HOW DOES TECHNIQUE AND TECHNIQUE MODIFICATION IMPACT ON KNEE LOADS IN SPORTING TASKS?

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ABSTRACT

Anterior cruciate ligament (ACL) rupture is a serious and debilitating injury that usually results in an athlete undergoing reconstructive surgery and remaining out of sport for an extended period. Therefore the incidence of this injury although only moderate (approximately one per professional Australian football team per year) when considered from a social and sporting cost perspectives is of serious concern. However, the non-contact nature of the majority of occurrences of this injury indicates that it may be possible to reduce the incidence with interventions aimed at modifying the movement and/or physical characteristics of individual athletes. Previous research aimed at reducing the risk of non-contact ACL injury has focused on improving support of general knee loads, particularly valgus and internal rotation moments, which are known to load the ACL, during sporting tasks through the utilisation of balance and plyometric training. While technique cues have been included in a number of these training programs there has been no research that has investigated training to change isolated aspects of sidestep cutting and landing techniques and their effect on valgus and internal rotation moments at the knee, the moments thought to cause non-contact ACL injury. This was the overarching theme of this thesis.

Most non-contact ACL injuries occur during either sidestep cutting or landing tasks, as such, the relationship between technique and knee loads was investigated within these two tasks. The first study presented in this thesis investigated how performing sidestep cuts with various extreme postures affected knee moments. It was identified that peak valgus loads during the weight acceptance phase of the sidestep cut were increased when performed with either increased torso lean over the support leg or wide placement of the support leg. Wide foot placement also resulted in increase peak internal rotation moments. Sidestep cuts, with torso rotation towards the support leg also increased peak knee internal rotation moments. As these postures were reflective of those observed during actual non-contact ACL injuries it was concluded that these three postures should be avoided when performing a sidestep cut.

The next study investigated the effectiveness of a six week technique modification program aimed at avoiding the three high loading techniques, identified in the first

study, for reducing knee moments during sidestep cutting. Following the intervention participants performed the sidestep cut with a foot placement closer to the midline of the body and a more upright torso. These kinematic changes were accompanied by a reduction in the peak valgus moment occurring during the weight acceptance phase of the sidestep cut. This intervention may then reduce at least one factor identified as being a risk for an athlete of sustaining a non-contact ACL injury.

Studies three and four investigated the relationship between technique and knee loads during landing tasks. The first of these two studies investigated the effect of ball positioning in a functional landing task on both full body kinematics and knee moments. When participants were required to take possession of a ball during flight that was swinging towards their support leg they demonstrated increased valgus moments compared with when the ball was swung away from the support leg. The whole body segmental kinematics of the high loading ball movement reflected body postures observed when injury occurs in a game situation. However, the high loading task exhibited a more flexed knee posture, contrary to the results expected from the literature. The second of these two studies further investigated the relationship between whole body kinematics and knee moments. Intra-participant correlations were performed between all kinematics and each knee joint moment, with the intention of identifying mean correlations significantly different from zero. Increased valgus moments were significantly correlated with increased knee flexion, hip flexion, torso lean and torso rotation towards the support leg, and foot and knee external rotation. Increase internal rotation moments were significantly correlated with reduced hip abduction and external rotation, increased ankle inversion, knee external rotation and torso lean away from the support leg. Again these results reflected joint positions observed in injury, except for knee flexion and hip flexion angles. It was identified that while there may be statistically significant effects for knee angle the difference in magnitude may not result in functional differences.

The final study investigated the effect of a six week technique modification program on landing tasks. The technique modification aimed at bringing athletes' torsos upright and forward facing, based upon the results of the previous studies. It also aimed to increase knee flexion angle, as this is still the current literature recommendation. Post-intervention participants displayed an increase in maximal knee flexion angles but no change in torso positioning. This kinematic change was correlated to a significant increase in peak internal rotation moments, with no change in valgus or flexion moments. Although, due to the angle at which the peak internal rotation moment occurred it was identified that this increase in moment may not increase the risk of non-contact ACL injury risk, due to the increased potential for muscular support and decreased transmission of the moment to the ACL. However, it was concluded that the technique modification program may not be appropriate for reducing the risk of non-contact ACL injury, within the particular landing task chosen.

Overall this thesis identified that whole body kinematics are related to knee moments during sidestep cutting and landing. Kinematics associated with increase valgus and internal rotation moments at the knee tended to reflect joint posture observed during actual non-contact ACL injuries. Secondly a six week technique modification program is capable of modifying both sidestep cutting and landing technique. Technique changes result in changed knee moments. However, the complex nature of the relationship between technique and knee loads indicates that any potential intervention aimed at reducing the risk of non-contact ACL injury, should be tested in the laboratory utilising tools such as neuromuscular modelling and stochastic modelling to ensure the planned intervention has the potential to be successful prior to implementing the protocol in an epidemiological testing scenario.

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DEFINITIONS AND ABBREVIATIONS

ACL	Anterior Cruciate Ligament
AE	Landing task where the ball is swung away from the support leg early in approach (Chapter 6)
AFL	Australian Football League
AL	Landing task where the ball is swung away from the support leg late in approach (Chapter 6)
ANOVA	Analysis of variance
F_{Close}	Foot placed close to the midline of the body at initial contact (Chapter 4)
F_{In}	Foot turned in at initial contact (Chapter 4)
F_{Out}	Foot turned out at initial contact (Chapter 4)
F_{Wide}	Foot placed away from the midline of the body at initial contact (Chapter 4)
K_{Flexed}	Knee flexed at initial contact (Chapter 4)
$K_{Straight}$	Knee straight at initial contact (Chapter 4)
Knee Flexion Moment	Moment which if applied with no resistance will cause the knee to flex. Reported as external and negative
Knee Internal Rotation Moment	Moment which if applied with no resistance will move the tibia to rotate medially relative to the femur posture. Reported as external and negative
Knee Valgus Moment	Moment which if applied with no resistance will move the knee into a "knock-kneed" posture. Reported as external and positive

NS	Normal sidestep cut (Chapter 4)
TE	Landing task where the ball is swung towards the support leg early in approach (Chapter 6)
TL	Landing task where the ball is swung towards the support leg late in approach (Chapter 6)
$T_{Opposite}$	Torso leaning in the opposite direction to the sidestep cut at initial contact (Chapter 4)
$T_{Rotated}$	Torso rotating in the opposite direction to the sidestep cut at initial contact (Chapter 4)
T_{Same}	Torso leaning in the same direction as the sidestep cut at initial contact (Chapter 4)
UWA	The University of Western Australia

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STATEMENT OF CANDIDATE CONTRIBUTION

The work involved in designing and conducting the studies described in this thesis has been conducted principally by Alasdair Dempsey (the candidate). The thesis, outline and experimental design of the studies was developed and planned by the candidate, in consultation with Associate Professor David Lloyd and Professor Bruce Elliott (the supervisors). All participant recruitment was carried out by the candidate, along with the actual organisation, implementation and undertaking of data collection sessions and training sessions.

The candidate was responsible for all data analysis and original drafting of all chapters contained within this thesis, as well as all publications arising from this thesis. The supervisors have provided feedback on all drafts of chapters contained within the thesis. Chapters previously published as peer review publications received some feedback from all authors. All authors have given permission for work listed in *Publications Arising from this Thesis* to be included in the thesis.

