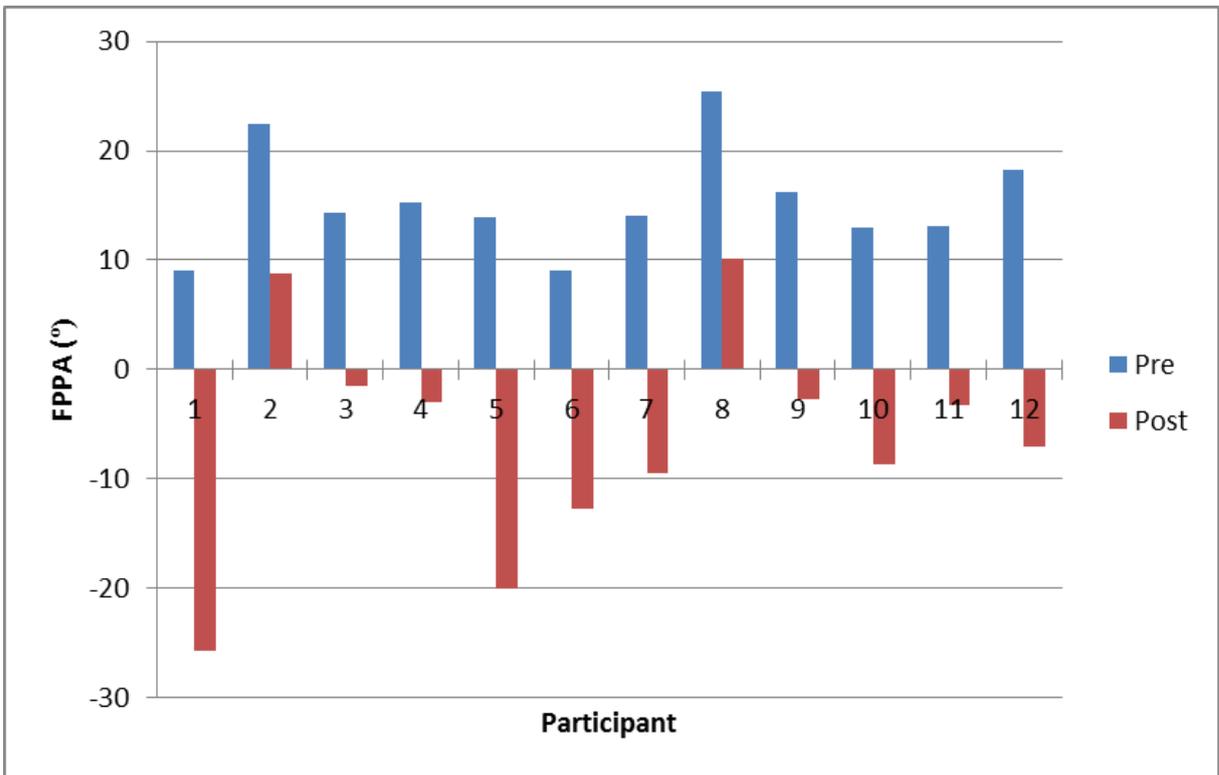
Figure 6.1 - Change in FPPA from baseline to post feedback in intervention group partcipantswho exceeded normative values in the drop jump task.

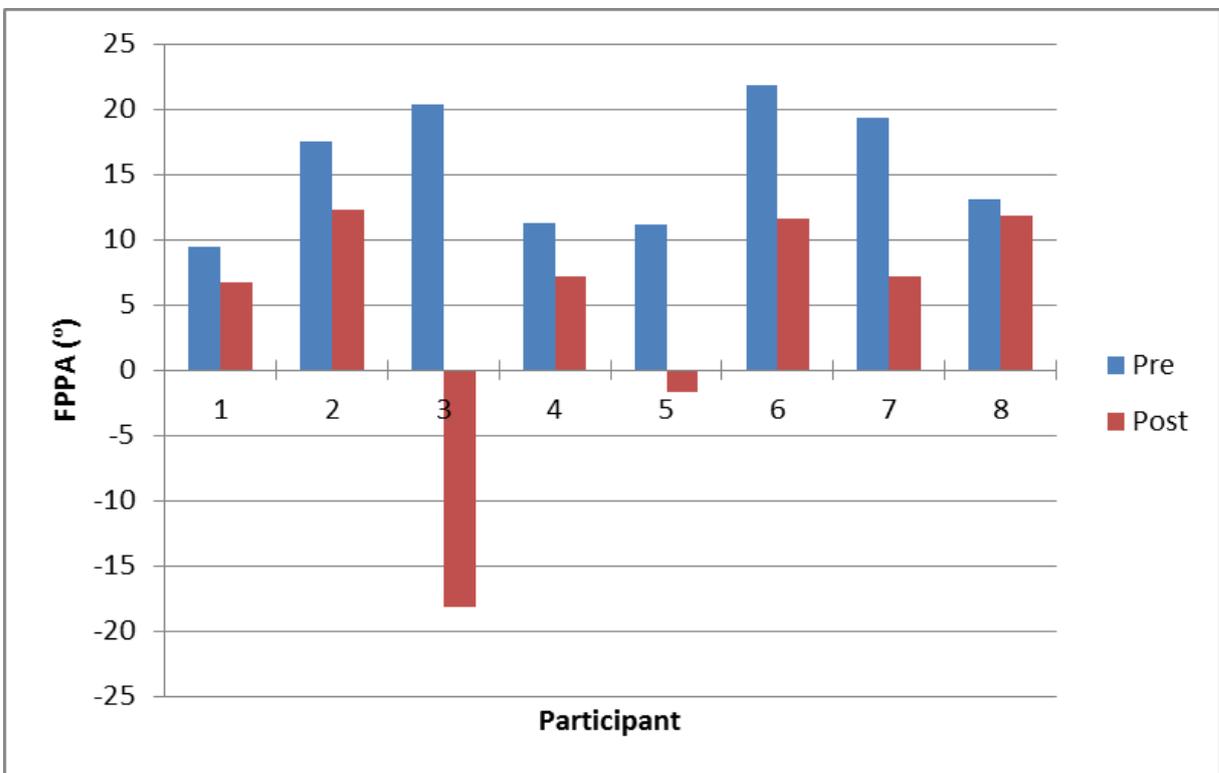*Figure 6.2 - Change in FPPA from baseline to post feedback in intervention group partcipantswho exceeded normative values in the single leg landing task*.

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6.5. Discussion

It was expected that augmented feedback would produce significant short-term changes in lower limb alignment and GRF experienced during the DJ and SLL landing tasks. Overall, feedback resulted in softer landing and decreased FPPA of the knee in both tasks, which could help to decrease the risk of injury to the ACL and PFJ.

Dynamic knee valgus during landing tasks has been linked to ACL and PFJ injury (Hewett et al., 2005; Myer et al., 2010) and therefore reduction in these movements has the potential to decrease risk of injury. Previous studies have shown that feedback can reduce frontal plane 3D hip and knee motion during DJ and stop-jump tasks (Herman et al., 2009; Mizner et al., 2008) which in turn would lead to a decrease in dynamic knee valgus. It was not known prior to this study whether feedback would lead to changes in FPPA during the DJ or SLL tasks. The results show that a self and expert combination feedback protocol leads to a significant decrease in 2D FPPA during the DJ and SLL tasks. As FPPA is a combination of frontal and transverse plane hip and knee kinematics these results are in line with those of previous studies. Additionally, no changes in FPPA were seen in the control group between baseline and repeat tests, which further increases the validity of the changes seen in the feedback groups. This also suggests that the significant reductions in FPPA in the feedback group were not due to fatigue or learning effects, but could be clearly attributed to a change in technique as a result of the feedback protocol.