Alasdair Dempsey	A\Prof David Lloyd	Prof Bruce Elliott
Candidate	Coordinating Supervisor	Supervisor

PUBLICATIONS ARISING FROM THIS THESIS

Following is a list of publications arising either directly from the chapters presented within this thesis, or from data collected in preparation for this thesis.

Journal Articles

Dempsey AR, Lloyd DG, Elliott BC, Steele JR, Munro BJ, Russo KA. The effect of technique change on knee loads during sidestep cutting. *Medicine and Science in Sports and Exercise*. 2007; 39(10):1765 - 1773. *(This paper is presented as Chapter 4)*

Dempsey AR, Lloyd DG, Elliott BC, Steele JR, Munro BJ. Changing sidestep cutting technique reduces knee valgus loading *American Journal of Sports Medicine.* 2009;37(11):2194-2200. *(This paper is presented as Chapter 5)*

Dempsey AR, Lloyd DG, Elliott BC, Munro BJ, Steele JR. How does ball movement direction affect knee loads and full body kinematics in an ecologically valid landing task? *American Journal of Sports Medicine.* (Submitted). *(This paper is presented as Chapter 6)*

Dempsey AR, Lloyd DG, Elliott BC, Munro BJ, Steele JR. Associations between whole body positioning and knee loads in functional tasks. *American Journal of Sports Medicine.* (Submitted). *(This paper is presented as Chapter 7)*

Dempsey AR, Lloyd DG, Elliott BC, Munro BJ, Steele JR. Can technique modification training reduce knee loading in landing tasks? *American Journal of Sports Medicine.* (Submitted). *(This paper is presented as Chapter 8)*

Conference Proceeding

Dempsey AR, Lloyd DG, Elliott BC, Russo K. What affect does different sidestepping technique have on knee loads? Paper presented at: 2nd Australian Association for Exercise and Sports Science Conference and the 4th Sports Dieticians Australia Update: From Research to Practice 2, 2006; Sydney, Australia. *(This abstract is related to Chapter 4)*

Dempsey AR, Lloyd DG, Elliott BC. Does peak vertical ground reaction force correlate with peak knee moments in functional landing tasks? *Journal of Biomechanics.* 2007;40(S2):S245. *(This abstract is related to Chapters 6-8)*

Dempsey AR, Lloyd DG, Elliott BC. Can full body technique change modify knee loads in sidestepping? Paper presented at: 3rd Australian Association for Exercise and Sports Science Conference and the 5th Sports Dieticians Australia Update: From Research to Practice, 2008; Melbourne. *(This abstract is related to Chapter 5)*

Dempsey AR, Elliott BC, Munro BJ, Steele JR, Lloyd DG. Increasing knee flexion in landing tasks may not reduce the risk of non-contact anterior cruciate ligament injury. Paper presented at: 7th Australasian Biomechanics Conference; 2009; Gold Coast, Australia. *(This abstract is related to Chapter 8)*

CHAPTER 1 GENERAL INTRODUCTION

1.1 Introduction

The anterior cruciate ligament (ACL) is one of the four primary ligaments in the knee. A rupture of the ligament is extremely debilitating and sufferers will usually require a knee reconstruction in order to return to activities involving a change of direction, such as team sports.[48] Unfortunately the incidence of ACL injuries is high in most team sports. In Australia, amongst the approximately 680 professional Australian Football League (AFL) players there have been, over the last decade, on average 12 new ACL injuries a year.[180] As this represents a small proportion of the almost 270,000 Australians participating in Australian football,[10] even conservative extrapolations of the professional data to the wider community would result in a high number of ACL injuries annually from this one sport. Similar injury rates are observed in other team sports.[23, 80, 83, 154, 157] With the cost of one surgery in the range of A$8000-A$9000,[174] and all patients incurring further costs in rehabilitation, the total outlay to the economy is large. Sufferers of ACL injuries are also at increased risk of developing knee osteoarthritis later in life, a disease with its own considerable costs, both financial and to the individual's quality of life.[2, 222]

Over 50% of sporting ACL injuries occur with no contact with other players, particularly during sidestep cutting and landing.[38] The non-contact nature of so many ACL injuries makes these an ideal target for preventative interventions, as a change to the physical and/or movement characteristics of the individual has the potential to reduce their injury risk. This removes the need to make modifications to the rules or nature of the sport, such as occurred in the AFL, where the rules regarding the ruckman's approach to centre bounces was modified in an attempt to reduce the incidence of posterior cruciate injuries.[180] In order to develop the most effective interventions the predisposing risk factors associated with ACL injuries need to be identified. These risk factors have been identified as being both external and internal to the athlete, and can be placed into one of four broad groupings: anatomical, hormonal, environmental and neuromuscular biomechanical.[78, 197] Potential interventions within the first three categories have ethical and practical limitations, leaving neuromuscular biomechanical interventions as the ideal area for research into non-contact ACL injury prevention.

To establish the neuromuscular biomechanical risk factors there first needs to be an understanding of the aetiology of the injury. Cadaveric studies have shown that the ACL is loaded when anterior, valgus and internal rotation loads are applied to the tibia.[139] Further, when two of these loads are applied in combination the resulting strain is significantly increased.[140] This is particularly true when the knee is in an extended posture. Video analysis of actual injuries occurring in game show that the knee tends to collapse into valgus and internal rotation, particularly when the knee is close to full extension.[38, 168] These loading patterns linked with increased risk of ACL injury, have also been corroborated by laboratory studies that have analysed sidestep cutting and landing manoeuvres. During sidestep cutting subjects have been shown to exhibit higher valgus and internal rotation loads than when running.[14] Further these loads increased when the task was performed at the 'spur of the moment', an oft seen feature of actual injuries.[13] In landing tasks, individuals who experience higher valgus loads have also been shown to have an increased risk of suffering an ACL injury.[91]

As ligament injury is a result of the applied load being greater than the ligament's ability to support the load, an important step in developing non-contact ACL injury prevention programs is to establish how to reduce the load being applied to the ligament. It has been shown that the co-contraction of muscles crossing the knee joint is able to support a large proportion of the applied valgus and internal rotation moments.[15] As such, there have been a number of prevention programs developed aimed at increasing muscle strength and/or co-contraction.[31, 90] The majority of such interventions have been successful in reducing non-contact ACL injuries in the field.

A second path to prevention is to reduce the loads generated at or applied to the knee. Combining this with an increase in the muscular support, would further take an athlete away from the point of rupture of the ACL. Video analysis of injury has indicated that individuals often have similar body postures at initial foot contact.[24, 37] As joint loading is related to the position and acceleration of body segments it can be assumed that technique has some relationship with knee loading. While it has been previously recommended that technique should form part of prevention programs for ACL injuries,[129] there is a paucity of research into the relationship between whole body technique and knee loading in sporting tasks. The work undertaken so far has focused on the lower limb,[91, 150, 210] however more recent work suggests that the upper body is also important.[36, 230] In order to develop best practice technique interventions there needs to be a better understanding of the relationship between whole body kinematics and knee loading in sporting tasks, particularly sidestep cutting and landing.

Despite the limited investigation into the relationship between technique and knee loading some plyometric based studies, which have successfully reduced the risk of injury, have included some emphasis on technique. Although it must be acknowledged that the emphasis on technique was within the context of the plyometric drills and may not be related specifically to sporting manoeuvres.[211] The one intervention study to date utilising pure technique modification within the team sport setting, trained athletes to use two-footed landing, multi-step decelerations and cross over cuts.[87] The cross over cut in particular represents a major modification to the standard cutting technique seen in all team sports. The effect of the technique modification on knee loads was also not included in the research design.

This leaves us with the question of how does technique and technique modification affect knee loads in sporting tasks, specifically sidestep cutting and landing?

1.2 Statement of the Problem

High valgus and internal rotation moments are related to a high strain on the ACL, and should this strain become too great the ligament will rupture.[140] Previously, prevention programs have focused on increasing an athlete's ability to support this load; however, another avenue of prevention is to reduce the load generated at the knee. In practice it would appear that ACL injuries are commonly linked with certain postures, indicating that there may be a link between said postures and knee loading. Despite this currently there is a dearth of research into the impact of movement technique on knee loading in sporting tasks. Should there be certain techniques that produce high valgus and internal rotation moments, it is logical to suggest that athletes using said techniques will be at a greater risk of suffering a non-contact ACL injury than those who use techniques related to lower load profiles. The question then logically may then be posed as to whether one can develop technique modification programs to reduce knee loads? Should this be possible, then the combination of such training with neuromuscular interventions previously shown in the literature reduce ACL injury rates, should further decrease an athlete's risk of injury.

1.3 Aims

The overarching theme of this thesis was to identify how technique modification in sporting tasks affected knee loading, particularly external valgus and internal rotation moments. This was undertaken in the context that technique modification may be able to reduce the risk of non-contact ACL injuries, a serious, oft occurring injury within team sports. As such the sporting manoeuvres studied were; sidestep cutting and landing due to the large percentage of non-contact ACL injuries occurring during these tasks.[38] In order to develop technique modification programs there was a need to identify joint postures associated with high loads. To date there has been a paucity of research into this relationship in sidestep cutting and landing. Therefore, initially studies were conducted to better establish the relationship between whole body kinematics and joint moments. The results from these studies formed the basis for the development of the technique modification programs for sidestep cutting and landing. As such the specific aims for this thesis are as follows:

1. Identification of sidestep cutting techniques associated with high valgus and internal rotation moments;

2. Testing if a sidestep cutting technique modification program based upon avoidance of the identified "high loading" techniques is capable of reducing external valgus and internal rotation moments in sidestep cutting;

3. Identification of landing techniques associated with high valgus and internal rotation moments; and

4. Testing if a landing technique modification program based upon recommendations from the literature and joint posture linked to higher

loading, is capable of reducing external valgus and internal rotation moments in landing.

1.4 Structure of the Thesis

As per the accepted requirements of The University of Western Australia (UWA), this thesis presents a series of published or submitted papers focused upon the previously stated aims. Following a *Literature Review* (Chapter 2 and *General Methods* (Chapter 3 there are five chapters presented as papers, two of which have been published and three submitted. This is followed by a *General Discussion* (Chapter 9), which summarises the results from the previous papers and discusses the implications of said results. It also provides recommendations for further research directions. Following is a brief outline of Chapter 4 – Chapter 8 .

1.4.1 Chapter 4 – The Effect of Technique Change on Knee Loads During Sidestep Cutting

Chapter 4 addresses the first aim of the thesis, investigating the relationship between sidestep cutting techniques and knee loadings. Participants were required to undertake sidestep cuts with varying imposed techniques, approaching the extremes of selected body postures. Therefore the aim of the study was:

- To identify if modifying sidestep cutting technique creates substantial and functionally important changes to knee moments.

It was hypothesised that:

- The varus/valgus, internal/external rotation and flexion/extension moments would be affected by changes in sidestep cutting technique.

1.4.2 Chapter 5 – Changing Sidestep Cutting Technique Reduces Knee Valgus Loading

This chapter is concerned with Aim 2. Based upon the results from Chapter 4 a six week technique modification program was developed and implemented, teaching a safe sidestep cutting technique. Participants were tested both pre- and post-technique modification program. Therefore the aim of this study was:

- To examine whether changes to sidestep cutting technique reduces knee moments.

It was hypothesised that:

- During sidestep cutting participants would display significant changes in the technique variables describing the safe sidestep cutting technique from pre- to post-technique modification; and

- That this would be accompanied by reductions in the three-dimensional knee moments from pre- to post-technique modification.

1.4.3 Chapter 6 – How Does Ball Movement Direction Affect Knee Loads and Full Body Kinematics in an Ecologically Valid Landing Task?

This chapter addresses Aim 3 of the thesis and investigated the impact of ball positioning in landing tasks on knee moments and full body kinematics. Participants were required to take off and land, while gathering a ball that was swung under the control of rig, which was suspended from an overhead gantry. Kinetics and kinematics were assessed based on their relationship to non-contact ACL injury risk. The aims of the chapter were:

- To investigate the effect ball movement in an ecologically valid landing task on knee moments and full body joint kinematics; and

- If specific ball movements produce knee moments associated with increased risk of non-contact ACL injury, then further examination of the full body kinematic differences exhibited during those landings would be undertaken.

It was hypothesised that:

- Variations in the task would result in differing knee joint moments, which would be accompanied by a change in kinematics; and

- The full body kinematic differences displayed during high loading landings would be similar to the body positions observed from video analyses of actual injuries.

1.4.4 Chapter 7 – Associations between Whole Body Positioning and Knee Loads in Functional Tasks

This chapter is also concerned with Aim 3. Its primary focus was to understand the relationship between technique and valgus and internal rotation moments in landing tasks. Variations in full body kinematics and knee moments produced by the different ball movement patterns described in Chapter 6 were used to identify relationships between full body kinematics and knee moments. The specific aim of this chapter was:

- To identify which full body joint postures at initial foot contact were associated with peak knee moments related to increased risk of non-contact ACL injury.

It was hypothesised that:

- Joint postures associated with increased load would be similar to those that occur during actual injury as reported in the literature.

1.4.5 Chapter 8 – Can Technique Modification Training Reduce Knee Loading in Landing Tasks?

This chapter is concerned with Aim 4. A six week technique modification program was developed based upon the literature recommendation of increasing knee flexion angles and to avoid torso posture identified to cause higher knee moments in Chapter 6 and Chapter 7 . Participants were tested immediately prior to and following their participation in the technique modification program. The aim of this study was to:

- Investigate the effect of a technique modification program, aimed at having the torso upright and forward facing at initial foot contact with a flexed knee joint, on whole body kinematics and knee joint moments.

It was hypothesised that:

- The technique modification program would change joint kinematics; and

- This change would result in reduced peak internal rotation and peak valgus knee moments.