In the DJ task, FPPA reduced by 23.9º from baseline to post feedback in the intervention group, which was approximately 15º greater than the SDD reported in chapter three. Furthermore, figure 6.1 shows that all changes from baseline to post-feedback in individuals with high FPPA, who the intervention would specifically target, exceeded the 9-9.8º SDD value previously determined in chapter three. These results, accompanied by the lack of change in control group FPPA show that the changes were due to a true change in performance and not that of measurement error between tests. Interestingly, the simple feedback protocol demonstrated in this study led to greater reduction in FPPA during the DJ task than has been observed after a four-week jump training programme (Herrington, 2010). This demonstrates the potential for immediate feedback to bring about greater changes in dynamic knee valgus than training (Herrington, 2010). Additionally, the feedback protocol can be completed in a shorter time than a single training session. Training programmes which aim to change lower limb biomechanics are commonplace in the literature but are often time-consuming for athletes (Chappell & Limpisvasti, 2008; Grandstrand et al., 2006; Hewett et

al., 1999; Pfeiffer et al., 2006). The expert plus self feedback protocol used in the current study took approximately 15 minutes to complete. Additionally, the changes in GRF and knee flexion displacement brought about using this protocol have been shown to be retained one week later (Onate et al., 2005), although it remains to be seen whether the changes are retained over a longer period. If this is the case, feedback may be a quicker and simpler tool for bringing about those changes which decrease ACL and PFJ injury risk. Furthermore, the use of feedback to achieve short-term improvements prior to a training intervention being undertaken may lead to even greater improvements than either method in isolation.

The decrease of 5.2º in the SLL task was within the SDD reported in chapter three, although it was outside of SEM. When considered in conjunction with the lack of change in control group FPPA, the results indicate that this change was outside of measurement error, but could not be considered to be a truly significant change. It may be that the feedback protocol used, which was modified from a validated scoring system used with the bilateral DJ task, was insufficient to bring about changes in a unilateral task with higher load demands, and that further interventions would be required to bring about a significant change. Figure 6.2 shows that the change in FPPA from pre to post feedback exceeded the SDD value for the SLL task in half of the high FPPA participants. This helps explain why the mean change for all participants did not exceed SDD for the SLL task and demonstrates that changes in FPPA in this unilateral task may require more than simple feedback in some cases.

A reduction in peak vGRF reduces the force experienced and subsequently lessens the demands on the active and passive restraints of the knee leading to a potential decreased injury risk. The findings of the current study do not support those of previous studies, where augmented feedback resulted in decreased vGRF (Cronin et al., 2008; Herman et al., 2009; Mizner et al., 2008; Onate et al., 2005; Onate et al., 2001; Prapavessis & McNair, 1999). The reduction in peak vGRF of 0.18BW (6.6%) for the DJ was not significant, and is lower than reductions noted in previous studies (Herman et al., 2009; Mizner et al., 2008; Onate et al., 2005; Onate et al., 2001; Prapavessis & McNair, 1999). Mizner et al. (2008) noted a decrease in GRF of 0.67BW (20%) in the same DJ task from a similar height. The differences may be attributed to the different populations tested, Mizner and colleagues (2008) tested collegiate women athletes, whereas the current study used both men and women recreational athletes. The GRF's exhibited by recreational athletes in this study pre-feedback (2.73BW) were already much lower than observed in the collegiate women athletes pre-feedback (3.35BW) and close to those observed post-feedback (2.68BW). It could be argued that collegiate

athletes are more receptive to feedback and were able to make greater changes than recreational athletes. It may also be that the verbal and auditory feedback used in the Mizner study, where athletes were instructed to land as softly as they could and make the sound of their landing 'as quiet as possible' had a greater impact on GRF than the combination feedback used in the current study. However, McNair et al. (2000) noted that no significant differences in GRF reduction were seen between auditory and technical instruction in a bilateral drop landing task.

It could be argued that the vGRF would not significantly decrease following the feedback protocol because whilst the hip and knee are being asked to absorb more force in the sagittal plane by increasing flexion excursion, they are also being asked to resist more force in the frontal plane by reducing hip adduction and knee valgus excursion. Therefore, whilst in one plane the hip and knee are becoming more compliant, they are also becoming stiffer in another plane. Whilst a small decrease in vGRF may be seen as the increase in hip and knee flexion is likely to be greater than the reduction in frontal plane hip and knee excursion, this may not lead to significant changes overall.

The small decrease in vGRF in this study could also be explained by changes in attentional focus resulting from feedback (Wulf & Dufek, 2009). Internal focus, where participants focus on their own body movement, can result in a decreased vertical jump height (Wulf & Dufek, 2009). It is possible that post-feedback, participants focus became more internal than during baseline testing, whereby their focus was on their joint movement, which is underlined by the decreased vertical jump height and therefore only small decrease in vGRF.

Despite the lack of change in vGRF in the DJ task, it was noted that there was a significant increase in contact time during the initial landing. This increase in contact time would lead to a decrease in the rate of loading experienced by the hip, knee and ankle joints during the initial landing, therefore decreasing injury risk. The increased contact time may also explain the significant decrease in jump height seen from pre to post feedback. During a plyometric exercise such as the DJ, when contact time is increased, the reactivity of the individual decreases. If the eccentric phase of the activity is lengthened, as suggested by the increased contact time and emphasis on increasing hip and knee flexion in the feedback protocol, this will reduce the amount of muscle recruitment for the concentric phase and therefore reduce jump height. This is also likely to lead to an increased amortisation phase, i.e. the transition between the eccentric and concentric phases of the jump, which leads to a decrease in power

production from the working muscles, leading to a decrease in jump height. Therefore, whilst injury risk may be reduced by an increase in contact time, performance may suffer as a result. In contrast, Mizner et al. (2008) found that jump height did not change post-feedback, despite a reduction in vGRF and increase in contact time. Therefore it is unclear whether these changes would results in a decrease in performance.

No study has assessed the effect of feedback on landing forces during a single leg task. The results of the current study demonstrated a significant decrease in GRF during the SLL task of 0.25BW (8.3%) post feedback. Whilst again this is a small percentage change, the associated effect sizes were greater than demonstrated in the DJ task. This decrease may be more important than that noted during the bilateral DJ task as the force in this case is experienced within only one limb. Therefore the clinical significance of this finding may be more important than noted for the DJ task. Furthermore, it was interesting to note that GRF was higher in the SLL task compared to the DJ task. This may in part provide some explanation for the increased likelihood of injury during unilateral landings, as demonstrated by Faude et al. (2005).

The augmented feedback model used in the current study was based on the expert plus self combination used by Onate et al. (Onate et al., 2005) which combines verbal and visual feedback. This model allows participants to compare their own performance against that of an expert and has been shown to result in decreased vGRF and knee valgus moments, increased hip abduction and flexion angles and increased knee flexion angles (Herman et al., 2009; Onate et al., 2005). Verbal feedback alone has been shown to decrease vGRF and increase knee flexion angles although it unclear whether changes in frontal plane knee angles can be achieved consistently (Milner, Fairbrother, Srivatsan, & Zhang, 2012; Mizner et al., 2008). Rucci and Tomporowski (2010) found that a combination of video and verbal produced no greater effect on power clean performance than verbal feedback alone. Furthermore, verbal feedback alone produced greater changes in performance than video only, suggesting that the verbal feedback was the key component leading to changes in performance. However, the video and verbal feedback protocol in the Rucci and Tomporowski (2010) study involved only video of the participant's performance, which has previously been shown to be less effective than a combination of the self and expert model (Onate et al., 2005). It may be that the most important aspect of the verbal and video feedback protocol, and that which would result in the greatest improvement in performance, is of expert modelling combined with the verbal cues.