1.5 Significance of the Thesis

A reduction in the rate of non-contact ACL injuries will be beneficial for both athletes, who may be able to avoid an ACL rupture, and the wider community, through reduced health budget costs associated with the initial injury and future treatment of linked diseases. Currently prevention strategies have tended to focus on increasing the player's intrinsic balance, which may affect the ability of the musculature around the knee joint to support loads applied to the knee and possibly indirectly alter knee loading. However, individuals with high loadings at the knee are still at increased risk of suffering an ACL rupture relative to their lower loading counterparts. The combination of an intervention capable of changing the applied load at the knee, combined with increasing the ability of the individual athlete to support said load, has the potential to reduce the risk of injury. While technique has been linked to varied knee loading[150, 210] there have been no studies investigating how full body kinematics in sidestep cutting and landing affect knee loads. This thesis identifies the full body kinematics associated with high knee moments linked to non-contact ACL injury. Further, it is the first to investigate if technique modification, on its own, is capable of reducing knee moments in both sidestep cutting and landing tasks. Should it be possible to reduce knee loading, the results from this thesis will enable the development of more effective preventative training programs for non-contact ACL injuries.

1.6 Delimitations

Testing was delimited to the Sports Biomechanics Laboratory in the School of Sport Science Exercise and Health at UWA. Whilst it would be ideal to collect data during a competitive scenario, within team sports where ACL injuries are common, this approach is not currently feasible with the required measurement of accurate and repeatable kinetic and kinematic data. In order to overcome this delimitation, ecologically valid tasks were used during the testing protocol. Participants' approach speed was also delimited during sidestep cutting trials to enable analysis between subjects and across time points. The chosen speed was similar to that seen in injury.[38]

Participants in this study were delimited to healthy, male team sport athletes. Team sport athletes were selected as they have experience in performing both sidestep cutting and landing manoeuvres. As two chapters focused on change due to training this was essential as inexperienced athletes may have experienced changes in knee moments through continual practice in sidestep cutting and landing regardless of the content of the training. All participants were required to be healthy in order that the results are applicable to the general athletic population. The studies were delimited to male participants, as studies have shown that the menstrual cycle may have an effect on ACL injury rate.[207]

CHAPTER 2 LITERATURE REVIEW

2.1 Introduction

As this thesis is presented as a series of papers, each chapter contains a focused literature review. Therefore the aim of this review is to provide a general overview of the structure and function of the ACL, mechanisms of ACL injury in a team sport setting, factors that predispose an individual to suffer such an injury and why technique modification is a potential avenue to prevent non-contact ACL injuries.

2.2 Are ACL Injuries an Appropriate Target for Prevention?

When assessing the need for a prevention program for sporting injuries the initial step is to identify the burden of the injury.[62, 218] This assessment can follow standard risk analysis procedures, where both the likelihood and magnitude of risk are combined into a matrix ranging from low likelihood, low risk to high likelihood, high risk. Once the matrix has been established it is possible to identify the injuries that have the greater need for prevention, particularly those identified as being high risk. Within the sporting setting the severity (magnitude of risk) and incidence (likelihood of risk) are both assessed and it is these factors that we then use to identify if an injury is worthy of intervention.

2.2.1 Incidence

2.2.1.1 General Population

It is hard to estimate the ACL injury rates in the general population, as capturing all injuries within a given population, particularly retrospectively is difficult. O'Hara and colleagues[166] calculated the incidence from individuals who attended the Kaiser-Permaente Medical Centre in San Diego, where members of the Kaiser Heath Plan in San Diego receive the majority of their medical treatment. Within this population the injury rate was 0.30 injuries per 1000 health care members per year, with over two-thirds of injuries arising from sporting activities.

As the majority of injuries occur during sporting activities, assessment of incidence within these activities is required.

2.2.1.2 Sporting Population

There have been numerous studies that have reported the incidence of injury in team sport settings (Table 2-1). Within the professional AFL there are approximately 12 new injuries a year for players registered at the 16 clubs.[180] This represents injuries occurring to a pool of approximately 680 players, out of approximately 270,000 Australian Football participants nationally.[10, 180] Based on the AFL data it would be reasonable to expect a significant number of ACL injuries to occur amongst Australian football participants nationally. In fact ACL injuries have been identified to be the third most common injury arising from Australian football reporting to sports medicine clinics.[71] Similar incidences are reported across a wide variety of team sports (soccer, basketball and European handball) (Table 2-1). In all it represents a moderately high incidence of ACL injury within the team sport setting.

Another point of interest to note is the increased incidence of injuries amongst female athletes when compared with their male counterparts.[23, 80, 83, 154, 157] This discrepancy in injury rates is a concern and as yet there is no well accepted explanation. It has been proposed that male/female differences may be used to better understand causes of ACL injury.[77] This increased understanding will allow for the development of better prevention programs.

It needs to be noted that there are a large number of ACL injuries occur during skiing, but these injuries are not being considered in this review as these have a different aetiology to injuries sustained during team sports.[78, 166]

2.2.2 Severity

Within the AFL, ACL injuries result in the highest number of missed games per injury.[180] Similar results have been identified in other sports.[43, 163] This is due to the standard treatment of reconstruction surgery followed by extensive rehabilitation. While some sufferers of injury do not require surgery, in the vast majority of cases where the ACL is ruptured, the treatment option of choice is a reconstruction.[20, 23, 48, 75, 161] Those not undergoing surgical reconstruction have a greater risk of suffering 'giving way'

Table 2-1 Incidence of anterior cruciate ligament injury for various sports.

Author	Sport/s	Incidence	Male Incidence	Female Incidence
Bjordal[23]	Soccer	0.063 [2]	0.057 [2]	0.102
Caraffa[31]	Soccer		1.15 [3]	
Dallalanna[43]	Rugby Union		0.42 [2]	
Gwinn[80]	Basketball		0.089 [1]	0.478 [1]
	Rugby Union		0.129 [1]	0.511 [1]
	Soccer		0.081 [1]	0.768 [1]
Harmon[83]	Basketball		0.080 [1]	0.297 [1]
	Soccer		0.123 [1]	0.321 [1]
Lamson[118]	American Football		0.013 [4]	
Levy[123]	Rugby Union			0.36 [1]
Liederbach[126]	Dance		0.004[1]	0.012[1]
Mihata[154]	Basketball		0.08 [1]	0.28 [1]
	Lacrosse		0.17 [1]	0.18 [1]
	Soccer		0.12 [1]	0.32 [1]
Mykleburst[157]	European Handball		0.06 [2]	0.31 [2]
Mykleburst[159]	European Handball			0.14 [2]
Orchard[177]	Australian Football		0.82 [1]	
Pfeiffer[187]	Basketball			0.111 [1]
	Soccer			0.107 [1]

Incidences are shown as male, female or overall depending upon the results in the relevant paper. Superscript numbers indicate incidences units: 1) injuries per 1000 exposures; 2) injuries per 1000 hours; 3) injuries per team per season; 4) injuries per athlete. Caution should be used in comparing the studies as the methods of calculating the same unit is not always consistent.

episodes where the knee collapses causing further interarticular damage.[27, 39, 111, 164, 165] The main aim of reconstruction surgery is to enable the injured individual to return to their pre-injury activities, particularly sports involving change of direction manoeuvres. In fact, Fink and colleagues[63] found that individuals who had undergone a surgical reconstruction were more likely to have returned to sport than those who adopted a more conservative non-surgical treatment approach. Following a reconstruction it is possible to return to the same level of competition, with return rates reported up to 76% at 12 months post surgery.[213] However, return rates should be viewed with caution since these depend on the length of follow up period being assessed. Smith et al.[213] reported a 10% reduction in sport participation 1 to 4 years post surgery, where as von Porat and colleges[222] found a 20% reduction in participation 7 and 14 years following surgery. ACL reconstruction surgery is therefore successful in allowing athletes to return to sport, however athletes are not able to directly return to competition following surgery.

Prior to returning to sport after reconstruction surgery an extensive rehabilitation is required. The standard rehabilitation period prior to returning to full competition is between 4 and 12 months, with this period longer for those following reconstructions utilising hamstring or patella tendon graft.[21, 48, 61, 161] This combination of surgery and rehabilitation result in ACL injuries being the most expensive sporting knee injury to treat.[45]

Requirements for surgery and significant periods of rehabilitation are, on their own, sufficient to class ACL injuries as severe, but there are further reasons for this classification. Following their return to sport, athletes who have undergone a reconstruction are at increased risk of suffering a further ACL injury.[177] This increased risk is to both the previously injured limb and the contralateral limb. These surgically treated athletes are also at increased risk of developing knee joint osteoarthritis in comparison with the general population.[1, 161, 196] Various studies have reported that between 40% and 80% of ACL injury sufferers have developed radiographic changes indicative of osteoarthritis at the knee between 6 and 14 years post surgery.[55, 63, 160, 167, 222]

Development of osteoarthritis can have a large impact on sufferers both in terms of quality of life and financially. The average cost in Australia to an osteoarthritis sufferer in 2004 was in excess of A$1,000 with the value expected to be greater than A$2,000 by 2010.[2] After ACL reconstruction surgery there are changed articular kinematics including tibiofemoral contact points.[201] As articular loading has been shown to be predictive of osteoarthritis development,[5] in individuals who return to sport the combination of altered articular loading with high impact and rotation loads may be the cause of the increased risk of osteoarthritis. In fact leading researchers have posed the question "…whether return to high level pivoting sports really is in the athlete's best interest – if long term knee health is the primary concern."[161]

2.2.3 Contact versus Non-Contact ACL Injuries

It would appear that ACL injuries occurring during team sports have both a high severity and moderately high incidence. Therefore these injuries qualify as a primary target for prevention programs, particularly as there is the potential for intervention that may reduce the incidence rate, which will now be explained. An accepted mechanism for ACL injuries is forceful lateral contact to the knee.[24, 116] Should this be the primary cause of injury, interventions would have to focus on modification of contact situations within the game settings. This can be achieved through techniques such a rule modification, as seen in Australian football for posterior cruciate ligament injuries.[180] However within ACL injuries there is not this requirement since the majority of injuries are non-contact in nature (Table 2-2). The non-contact nature of the injury suggests there may be mechanisms and/or risk factors, both internal and external, which directly relate to the athlete. The identification of internal mechanisms and risk factors will allow for the development of prevention protocols which are focused on modifying the physical and/or movement characteristics of individual athletes, reducing the requirement for major competition wide interventions or modifications to the rules of high risk sports.

The results in Table 2-2 need to be viewed with some caution, as the definition of non-contact injuries across the spectrum of research designs has not been clearly defined. Particularly injuries arising when there has been contact to the body at a site other than the injured leg. More recently the definitions of contact – contact to the injured knee; indirect contact – contact to the body other than the injured knee; and non-contact – no contact to the injured athlete have been proposed.[142] However, it is still reasonable to accept that a significant number of ACL injuries are non-contact, and therefore preventions that target injuries of this nature have the potential to reduce injury risk.

Table 2-2 Percentage of non-contact injuries

Author	Sport/s	% Non-Contact
Arendt[7]	Soccer	57
	Basketball	77
Boden[24]	Multiple	72
Cochrane[38]	Australian Football	56
Lamson[118]	American Football	55
Luthje[134]	Soccer	57
McNair [152]	Multiple	70
Mykleburst[157]	European Handball	88
Mykleburst[159]	European Handball	51
Olsen[168]	European Handball	65
Orchard[177]	Australian Football	76

2.2.4 Development of Prevention Programs

ACL injuries, in particular those which occur in non-contact situations, are worthy of, and require, the development of prevention programs. In order to develop prevention programs there needs to be an understanding of the aetiology of injury.[62, 218] This requires understanding of how the ACL is stressed and what manoeuvres within the sporting setting have the potential to produce this loading. The next three sections attempt to summarise the current knowledge of the structure and function of the ACL, risk factors for non-contact ACL injury, and neuromuscular biomechanical causes of non-contact ACL injury.

2.3 The ACL

2.3.1 Functional Anatomy

The ACL runs from the intercondylar area anterior to the intercondylar eminence of the tibia posteriorly through the intercondylar fossa to the posterior part of the medial side of the lateral femoral condyle.[11, 29, 186] The ligament can be divided into anteromedial and posterolateral fibre bundles, and while there is some disagreement over this separation from an anatomical standpoint, it has been accepted that there is a functional separation of these fibre bundles.[3, 29, 186] The anteromedial bundle is taut in flexion, while the posterolateral bundle is taut in extension.[3, 74, 225] Despite these functional differences, for this thesis the ACL will be treated as a single ligament.

Even though the primary function of the ACL is to prevent anterior tibial translation relative to the femur, it also supports rotations in both the varus/valgus and internal/external rotation directions.[3, 30, 74, 143, 186] Sectioning of the ACL has been shown to reduce stiffness at the knee in both varus/valgus and internal/external rotation directions.[69, 81, 138, 191, 203, 219] This is particularly true for valgus and internal rotation.[190, 191, 229]

2.3.2 Ligament Loading

Ligament injury occurs when the applied load becomes greater than that able to be supported by the ligament. Therefore, to develop or refine prevention programmes it is essential to understand both how externally applied loads to the knee translate to the ACL loading, and what factors decrease the ability of the ligament to resist the applied load. Not-withstanding the importance of ligament strength and factors that affect this, the focus of this thesis will be to assess factors that affect externally applied loads to the knee and the translation of these to ACL loading.