Figures 6.3 and 6.4 provide examples of the changes seen from pre to post-feedback in the DJ and SLL tasks respectively. In figure 6.3 increases in hip, knee and trunk flexion are evident, leading to greater dissipation of forces through these joints accompanied by an increase in stance width. Further, decreases in dynamic knee valgus can be seen, in particular decreases in hip adduction and knee valgus. Each of these changes reduces the risk of injury to the ACL and PFJ.
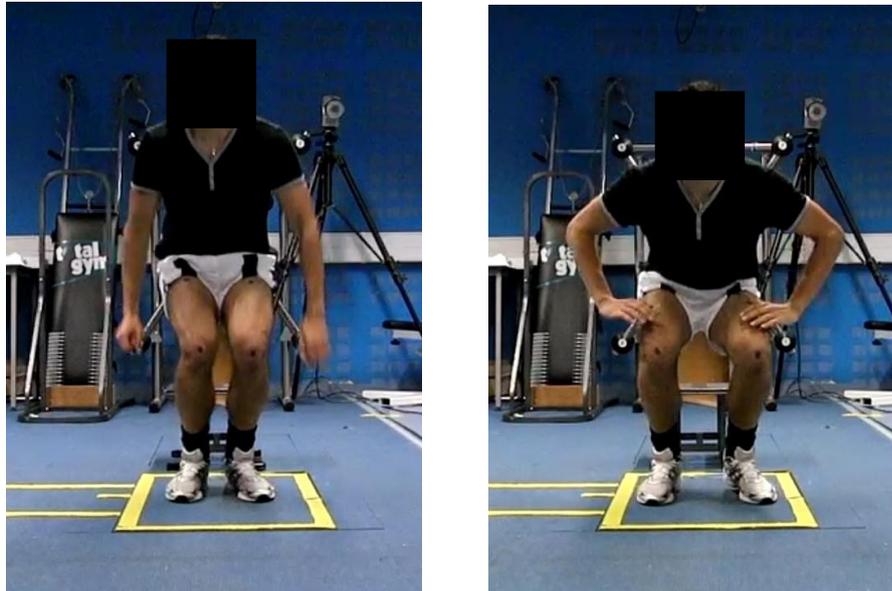
Figure 6.3 – Example photograph of changes in drop jump technique from pre to post feedback (participant 10 from figure 6.1).

In figure 6.4 a decrease in FPPA can be seen with an increase in hip, knee and/or trunk flexion, although the participant still exhibits a sideways trunk lean.
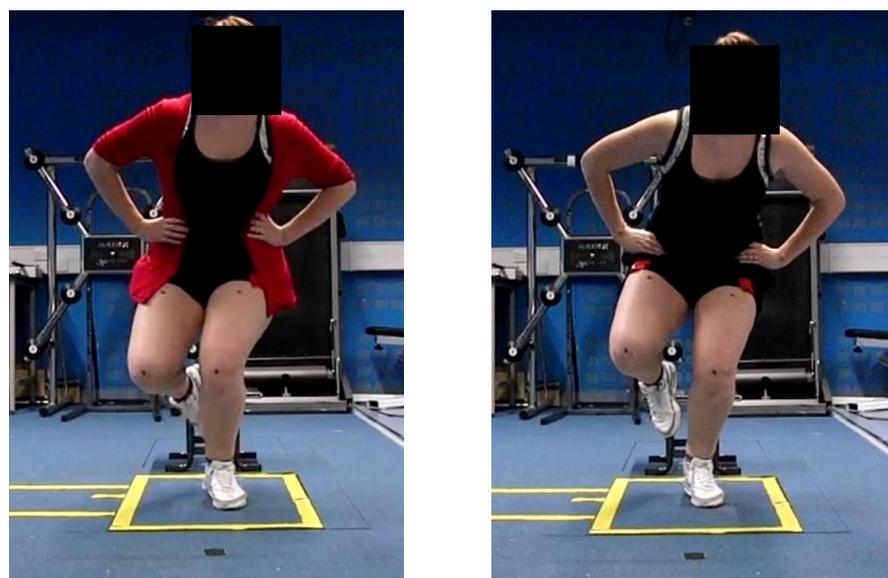
Figure 6.4 – Example photograph of changes in single leg landing technique from pre to post feedback (participant 2 from figure 6.2).

The findings of this study may be limited to the specific population of recreational athletes involved and may not translate to other populations such as elite athletes. It is unclear whether the immediate changes in performance observed would be retained for a longer period of time and further work is needed in this area. Furthermore, whether the beneficial changes seen in the current study would translate to an improvement in dynamic knee valgus during cutting tasks is also unclear and again further research into the transfer of learning across different motor skills is warranted.

6.6. Conclusion

The results of this study suggest that augmented feedback, through the use of a combination of self and expert video and verbal feedback, is able to reduce dynamic knee valgus, measured via 2D FPPA, in both the DJ and SLL tasks. In all cases, individuals who exhibited high FPPA in the DJ task had a significant reduction in FPPA post-feedback, which was greater than measurement error previously established. In the SLL task, fifty percent of individuals who exhibited high FPPA had a reduction which was above SDD values after feedback. This suggests that the feedback protocol in this study did not bring about a truly significant change in all participants and other factors should be considered in those who fail to demonstrate a significant change.

The amount of force experienced at the knee was reduced in both the DJ and SLL tasks, as demonstrated by a significant reduction in vGRF in the SLL task and an increase in contact time during the DJ task. Each of these changes will help to reduce risk of ACL and PFJ injuries. The decrease in jump height seen in this study suggest that the reduction in injury risk may be at the cost of performance, although other studies have shown that performance does not change despite decreases in injury risk related variables, therefore further study is warranted.

Further investigation into the retention and transfer of these improvements is needed to support the use of feedback as a tool for decreasing injury risk prior to, or as part of, the implementation of more time consuming training programmes.

Chapter 7

Prospective Assessment of Anterior Cruciate Ligament Injury Risk in a Women's Football Player

7.1. Aim

The aim of this study was to prospectively examine the potential of 2D FPPA, hop for distance tests, and the SEBT to predict non-contact ACL injury occurrence.

7.2. Introduction

The majority of ACL injuries occur during a non-contact situation, typically during decelerating movements such as landing and cutting (Boden et al., 2000; Boden et al., 2009; Krosshaug et al., 2007a). Further, women are twice as likely to suffer a non-contact ACL injury than men (Agel et al., 2005; Arendt et al., 1999; Deitch et al., 2006). Typical non-contact ACL injury incidence rates in women's football and basketball range from 0.13-0.22 per 1000 exposures (Agel et al., 2005; Hewett et al., 1999). Women exhibit abnormal or poor NMC, often characterised by the presence of dynamic knee valgus, during landing and cutting manoeuvres (Herrington & Munro, 2010; Kernozek et al., 2005; Zeller et al., 2003). It has been postulated that this contributes to greater incidence of ACL injury when compared to men. Tests which examine NMC may therefore be useful in identifying those considered at high-risk of suffering an ACL injury.

In chapter three it was identified that 2D FPPA significantly correlates to 3D measures of frontal and transverse plane hip, knee and ankle motion during the DJ, SLL and SLS screening tasks. These findings supported earlier work in which similar results were noted for the SLS, side-step and side-jump tasks (McLean et al., 2005b; Willson & Davis, 2008b) and demonstrated the validity of 2D FPPA for assessing dynamic knee valgus. Increases in frontal and transverse motion at the hip, knee and ankle contribute to dynamic knee valgus which has been linked to increased ACL load and injury risk (Hewett et al., 2005; Markolf et al., 1995). It was concluded that whilst 2D FPPA is not suitable for quantification of subtle 3D joint motions it may provide clinicians with a useful tool for identifying those who demonstrate dynamic knee valgus and may therefore be at increased risk of ACL injury. Therefore, further

investigation of the use of 2D FPPA for ACL injury prediction by way of a prospective study was warranted.

In addition to 2D FPPA, the hop for distance tests and SEBT have been discussed. The SEBT has previously been shown to predict overall lower limb injury (Plisky et al., 2006) and detect functional deficits in those who have experienced an ACL injury (Herrington et al., 2009). This suggests that the SEBT may have the potential to predict ACL injury occurrence, although this has not previously been studied. The hop for distance tests are also able to detect differences between ACL reconstructed (ACL-R), ACL-D and uninjured limbs (Barber et al., 1990; Goh & Boyle, 1997; Krosshaug et al., 2007a; Noyes et al., 1991; Petschnig et al., 1998). As a result, there may also be potential for functional deficits between limbs on the hop test to predict future ACL injury risk.

In order for the potential of 2D FPPA, the SEBT and the hop for distance tests to predict future ACL injury risk to be established, a prospective study which investigates these parameters in a high-risk population is needed. If these tests are able to detect deficits in neuromuscular control which then link to ACL injury, screening of athletes to identify those who demonstrate high risk movement strategies could be undertaken more easily. Additionally, this would allow for the development of more targeted intervention strategies to reduce injury risk.

The aim of this chapter was therefore to prospectively examine the potential of 2D FPPA, hop for distance tests, and the SEBT to predict non-contact ACL injury occurrence. To achieve this aim a prospective study over a nine month competitive season of elite women's football and basketball players was undertaken.

7.3. Method
Participants
All 24 clubs from the English FA Women's Premier League National and Northern divisions and all eight clubs from the English Women's Basketball Division One received an invitation to participate in the study. Invitations were sent via e-mail to the secretary and/or coaches of each national league team requesting if their players would participate in pre-season testing; those who responded were eligible for inclusion in the study. Follow-up e-mails were sent on two further occasions to those who did not reply. Teams were recruited in May 2009 for testing between June and September 2009. Previous studies have reported an average

annual/seasonal number of non-contact ACL injuries among women's football and basketball players of 1.98% (Gilchrist et al., 2008; Heidt et al., 2000; Hewett et al., 1999; Hewett et al., 2005; Mandelbaum et al., 2005; Soderman et al., 2000). Therefore to gain a sample of twenty non-contact ACL injuries, with a power of 0.8, alpha of 0.05 and beta of 0.2, 1000 participants would be required (Faul et al., 2007).

All participants were involved in the sports on a part-time basis and undertook training and competition a minimum of three times per week. Participants were required to be free from lower extremity injury for at least six months prior to testing, and have no history of lower extremity surgery or ACL injury. Injury was defined as any musculoskeletal complaint which stopped the participant from undertaking their normal exercise routine. Prior to testing participants were required to self-report if they did not meet any of the following criteria. The study was approved by the University Research and Ethics Committee and all participants gave written informed consent prior to participation.

All testing was undertaken by three trained researchers at the club's own training facility. The researchers were each responsible for one test, therefore improving reliability between tests. Participants were tested during their pre-season programme and subsequently tracked for ACL injury during the following nine-month competitive season. The testing consisted of: height, weight and leg length measures; 2D analysis of FPPA during the DJ, SLL and SLS; hop for distance tests and the SEBT.

Protocol

Subjects' height and weight were recorded using a combined digital scales and stadiometer (Seca Delta, Seca UK). Leg length was measured from the anterior superior iliac spine to the distal tip of the medial malleolus using a standard tape measure while participants lay supine. Leg length was used to normalise SEBT excursion distances by dividing the distance reached by leg length then multiplying by 100 (Gribble & Hertel, 2003). Participants completed each of the screening tasks and the order was randomised to account for effects of fatigue.

<u>2D analysis</u>

Camera setup

A commercially available digital video camera (Sony Handycam DCR-HC37) sampling at 25Hz was mounted on a tripod at a height of 50cm, three metres anterior to the participants landing target. The camera recorded frontal plane video footage. The 3-4-5 rule was used to

ensure that the camera was placed perpendicular to the plane of motion to reduce the likelihood of perspective or parallax error. The digital video footage was later downloaded onto a desktop PC for analysis.

The same procedure for placement of markers to measure FPPA was used as previously described in chapter three (page 89). Participants were allowed practice trials prior to each test until they felt comfortable, this was typically two to three trials. After familiarisation each participant performed three trials of each task. The sequence of tasks and limb were randomised. Both limbs were tested and analysed for all tests.

Screening tasks

The DJ, SLL and SLS tasks were undertaken as described in chapter three (section 3.3).

Frontal Plane Projection Angle (FPPA)

Measurement of FPPA was undertaken using the same method as previously described in chapter three (section 3.3).

Hop tests

The single hop for distance, triple hop for distance, six-metre timed hop and crossover hop for distance tests were undertaken as described previously in chapter four (section 4.3.3). In light of the results of chapter four the number of practice trials allowed were as follows; for the single and triple hop for distance tests participants were allowed three practice trials, for the crossover and timed hop four practice trials were given.

Star excursion balance test (SEBT)

The SEBT was undertaken as previously described in chapter four (section 4.4.3).

In accordance with the findings in chapter four, each participant performed four practice trials, followed by three measured trials in each direction with one leg before switching to the other leg. Reach direction and stance leg order were randomised. One minute recovery was allowed between each reach direction.

Athlete tracking and injury reporting

Weekly e-mails were sent throughout the season to coaches of each team to check whether any ACL injuries had occurred. In any case where a coach reported an ACL injury, an injury report form was forwarded for completion by the athlete, with clarification of any questions

provided by the principal investigator. Separate injury report forms were designed for basketball (appendix 2) and football (appendix 3) due to the different nature of contact and time periods used between the sports. These forms were based upon those used in the NCAA Injury Surveillance System (Dick, Agel, & Marshall, 2007) and by Finch, Valuri and Ozanne-Smith (1999).

Only one participant suffered an ACL injury during the study period, therefore statistical analysis to identify which factors might be linked with injury was not possible. Information from the completed injury report form (appendix 4) indicated that the ACL injury mechanism was non-contact and occurred during landing. Consequently, a case study will now be presented for this athlete.

7.4. Results

Three football and three basketball teams responded to the initial invitation. The final sample consisted of 84 players, 48 women's football players and 36 women's basketball players. Participant demographics are presented in table 7.1.

Table 7.1 – Participant demographics.

Sport	Age (years)	Height (cm)	Weight (kg)
Football	20.2 ± 3.2	161.6 ± 6.9	60.5 ± 9.0
Basketball	21.9 ± 3.6	171.0 ± 6.3	69.1 ± 11.0

7.4.1 Case Study Results

The injured participant was a 20 year old women's football player. The injury was sustained in a non-contact situation, the player reporting that her left knee gave way when she landed after jumping to head the ball. The ACL injury to her left knee was later confirmed by MRI. Her completed injury report form can be found in appendix three. The results of the injured player's pre-season testing are presented in table 7.2, alongside mean values for football and basketball players in this study. Football and basketball players were considered separately as a previous study conducted found differences in 2D FPPA between the sports (Munro, Herrington, & Comfort, 2012).