Markolf and colleagues[139] applied loads to cadaveric knees with force transducers implanted in bone at the tibial insertion of the ACL. They identified that anterior drawer, valgus and varus torques and internal and external rotation torques all caused loading at the ACL, the level of which decreased with increasing knee flexion. Similar effects of knee angle have been identified in other studies. [69, 70, 72, 74] However, loading in one plane is unlikely to be representative of that occurring during sporting tasks. Following this, the same research group applied combinations from two loading directions to the cadaveric knees at a number of flexion angles.[140] They identified that loads applied in combination resulted in increased ACL strain (Figure 2-1). ACL loading increased below 10° of knee flexion for internal rotation and anterior drawer and between 10° and 40° of knee flexion for a combination of valgus and anterior drawer. The combination of internal rotation and valgus loading also resulted in large increases in ACL loading between 10° and 40° of knee flexion, compared with levels recorded for internal rotation at the same knee flexion angle. Gabriel and colleagues[72] have also demonstrated that high ACL loads can be generated through a combination of valgus and internal rotation. Cadaveric models of impact loading with the knee positioned to generate valgus and flexion loads has also been shown to cause higher loads on the ACL, than those generated from simply flexion loads.[224]

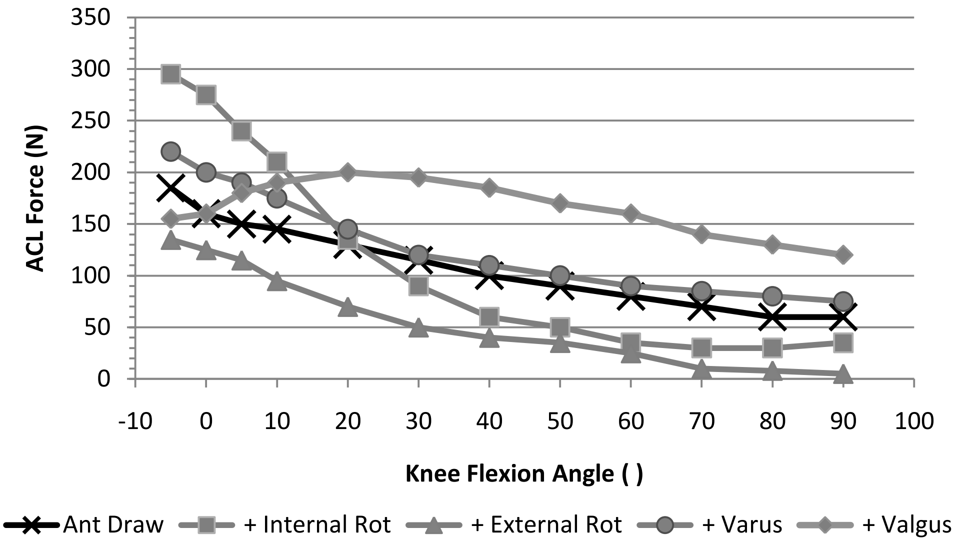

Figure 2-1 Effect of combining anterior drawer loads with out of plane loading. (Adapted from Markolf et al.[140]).

The previously described studies were all based on cadaveric data. While providing a good representation of the loading of the ACL, it is clearly not ideal. To overcome this there have been a series of studies that have investigated ACL strain *in vivo*.[17-19, 64-66] These studies support the notion from cadaveric studies that ACL loading is moderated by knee flexion angle. They also show that anterior drawer forces arising from quadriceps action leads to increased strain on the ACL. The ACL is also strained by internal rotation loads. While in unweighted situations valgus loads were not shown to strain the ACL; however during weight bearing valgus loading did strain this ligament[65]. As non-contact ACL injuries occur during stance,[24, 38, 116, 168] from an injury point of view this weight bearing loading is highly relevant.

2.3.3 Muscle Activation and Ligament Loading

The *in vivo* studies undertaken by Beynnon and colleagues[17, 18] have demonstrated that at flexion angles less than 50° isolated quadriceps contraction increases strain on the ACL. This finding supported the conclusions from cadaver based studies,[97, 125, 139] all suggesting that reducing quadriceps contraction during sporting tasks may reduce ACL loading. However Annue et al.[9] found that contraction of the quadriceps at 30° of knee flexion, increased the stability of the knee and additional external load was required to rupture the ACL. The contraction of the gastrocnemius muscle has also been show to increase the strain on the ACL.[66] Conversely the natural action of the hamstrings will reduce anterior drawer at the knee, and both *in vivo* and cadaveric studies have identified that co-contraction of the quadriceps and hamstrings muscle groups can reduce the applied load to the ACL.[18, 66, 124, 141] Therefore it would appear that while the contraction of quadriceps in isolation has the potential to increase the load on the ACL, co-contraction of the musculature crossing the knee reduces the applied load. Co-contraction would therefore appear to be beneficial in terms of reducing the risk of ACL injury.

2.3.4 The Anterior Drawer versus Valgus Loading Debate

There is debate within the injury literature as to which loading is the most important in regard to non-contact ACL injuries.[149, 217] In particular is the anterior drawer load generated by the quadriceps in landing and sidestep cutting tasks sufficient to rupture the ACL? DeMorat and colleagues[50] identified that a quadriceps load of 4500N applied at 20° of knee flexion was capable of rupturing the ACL in cadaveric knee. However, it has been suggested that at 20° the quadriceps are not capable of producing this load.[149] DeMorat et al. also had no simulated hamstring activation during testing, therefore not reflecting the co-contraction seen in sporting tasks *in vivo*.[15] Modelling work by McLean and colleagues[147] found that quadriceps action on their own were not sufficient to rupture the ACL, even with the no activation of the hamstrings. Rather they argue that valgus loading is required. When compared to straight running in sidestep cutting, Besier and colleagues[14] found that there was no difference in extension moments that needed to be generated by the quadriceps, but large valgus and internal rotation moments were applied. This also suggests that these latter two loading directions are critical for ACL injury. The posterior directed ground reaction force has also been identified as being capable of causing a posterior drawer force, countering any force generated by the quadriceps.[188]

However, there is yet to be an analysis of loading environment and muscular support during injury *in vivo*, and such a design is unlikely, the debate remains. The middle ground may provide the best compromise. In fact recent work by Lin and colleagues[127] identified that during simulations of a stop jump task, loads on the ACL capable of causing injury occurred when there was loading in all three planes compared to repetitions resulting in safe loading. Therefore for this thesis it will be assumed that during sporting tasks the quadriceps pre-load the ACL with anterior drawer and the addition of valgus and/or internal rotation is required to rupture the ACL.

2.4 Risk Factors for Non-Contact ACL Injury

Risk factors can be grouped either as external and internal[92, 197] or into four groupings consisting of; environmental, anatomical, hormonal and neuromuscular biomechanical factors.[78] Environmental risk factors are equivalent to external risk factors, while the remaining factors fall within the internal grouping. A further delineation can be made, between those risk factors which affect loading of the ligament and those which affect the strength of the ligament. This is important when assessing the potential for development of intervention programs. With reference to the stated risk factors the strength of the ligament is affected by an individual's hormonal environment and anatomy. While interventions within these risk factors are theoretically possible there are related ethical issues. Ligament loading is affected by the external environment as well as the individual's neuromuscular biomechanics. Much of the work on environmental risk factors has focussed on sporting surfaces,[169, 181] with indications of weather effects.[175, 178] As such interventions into the environmental factors have major practical limitations, particularly when aiming to reduce injury at the community sport level. Therefore neuromuscular biomechanical factors have the best potential to provide prevention protocols to reduce the incidence of non-contact ACL injury.

The remainder of this section will briefly discuss risk factors for injury with limited scope for intervention. Neuromuscular biomechanical risk factors will be addressed in more detail within the next section.

2.4.1 External

Much of the work on external risk factors has focused on the interaction between the stance foot and the ground. The general argument is that an increase in friction between the foot and the ground will cause higher knee loads, and in turn higher ACL loading.