The left limb of the injured athlete did not demonstrate any significant deficits when compared to the right, as demonstrated with all LSI scores being above 95%. Interestingly, the

right, uninjured limb exhibited detrimental NMC characteristics in comparison to the left, injured limb across most variables. This was particularly evident in the DJ, SLS and crossover hop for distance tasks. In the DJ and SLS tasks FPPA of the right limb was 4º and 8.5º greater than the left respectively, which is also greater than the SEM reported for both tests in chapter four, suggesting it was not due to measurement error. She also hopped 48cm further on her left limb in the crossover hop test, which when normalised was an increase of 50%. The only tasks where the left limb demonstrated deficits in comparison to the right were the SLL task and the anterior, posterior and posterior-lateral directions of the SEBT. Of these differences, only the anterior and posterior directions of the SEBT were greater than the SEM reported earlier. However, LSI in all cases was greater than 95%.

Comparison of the injured athlete to the mean values of women footballers reveals a mixed picture. She exhibited greater 2D FPPA in all tasks and performed worse than her peers in the crossover hop for distance and six-metre timed hop test. However, she hopped further on the single and triple hop for distance tests and excursion distance were better in all directions of the SEBT.

The injured athlete exhibited 4.8º, 5.9º and 4.2º greater FPPA in the DJ, SLL and SLS task, indicating that her lower limb control was inferior to that of the mean value for women footballers. Moreover, these differences were above the reported SEM values, indicating that they are outside of measurement error. Additionally, she exhibited lower scores, with the differences greater than SEM, in the crossover hop for distance and six-metre timed hop test compared to mean scores of women footballers. In contrast, the injured athlete hopped 2.9cm and 31.4% further on the single hop for distance. The normalised score was greater than SEM, whereas the raw score was within SEM. On the triple hop for distance test, the injured athlete hopped 19.1cm and 90.3% further than the average women footballer, again the normalised score was greater than SEM and the raw score was within SEM. Whereas, the deficit evident in the crossover hop was greater than SEM. The injured athlete demonstrated higher SEBT values in all directions. Once again these values were greater than SEM values.

Table 7.2. Results of pre-season screening tests for the Anterior Cruciate Ligament injured player, women's football and women's basketball players.

	ACL injured athlete			Football	Basketball
	Left (injured)	Right	LSI (%)	Mean (SD)	Mean (SD)
2D FPPA					
Drop Jump (°)	8.2	12.2	-	3.4 (8.5)	-1.4 (9.3)
Single Leg Land (°)	11.2	10.9	-	5.3 (5.6)	9.8 (5.6)
Single Leg Squat (°)	15.3	23.8	-	11.3 (7.4)	8.8 (5.7)
Hop Tests					
Single hop (cm)	152.3	150.0	101.5	149.4 (16.9)	164.3 (16.8)
Single hop (%)	203.1	197.4	102.9	172.7 (21.3)	187.9 (16.9)
Triple hop (cm)	485.7	460.0	105.6	466.6 (75.5)	533.7 (47.2)
Triple hop (%)	647.6	605.3	106.9	537.3 (96.3)	594.9 (52.1)
Crossover hop (cm)	420.7	372.7	112.9	446.3 (60.7)	504.9 (55.0)
Crossover hop (%)	560.9	490.4	114.4	514.6 (74.8)	568.9 (60.5)
Timed hop (s)	2.09	2.80	-	2.06 (0.31)	1.82 (0.14)
Star Excursion Balance Test					
Anterior (%)	116.9	120.2	97.3	92.1 (13.4)	95.3 (7.4)
Anterior-medial (%)	124.4	105.3	118.2	96.6 (8.9)	91.7 (9.7)
Anterior-lateral (%)	97.3	95.2	100.3	87.1 (11.5)	87.4 (11.1)
Medial (%)	123.1	99.5	123.7	91.4 (9.5)	90.1 (8.6)
Lateral (%)	84.2	78.5	107.3	79.3 (13.0)	92.9 (8.8)
Posterior (%)	98.7	103.1	95.7	82.7 (11.1)	87.1 (8.6)
Posterior-medial (%)	112.9	104.0	108.6	88.5 (9.3)	88.5 (7.1)
Posterior-lateral (%)	94.7	96.9	97.9	81.4 (10.8)	86.5 (8.0)

7.5. Discussion

Prospective investigation of NMC characteristics exhibited by athletes who subsequently suffer ACL injury is important to identify factors which could reduce injury risk. This study prospectively assessed 2D FPPA, hop for distance tests and the SEBT in women's football and basketball players. In the follow-up period, only one athlete sustained an ACL injury meaning statistical analysis of differences between injured and uninjured athletes was not possible. A case study was therefore presented.

Knee valgus angles, moments and differences between limbs have been cited as predictors of ACL injury (Hewett et al., 2005). Significant correlations between FPPA and knee valgus angles and moments in the DJ, SLL and SLS tasks were found in chapter three and have previously been shown in SLS and side-jump tasks (McLean et al., 2005b; Willson & Davis, 2008b). Therefore, an increase in FPPA will result in greater knee valgus motion and a potential increase in ACL injury risk. The injured athlete in this study exhibited greater FPPA during the DJ, SLL and SLS tasks than the mean value for football players, with the difference being greater than SEM values presented in chapter three. Although it is not known what specific FPPA values during these tasks are related to increased injury risk, this does support the notion than an increase in FPPA will increase ACL injury risk. Normative FPPA values for the DJ and SLL tasks have been presented (Herrington & Munro, 2010), with FPPA greater than 13º in the DJ task and 12º in the SLL task thought to indicate that an individual is demonstrating high-risk movement patterns, although these values have not been validated via a prospective study. The ACL-injured athlete in this study demonstrated FPPA within the range considered as normal by Herrington and Munro (2010). However, these values were taken from recreational participants and the results of the current study suggest that average FPPA in women's football and basketball players is lower than that of recreational athletes.

Asymmetry in knee valgus moments between limbs has been cited as an important risk factor for ACL injury (Hewett et al., 2005). Differences in NMC between left and right, or dominant and non-dominant limbs have also been shown (Cowley, Ford, Myer, Kernozek, & Hewett, 2006; Ford et al., 2003; Herrington, 2011) although limb dominance does not predict ACL injury (Hewett et al., 2005). The ACL injured athlete in this case study demonstrated greater FPPA on her uninjured limb compared to her uninjured limb in the DJ and SLS task, with these differences being greater than measurement error. Whereas FPPA was higher on the injured limb in the SLL task, although the difference was within SEM. This suggests that

asymmetry between limbs was not important for prediction of ACL injury in this instance, contrasting with previous findings of Hewett et al. (2005).

The SEBT can predict lower limb injury (Plisky et al., 2006) and highlight deficits between ACL-D and uninjured participants (Herrington et al., 2009). Plisky et al. (2006) found that girls with an LSI of 94% or less were six times more likely to sustain a lower limb injury, although thirty-five percent of injured athletes in the study demonstrated an LSI greater than 94%. The potential for the SEBT to predict future ACL injury was not supported by the results of this case study. The ACL-injured limb demonstrated greater excursion distances in most directions. Only in the anterior, posterior and postero-lateral directions did the injured limb demonstrate deficits compared to the right limb, although the anterior and posterior directions were the only deficits above SEM. In addition, LSI was greater than 95% in all directions.

Differences between uninjured limbs of ACL-D patients and those of control subjects, outside of measurement error values reported in chapter four, have been found in the medial and lateral reach directions (Herrington et al., 2009). The authors suggested that this may have predisposed the individuals to ACL injury, however the ACL injured athlete in this study exhibited greater excursion distances in all directions than the women's football mean. Furthermore, she demonstrated greater excursion distances compared to her uninjured limb in these directions. Overall, the results of this case study suggest that the differences between limbs or between athletes in the SEBT may not be sensitive to future ACL injury.

The results of the hop for distance tests are similar to those noted for FPPA and the SEBT. The ACL injured limb exhibited better raw and normalised scores than the uninjured limb in all four hop tests. The differences between limbs were greater than SEM for the triple, crossover and timed hop tests, again suggesting limb asymmetry was not a risk factor for ACL injury in this case. Additionally, the ACL injured athlete performed better than the mean women's football score in both the single and triple hop tests but worse in the crossover and timed hop tests. These differences were greater than SEM in all normalised scores. However, for raw scores of the single, triple and timed hop was this not the case, suggesting that the injured athlete's performance was not significantly worse than the average women's footballer.

According to these results, the crossover hop for distance test shows some potential for predicting those at greater risk of ACL injury. The crossover hop test includes both frontal and transverse plane components, which are likely to challenge knee stability more so than the sagittal plane dominant single and triple hop tests. This is particularly true for the ACL where the strain is increased when frontal and transverse forces are present (Berns et al., 1992; Markolf et al., 1995). Despite this, Noyes et al. (1991) reported that 42% of ACL-D patients had 'normal' symmetry (>85% LSI) during the crossover hop. Although as previously discussed, the validity of this 85% value has not been established. This case study suggests that the crossover hop for distance test may demonstrate the potential to screen for future ACL injury.

Normative values in a women's football and a women's basketball population have been presented in this study. In light of this case study, individuals who exhibit FPPA values or crossover hop scores above these normative values may be at greater risk of ACL injury. In particular, those athletes who exhibit values similar to or greater than those demonstrated by the ACL injured athlete in this study. Although not all athletes who exhibit poor NMC will suffer an ACL injury due to its multifactorial nature, there is an increased likelihood that they will.

The main aim of the study was to prospectively examine the potential of 2D FPPA, hop for distance tests, and the SEBT to predict ACL injury risk. These tests were used after it was identified that they had the potential to be useful for assessment of ACL and PFJ injury risk during large-scale screening and in the clinical environment. It was noted in this study that the use of three researchers to undertake these tests during large-scale screening was successful and workable. Screening of twenty players was able to be completed within a two-hour timeframe, which coaches and players also commented was acceptable.

The current study focused on women's basketball and football players as they are amongst the populations at greatest risk of ACL injury; therefore how well these findings can be related to other populations may be limited, particularly when studies have shown differences between sports in NMC characteristics (Cowley et al., 2006; Herrington, 2011). The original plan for was to run this prospective study over several season in order to gain the required number of participants. However, due to the small number of teams recruited in the initial testing period it was determined it would not be possible to recruit the required number of participants. The small sample size of this study meant that statistical analysis of the factors related to ACL

injury risk was not possible. This small sample size was due to difficulties in recruiting enough participants and is recommended that future prospective studies gain the support and backing of relevant governing bodies. There were numerous attempts to gain the backing of governing bodies prior to and during the undertaking of this study without success.

Several confounding variables were not accounted for in this study design which may have influenced the likelihood of ACL injury occurring; including menstrual cycle, hormone levels, joint laxity, femoral notch width index and shoe-surface variables. However, the contribution of each of these to ACL injury risk is currently under debate.

7.6. Conclusion

This case study presents the results of one ACL-injured participant who was prospectively tested during pre-season of her sport for FPPA, hop test and SEBT performance. As such, the results of this isolated case should not be taken as a reflection of the potential sensitivity of each of these tests for predicting ACL injury.

NMC of the women's footballer's ACL injured left limb was shown to be better than that of the uninjured right limb in this case study. This was in direct contrast to findings previously reported (Hewett et al., 2005) and suggests that limb symmetry may not be as important as previously thought. However, the injured athlete did demonstrate altered NMC during the DJ, SLL, SLS and crossover hop for distance tasks in comparison to the mean value for women's footballers. Furthermore, the injured athlete demonstrated better performance than her peers across the majority of FPTs in the study. Only in the crossover hop for distance test did she show deficits in comparison to the average women's footballer.

According to these results there may be potential for the use of 2D FPPA and crossover hop in large-scale screening programmes to predict future ACL injury risk. Further prospective investigation of this potential is therefore warranted.

Chapter 8

Summary, Conclusions and Recommendations for Future Work

8.1. Summary

Following a review of the literature surrounding the factors which contribute to ACL and PFJ injuries it was determined that a screening tool which could be used in the field to identify those who exhibited dynamic knee valgus, or assess symmetry of functional performance between limbs, was vital to help predict future injury risk. 2D FPPA was identified as an objective measure of dynamic knee valgus which also allowed for comparison between limbs. It was acknowledged that for 2D FPPA to be used in the field to assess dynamic valgus there was a need for the reliability and validity of this measure to be established. In addition, it was important to understand the factors which contribute to the demonstration of increased FPPA. This would allow for targeted intervention programmes to be used in those cases where individuals with excessive FPPA were identified. Furthermore, the use of feedback as a quick and simple tool to immediately reduce excessive dynamic knee valgus as a pre-cursor to time and labour intensive training interventions was also identified as useful in helping reduce injury risk. Further, the hop for distance tests and SEBT were recognised as measures of functional performance which allowed for assessment of limb symmetry and were able to detect deficits in injured populations. In order for these tests to be used in the field, a standardised protocol of practice trials and subsequent reliability was needed.

As a result the aims of this thesis were to:

1. Establish the reliability and validity of 2D FPPA during the drop jump, single leg landing and single leg squat tasks.
2. Establish the reliability and measurement error of the SEBT and hop for distance tests.
3. Establish what factors contribute to the demonstration of 2D FPPA during screening tasks.
4. Establish whether a simple feedback intervention can modify landing strategies during screening tasks.
5. Prospectively examine the potential of 2D FPPA, hop for distance tests and the SEBT to identify individuals at high risk of Anterior Cruciate Ligament injury.

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With respect to aim one, intra-rater, inter-rater, within-session and between-session reliability and measurement error of 2D FPPA during the DJ, SLL and SLS tasks was investigated. Intra- and inter-tester reliability for 2D FPPA was very high (ICCs 0.94-0.99) with little measurement error (SEM 0.67-1.89°). Within and between-session reliability was also good to excellent (ICCs 0.72-0.91) for the DJ, SLL and SLS tasks, except for the SLS in women where within-day reliability was fair (ICC= 0.59). Considering these results, it was determined that 2D FPPA when measured for the DJ, SLL and SLS task was highly reliable and reproducible within and between raters. Therefore FPPA can be used with confidence when following the instructions for measurement presented in chapter three. Further, 2D FPPA was found to reliable for use across multiple sessions. With respect to this, measurement error values for FPPA were also presented. The SEM values enable clinicians to accurately determine whether differences between limbs or individuals are greater than measurement error of the test. Whilst the SDD values allow for determination whether any observed changes in FPPA over time are due to a true change in performance.

To investigate the validity of 2D FPPA, the relationship between 3D measures of dynamic valgus (hip adduction, hip internal rotation, knee valgus, knee external rotation and subtalar joint complex pronation/eversion) and FPPA during the DJ, SLL and SLS was investigated. To this end, it was expected that increases in 2D FPPA would be associated with increases in 3D hip adduction, hip internal rotation, knee valgus, knee external rotation and subtalar joint complex pronation/eversion. Each of these variables has the potential to increase strain on the ACL and PFJ and therefore increase the risk of injury. The results of the study showed that increases in 2D FPPA significantly correlated to hip adduction and knee valgus angles across all tasks. Additionally, correlations were noted between FPPA and hip internal rotation in the SLL and SLS task, tibial external rotation in the DJ task and subtalar joint pronation/eversion in the DJ and SLS tasks. Overall, it was found that 2D FPPA correlated to 3D variables which contribute to dynamic knee valgus. Therefore 2D FPPA can identify those who demonstrate excessive dynamic knee valgus and are consequently at greater risk of injury.