2.4.1.1 Meteorological

Work by Orchard et al.[175, 178] identified that within the AFL, rainfall and evaporation measures were associated with non-contact ACL injuries. Specifically high evaporation in the month prior and low rainfall in the preceding year were associated with injury. They proposed that these factors resulted in a harder ground and therefore greater traction between the shoe and the ground. Investigations into ground hardness, within the same cohort, demonstrated a non-significant increase in risk of injury associated with instrumentally measured ground hardness.[176] However, this has not been supported through further analysis.[181] This probably because ground hardness is not necessarily related to foot-surface traction. Indeed, within the American National Football League very cold weather, when frozen ground conditions are possible, was associated with a reduction in ACL injuries.[179] The authors hypothesised that reduced foot-surface traction due to the frozen ground may have been the moderating factor.

2.4.1.2 Sports Surface

There have been a number of studies which have found that different surfaces are associated with a different level of risk for non-contact ACL injury. Orchard et al.[181] identified that injuries were more likely to occur on grounds using bermuda grass compared with rye grass. Although the authors did express the opinion that this result should be taken with caution, as there were a number of confounding factors, they thought that the bermuda grass, with a greater thatching than rye grass, may have high foot-surface traction, Within American football synthetic turfs have shown to have a reduced risk of injury compared with natural grass.[156] However, in older style artificial turfs, with higher foot-surface traction than new varieties, the inverse has been found to be true.[194] Investigations in European handball have found that there is an increased risk of injury on artificial floors for females but not males.[169] The artificial floors were found to have a greater coefficient of friction, suggesting this as the causal link. Further work is needed to definitively identify the surface characteristics that may increase risk of ACL injury. However, there are major practical and expense limitations in using this as a preventative tool at a nationwide community level.

2.4.1.3 Footwear

During participation in sports played on turf the vast majority of athletes will wear some form of shoe with cleats. The design of cleats has been shown to be a moderator of loads at the knee,[73] with shoes creating higher torsional resistance being associated with an increased injury risk.[118] However, while it may be possible to show that a certain cleat design may have an increased risk of injury, most athletes' first choice of shoe will be based upon performance characteristics. Increased liner traction has been shown to increase performance,[205] and to achieve this may require an increase in rotational torsion, know to increase injury risk.[118] An number of cleat designs in current use have been found to exceed proposed safe levels of rotational torsion release.[221]

2.4.2 Internal

2.4.2.1 Anatomical

There have been a number of anatomical features which are thought to increase the risk on ACL injury, including; Q-angle, knee valgus, foot pronation, femoral notch width, ACL geometry, joint laxity and anthropometric measures, such a tibia length.[77, 78, 92, 197, 208] However, current literature is not sufficient to provide clear causal links to ACL injury and should links become established, it is likely that there will be difficulty in providing an appropriate intervention.[78, 197]

2.4.2.2 Hormonal

Hormonal differences between males and females, particularly with reference to the hormones associates with the menstrual cycle, have been suggested as a potential cause of the disparity in ACL injury rates between males and females. It has been proposed that female sex hormones have the potential to modify ligament, strength,[227, 228] and joint laxity[206] across the menstrual cycle. These changes have been suggested to present a higher risk of injury during certain periods of the menstrual cycle. A review of seven studies investigating this relationship identified that females are at greater risk of suffering a ACL injury in the pre-ovulatory phase of the menstrual cycle.[95] However there are difficulties in accurately establishing the phase in which a athlete was in at the time of injury, so further work needs to be undertaken in this area to firmly establish a relationship.[95, 207] However, even with further understanding of the relationship, it is questionable how the knowledge could be used to develop appropriate interventions, apart from exclusions periods from playing the game.

2.5 Neuromuscular Biomechanical Causes of Non-Contact ACL Injury

Prior to developing prevention programs it is essential that there is an understanding of the neuromuscular factors that may cause or prevent injury. Investigations into this area either analyse actual injury through athlete interviews, retrospective video analysis, or through the laboratory analysis of sporting tasks shown to be associated with non-contact ACL injuries. The remainder of this section deals with these types of analyses.

2.5.1 Analysis of Injury

Analysis of actual injury situations is invaluable, as it provides; a guide to the kinematics at the time of injury, playing environment and game situation and potential causes of injury. These are factors such as contact, and indications as to the potentially dangerous loading environment at the knee. These analyses can be undertaken utilising athlete recall of the event, or through the analysis of videos of the injury event. Both techniques have their limitations. Interview and questionnaire studies are limited by the ability of the injured athlete to recall the situation at the time of injury, while video analyses are limited by the number of injuries they are able to access and the quality of video. However, it has been shown that there is consistency between the methods for variables describing play situations.[168] Following is a brief summary of the findings of each technique.

2.5.1.1 Interview and Questionnaire Studies

There have been a number of studies which have used some form of questionnaire or athlete interview to identify the characteristics of ACL injuries.[8, 24, 60, 84, 157, 158, 162, 168] The majority of investigations have reported that deceleration and change of direction involved in the sidestep cut, this cut being the most common sporting manoeuvre leading to injury.[8, 24, 60, 84, 157, 158] However, Nakajima and colleagues[162] reported a landing mechanism as the most common manoeuvre during injury. Landing was also identified in most other studies as the second most common mechanism.[24, 157, 158] There is little consistency between studies as to motion of the knee joint during injury. Boden et al.[24] reported that most injured athletes stated that their knee was close to full extension at the time of injury. However, within this study there were discrepancies with knee motion after injury with eleven reporting varus collapse and nine reporting valgus collapse. Mykelburst et al.[158] described similar variation between internal and external rotation of the tibia, while Arnold et al.[8] reported a more consistent 81.6% of athletes identifying internal tibial rotation as being linked to their ACL injury. It is difficult to interpret this variation, as much of it may be due to poor recall or understanding of questions by the injured athletes, demonstrated by six of 18 injured athletes responding "not sure" to the question of how the knee collapsed within Mykelburst et al.'s 1998 study.[158]

The two studies by Mykelburst and colleagues[157, 158] and the study by Olsen et al.[168] provide some information on the status of the athlete within the game at the time of injury. Most athletes were handling the ball in attack at the time of injury. While the majority of injuries were non-contact, athletes were often in close proximity to an opposing player at the time of injury, indicating that their movement may have been affected in some way by the game situation.[168] The largest limitation to this data is that it only sampled players from European handball. Further work should be undertaken to identify if this holds true in other sports.

2.5.1.2 Video Analysis of Injury

Video analysis of ACL injuries has found that, as with the questionnaire/interview data, the majority of non-contact injuries occur during sidestep cutting and landing tasks.[24, 38, [116, 168] This agreement indicates that these two sporting manoeuvres should be an integral feature in the design of laboratory research and prevention protocols. Athletes also tended to be in attacking situations, while in control of the ball, with opposing players in close proximity.[24, 56, 116, 168] These opposing players have been suggested to alter the movement of the injured athlete, or cause the injured athlete to perform a sudden change of direction manoeuvre.[24, 56, 168] There are some discrepancies in regards to travelling speed prior to injury. Cochrane et al.[38] reported that the majority of injuries occurred at a slow to medium jog (< 5 m/s), while the majority of injuries were classified as "high intensity running below sprinting" by Olsen et al..[168] This discrepancy may be due to differences in the study populations, Australian footballers for Cochrane et al. and European handballers for Olsen et al., but further work should be undertaken to better understand the relationship between approach speed and non-contact ACL injury.