Of particular interest in this study was the correlation between 2D FPPA and 3D knee valgus during the DJ task. Knee valgus angles and moments during the DJ task have been prospectively linked to ACL and PFJ injury occurrence (Hewett et al., 2005; Myer et al., 2010). Moderate correlations were evident between 2D FPPA and knee valgus angles and moments, suggesting that 2D FPPA could identify those athletes who demonstrate excessive knee valgus.

While 2D FPPA cannot quantify frontal and transverse plane joint motion independently in the same way 3D motion analysis can, it may be able to identify those who demonstrate high-risk behaviours during dynamic task and are at greatest risk of injury. Therefore, 2D FPPA would be useful for prospective examination of ACL and PFJ injury risk in environments where 3D analysis is unworkable, such as large scale screening in sports clubs or in clinic environments.

Chapter four sought to establish a standardised protocol for the hop for distance test and SEBT, and to assess the between-session reliability and measurement error of these protocols. It has been noted in previous studies that learning effects are present in the administration of these tests. The results of chapter four indicated that three practice trials were required in each of the hop tests, with the exception of the crossover hop tests in men where four trials were necessary. Subsequent reliability analysis showed good to excellent between-session reliability (ICC 0.76-0.90) for the hop tests, with the exception of the timed hop in men which showed adequate reliability (ICC=0.60). The reliability of the LSI scores was less encouraging but adequate (ICC 0.56-0.78), despite a lack of differences in LSI scores between weeks. It was found that four practice trials were sufficient for the SEBT, supporting previous findings (Robinson & Gribble, 2008b). This protocol demonstrated good to excellent between-session reliability for all directions (ICC 0.84-0.92). In contrast, reliability of the LSI between weeks was fair (ICC 0.30-0.55) and should be interpreted with caution, despite a lack of differences between weeks. It was acknowledged that the low variability may have negatively influenced the ICC scores.

The within and between-session SEM and SDD values presented for the hop for distance tests and SEBT give clinicians and researchers greater information regarding the scores achieved. The SEM value allows for the range within which the true score lies to be determined. The SDD value is particularly important when assessing the effect of interventions; changes between test sessions should be greater than the associated SDD for truly significant results, where changes are due to true changes in individual performance rather measurement error, to be determined (Fletcher & Bandy, 2008).

With regards to aim three, having established the reliability and validity of 2D FPPA for assessment of dynamic knee valgus, chapter five aimed to investigate which factors contribute to the demonstration and potential modification of high FPPA. If those who demonstrate high FPPA can be identified, then it is important to know what factors relate to FPPA in order to

create interventions to reduce its occurrence. The literature indicated that hip strength, ankle dorsi-flexion ROM and subtalar joint pronation may contribute to variance in FPPA. Therefore the relationship between these variables and FPPA was investigated. The results showed that the standing clam, a test combining hip abduction and external rotation strength, was the strongest predictor of FPPA in the DJ task. The standing clam was able to explain twenty percent of the variance in FPPA scores, and showed significant negative correlation (r= -0.44) where an increase in standing clam scores resulted in a decrease in FPPA. Significant correlations were also evident between the hip abduction (r= -0.34) and hip external rotation (r= -0.25) and DJ FPPA. However, these variables did not significantly contribute to the regression model due to collinearity between the hip strength variables. Gastrocnemius and soleus ROM and navicular drop did not correlate with DJ FPPA. None of these variables correlated to FPPA during the SLL task, indicating that other factors are responsible for increasing FPPA in the SLL. The standing clam test alone may be more useful for assessment of hip muscle strength in relation to individuals who exhibit high FPPA during the DJ task, rather than assessment of hip abduction and external rotation. However, it is also clear that hip strength is not the only factor which contributes to excessive FPPA. It was also noted in this study that differences in the measured variables between those who exhibit high FPPA and those who's FPPA is considered normal was not evident. Moreover, symmetry between high FPPA and normal limbs within subjects also showed no differences.

The use of augmented feedback to produce immediate changes in landing technique was investigated in chapter six. A feedback protocol based on the self and expert combination (Onate et al., 2005) and the LESS system was used. Significant reductions in FPPA were noted in both the DJ and SLL tasks. In the DJ task this change (24º) was greater than the SDD presented in chapter three and greater than the change observed after a four-week jump training intervention (Herrington, 2010). This change in FPPA was accompanied by a significantly greater contact time, which despite no changes in vGRF, indicates that the rate of loading was reduced, therefore reducing load on the lower limb. However, this increase in contact time was accompanied by a decrease in jump height which points towards a possible decrease in performance as a result of reduced injury risk. In the SLL task statistically significant decreases in FPPA and vGRF were exhibited post-feedback. The 5.2º decrease in SLL FPPA was within the SDD reported earlier. Additionally the 8% reduction in peak vGRF, whilst statistically significant, was small and the clinical significance may be questionable. Further analysis of the results showed that FPPA was reduced in all individuals who demonstrated high FPPA in the DJ, and that these changes were all greater than SDD.

All participants with high FPPA in the SLL task showed reductions, but only fifty percent were greater than SDD. The results suggest that a simple video feedback protocol can bring about positive changes in lower limb biomechanics during jumping and landing tasks which are likely to reduce ACL and PFJ injury risk.

Finally, with regards to aim five, chapter seven presented a prospective study which was undertaken to ascertain the potential for FPPA and FPTs to predict ACL injury. One women's footballer, from a sample of 84 women's football and basketball players tested, sustained a non-contact ACL injury during the study follow-up period. The case study of this athlete revealed that she demonstrated higher DJ, SLL and SLS FPPA scores than the average football or basketball players on both her injured and uninjured limbs. Additionally, the injured athlete's crossover hop for distance scores were lower than her peers. Previous research has suggested that limb symmetry is an important predictor of ACL injury risk (Hewett et al., 2005), however we found that the athlete in this case study exhibited better NMC on her injured than her uninjured limb. The case study results for this ACL injured athlete underline the potential for FPPA and the crossover hop for distance test to predict potential ACL injury risk.

8.2. Conclusion

The work undertaken in this thesis has expanded the knowledge on the use of 2D motion analysis and FPTs for assessment of injury risk behaviours in athletes.

Firstly 2D FPPA has been shown to be reliable within and between raters and across multiple sessions. Secondly, validity of FPPA was shown via significant correlations with 3D variables associated with ACL and PFJ injury. A reliable, standardised protocol has been established for the hop for distance tests and SEBT, with associated measurement error scores for evaluation of performance.

Identification of athletes who exhibit excessive FPPA may help to reduce injury occurrence via the use of interventions to reduce FPPA. Improvement of hip adduction and external rotation strength, as measured using the standing clam in this study, may lead to improvements in FPPA. However, a simple feedback protocol can result in rapid reductions in FPPA, potentially leading to an immediate reduction in injury risk. A combination of these approaches, where hip strength may supplement improvements already gained from feedback, may elucidate the greatest reductions in injury risk.

The results of the case study provide further support for the use of 2D analysis and suggest that FPPA greater than the average women's footballer may predict future ACL injury. Performance on the crossover hop for distance was also relatively poor in comparison to women's football mean performance in the ACL injured athlete, suggesting this test may have potential for screening for high risk individuals. However, whether the single, triple and timed hop tests and the SEBT can predict future ACL injury is unclear. Further prospective work is needed to confirm these initial findings.

Collectively, this work demonstrates the potential for 2D motion analysis to identify those who demonstrate excessive dynamic knee valgus and may therefore be at greater risk of ACL and PFJ injury. Moreover the use of feedback to improve movement strategies could help to decrease injury risk in a quick and easy fashion.

8.3. Recommendations for future work

The findings of this thesis and the subsequent discussion raise several questions for investigation in future work. Firstly, following the results of the reliability and validity of 2D FPPA shown in chapter three, it is recommended that the DJ and SLL tasks should be used in future studies. Further research into different athletic populations, including a variety of different elite sports and injured populations would be useful to ascertain whether average FPPA differs between sports. This would help to identify those athletes who are considered as demonstrating FPPA which leaves them at greater risk of injury.

The positive findings regarding 2D FPPA presented in the prospective case study in chapter seven, a further large-scale prospective study is warranted. Considering the results of the current prospective study, and those previous prospective and epidemiological studies conducted in this area (Agel et al., 2007; Faude et al., 2005; Hewett et al., 2005; Le Gall et al., 2008) any future large-scale study would be required to recruit a much greater number of participants who would be tracked over a number of seasons in order for potentially meaningful results to be obtained. In addition to identifying whether 2D FPPA has the ability to predict future ACL and PFJ injury risk, future work could also establish a cut-off value for those regarded to be at greatest risk and therefore in urgent need of intervention work to reduce this risk. Further investigation into the ability of the crossover hop for distance test as a predictor of potential ACL injury risk is also warranted considering the results of chapter seven.

Having established that the hip strength measured via the standing clam can only account for twenty percent of the variance in FPPA, further work on the identification of what factors contribute to demonstration of FPPA is necessary. Further assessment of these factors in individuals who demonstrate excessive FPPA will help to gain further understanding of how the factors may help to reduce excessive dynamic knee valgus and therefore reduce injury risk.

With regards to the ability of feedback to influence FPPA during landing tasks, further work on this area is warranted. Whether the short-term changes in FPPA noted in this thesis would be retained over a longer period remains to be seen. Furthermore, it is unclear whether improvements demonstrated during the relatively simple DJ and SLL tasks transfer to improvements in more complex tasks, such as change of direction or unanticipated

movements and further investigation is needed. The error measurement statistics presented in chapter three will also allow clinicians and researchers to accurately determine whether changes in FPPA which may result from feedback and intervention studies are due to a true change in performance or measurement error of the test.

Considering the factors mentioned in chapter five, whilst they are clearly not the only contributors to FPPA, any factor which can positively change FPPA is worth investigation. Therefore, the implementation of intervention studies and their effect on FPPA should be carried out. These interventions should include programmes which target individual factors such as hip strengthening, increasing dorsi-flexion ROM and improving balance, to establish whether they alone can improve individual landing strategies. This would allow for improved injury prevention strategies in those considered to be at high-risk.

Future studies using the hop tests and SEBT should follow the protocols outlined in chapter four. The ability of these tests to detect functional deficits in injured populations in light of the measurement error values presented is also warranted.

Appendices

Drop jump feedback questions list (chapter 6)

Frontal view

Did the model land….

	Yes	No
1. With knee valgus at initial foot contact?		
2. With sideways trunk lean?		
3. With both feet at the same time?		
4. With their feet shoulder width apart?		
5. With excessive knee valgus displacement?		
6. With their feet rotated more than 30º?		

Side view

Did the model land….

	Yes	No
1. Softly?		
2. With their knee flexed more than 30º at initial contact?		
3. With their hip flexed at initial contact?		
4. With their trunk slightly flexed?		
5. With their toes first?		
6. With further knee, hip & trunk flexion after landing?		

Single leg land feedback questions list

<u>Frontal view</u>

Did the model land….

	Yes	No
1. With knee valgus at initial foot contact?		
2. With sideways trunk lean?		
3. With excessive knee valgus displacement?		
4. With their feet rotated more than 30º?		

<u>Side view</u>

Did the model land….

	Yes	No
1. Softly?		
2. With their knee flexed more than 30º at initial contact?		
3. With their hip flexed at initial contact?		
4. With their trunk slightly flexed?		
5. With their toes first?		
6. With further knee, hip & trunk flexion after landing?		

Individual Injury Report Form (chapter 7)
Basketball

Please report any injury that occurs during organised practice or competition which:

- *results in the player being unable to complete the session*
- ***and/or** prevents the athlete from taking full part in subsequent training sessions or games for greater than 24 hours after the injury occurred.*

1.   **Athlete Name:** _____

2.   **Date of Injury:** _____

3.   **Injury occurred during**
  (please tick):

o   **Training**   o   **Game**

o   First half of training   o   Warm-up
o   Second half training   o 1st quarter
                                              o 2nd quarter
                                              o 3rd quarter
                                              o 4th quarter

4.   **Injury status**:
o   New injury
o   Ongoing injury
o   Recurrence of injury

5.   Was the injury due to **overuse** or **trauma**? _____

6.   **Mechanism of Injury**:
o   **Non-contact**   o   **Contact**
o   Landing   o   With other player
o   Turning   o   Fall
o   Running   o   Other _____
o   Other _____

Please describe the event surrounding the injury (including exact mechanism):
_____

7.   **Surface** (grass/astro/wood): _____

8.   **Injury detail**:

_____
Side (right/left/both)   Structure   Type of injury ("diagnosis")   eg. right knee MCL grade 2 sprain

9.   Was this diagnosis confirmed by other investigation (eg. MRI, arthroscopy)?

Individual Injury Report Form (chapter 7)
Football

Please report any injury that occurs during organised practice or competition which:

- *results in the player being unable to complete the session*
- ***and/or** prevents the athlete from taking full part in subsequent training sessions or games for greater than 24 hours after the injury occurred.*

1.   **Athlete Name:** _____

2.   **Date of Injury:** _____

3.   **Injury occurred during**
(please tick):

o	**Training**	o	**Game**
o	First half of training	o	Warm-up
o	Second half training	o	Beginning of 1st half
		o	End of 1st half
		o	Beginning of 2nd half
		o	End of 2nd half

4.   **Injury status**:
o   New injury
o   Ongoing injury
o   Recurrence of injury

5.   Was the injury due to **overuse** or **trauma**? _____

6.   **Mechanism of Injury**:

o	**Non-contact**	o	**Contact**
o	Landing	o	Tackle
o	Turning	o	Collision
o	Running	o	Kicked
o	Other _____	o	Other _____

Please describe the event surrounding the injury (including exact mechanism):
_____
_____

7.   **Surface** (grass/astro/wood): _____

8.   **Injury detail**: _____
Side (right/left/both)   Structure   Type of injury ("diagnosis")   eg. right knee MCL grade 2 sprain
9.   Was this diagnosis confirmed by other investigation (eg. MRI, arthroscopy)? _____

Individual Injury Report Form (chapter 7)
Football

Please report any injury that occurs during organised practice or competition which:

- *results in the player being unable to complete the session*
- ***and/or*** *prevents the athlete from taking full part in subsequent training sessions or games for greater than 24 hours after the injury occurred.*

1.   **Athlete Name:** x

2.   **Date of Injury:** 13th September 2009

3.   **Injury occurred during** (please tick):

o	**Training**	o	**Game**
o	First half of training	o	Warm-up
o	Second half training	o	Beginning of 1st half
		o	End of 1st half
		o	Beginning of 2nd half
		o	End of 2nd half

4.   **Injury status**:
- o   New injury
- o   Ongoing injury
- o   Recurrence of injury

5.   Was the injury due to **overuse** or **trauma**? Traumatic

6.   **Mechanism of Injury**:

o	**Non-contact**	o	**Contact**
o	Landing	o	Tackle
o	Turning	o	Collision
o	Running	o	Kicked
o	Other _____	o	Other _____

Please describe the event surrounding the injury (including exact mechanism)
I went up to header the ball and as I landed my knee gave way.

7.   **Surface** (grass/astro/wood): 3g astro

8.   **Injury detail**: Left ACL Ruptured ligament

9.   Was this diagnosis confirmed by other investigation (eg. MRI, arthroscopy)? MRI

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Ethical Approval Forms

Publications