All studies agree that at initial foot contact the knee was close to full extension, with no reported knee angle greater than 30°.[24, 38, 56, 116, 168] Interestingly, while females have been identified as having a greater risk of injury, Krosshaug et al.[116] identified that injured females were more flexed at the knee than their male counterparts during manoeuvres leading to injury. At initial contact these differences were of a mean magnitude of 6°, with the authors suggesting that knee flexion angle and anterior drawer from quadriceps contraction does not explain the differences in injury rates between males and females. Further investigation in this area is warranted.

Assessments of the frontal plane lower limb postures have also been performed. Ebstrub and Bojsen-Møller[56] reported that during three case studies the knee was in valgus at initial contact. Olsen et al.[168] and Krosshaug et al.[116] both reported estimates of knee valgus angle at initial foot contact. Krosshaug et al. reported angles of between 0° and 7°, while Olsen et al. reported higher values, ranging from 5° to 20°. Since both studies used multiple assessors the reported discrepancies may be caused by differing interpretations of valgus angle and/or viewing angle of the injury on the video. Krosshaug et al.[116] reported that the hip tended to be abducted, reporting angles of up to 38°. During sidestep cutting injuries a foot placement outside the knee was identified by Olsen et al.,[168] with a number of injuries identified as having "…an unusually wide foot placement." Other joint postures associated with injury are external foot rotation[168] and torso positioning out of alignment with the lower limb.[24]

There have been two recent studies which have compared videos of non-contact ACL injury to videos of similar tasks during which no injury occurred.[25, 96] Boden et al.[25] found that there was decreased ankle plantar flexion and increased hip flexion in the injured athletes, however there was no difference in knee flexion angle between the two groups. In the corresponding study by Hewett et al.[96] a trend towards increased torso lateral flexion in the injured athletes was identified. While a novel approach to investigating joint posture during injury, these studies were limited in the number of uninjured videos analysed, six in Hewett et al. and 27 in Boden et al. There is also no information provided as to the inclusion criteria used to select the videos of the uninjured manoeuvres. Further investigation into the performance characteristics of uninjured athletes should be undertaken utilising similar protocols used in studies investigating actual injury.

The majority of video studies have identified that the knee tends to collapse into valgus at the point of injury.[24, 38, 115, 168] This is indicative of an applied valgus load to the knee during the injury.[38] There is less agreement on tibial rotation, with some athletes demonstrating external rotation and some internal rotation.[24, 38, 115, 168] Cochrane et al.[38] also identified that for sidestep cutting tasks the most common direction of 'giving way' was internal rotation. These valgus and internal rotation directions of collapse are consistent with the knee loading directions that have been shown to create high forces in the ACL.[140]

The largest limitation in video analysis is the ability to source large numbers of videos of injury, of sufficient quality, to permit analysis. Within the seven studies described in this section, there have been a total of just 169 videos analysed,[24, 25, 38, 56, 96, 116, 168] which represents a small proportion of the incidence of ACL injuries. Cochrane et al.[38] reported that during the seven year period of review 78 ACL injuries occurred within the AFL, with videos available for just 37, with three of these not suitable for analysis. However, the consistency between the five studies suggests that the videos analysed are representative of typical ACL injuries.

The second limitation is the ability to accurately estimate joint positions and joint movement from un-calibrated video footage. Olsen et al.[168] attempted to limit this by having three independent assessors with experience within video analysis, assess the injury footage. However, they reported differences between assessors ranging from 5° and 10° for the three angles presented. In fact it has been shown that when compared with results from a 3D motion analysis system experienced observers analysing video footage from multiple cameras of the same trials underestimated knee flexion angle by 19°.[115] As the subject in these videos was wearing limited clothing it would be expected that errors may be magnified when analysing injuries from game settings where clothing obscures the joints to be analysed. Krosshaug and colleagues[117] have recently used an image matching technique[114] on two team sports where non-contact ACL injuries occurred; one landing and one sidestep cutting. This allowed for the generation of time series data for joint kinematics. During the landing knee flexion went from 13° at initial contact to 38°, 30 ms post-contact, with a reported valgus knee angle of 14°. In the sidestep cutting task at initial foot contact the athlete had an abducted and externally rotated hip with knee flexion of 11°. After 40 ms knee flexion had increased to 31°, with a peak valgus angle of 15° observed. As the greatest transmission of valgus loading to the ACL occurs between 20° and 40° of flexion,[140] this suggests that it is knee angles, within this range, which may be most dangerous from an injury perspective. Studies using these methods have the potential to significantly improve our knowledge of injury, although it is currently limited due to time demands as it takes approximately two months to analyse one second of video. Should further results be produced, we may be able to draw more definitive conclusions from this approach.

2.5.1.3 Summary of Injury Analysis

Non-contact ACL injures appear to occur when attacking and in control of the ball. The knee tends to ‘collapse’ into valgus, with associated internal or external rotation. At initial foot contact athletes tend to have an extended leg, abducted hip causing a wide foot placement outside the knee, and may also have an externally rotated foot and misaligned torso. While the information gained to date is invaluable, further research should be undertaken using the image matching techniques [114] to allow for a clearer understanding of the non-contact ACL injury mechanism.

2.5.2 Laboratory Analysis

In order to better understand the causes of non-contact ACL injury there has been numerous laboratory studies. These studies have focused on investigating the kinematics, kinetics and muscular support of sidestep cutting and landing tasks as these are, as previously stated, the sporting manoeuvres in which the majority of non-contact ACL injuries occur. Comparisons have been made to tasks with low injury risk, between males and females and investigations into the relationship between kinetics and kinematic as well as the relationship of both to injury.

2.5.2.1 Ecological Validity

While the laboratory testing has utilised landing and sidestep cutting tasks this does not necessarily make the testing ecologically valid. In order to be ecologically valid the tasks used in testing should be representative of the injury situations. Therefore laboratory tasks should be reflective of the attacking phase of sport and have features that cause the manoeuvre to be perturbed.

This has been better achieved in sidestep cutting tasks than landing. During their laboratory studies of cutting tasks Besier and colleagues[13] introduced unplanned sidestep and crossover cutting tasks in an attempt to better mimic injury situations. The unplanned tasks simulate the requirement to suddenly react to a defender, reflecting both features common to injury scenarios. The above research found that unplanned tasks resulted in an increase in both the valgus and internal rotation moments when compared with planned sidestep cuts. Unplanned sidestep cuts have now been incorporated in a number of studies investigating the relationship between non-contact ACL injuries and sidestep cutting.[100, 119, 120, 192, 193] Further McLean and colleagues[148] found that the addition of a static 'defender' altered participant kinematics in planned sidestep cutting tasks. Chaudhari et al.[36] have also demonstrated that the requirement to carry a ball results in increased peak valgus moments at the knee.

During landing tasks Sell and colleagues[204] required participants to perform a two foot stop jump task with a cue used to indicate the jump direction (vertical, left or right) provided just prior to landing. Borotikar and colleagues[26] undertook a similar protocol, but they utilised a one legged landing, randomly cued as planned and unplanned, followed by a jump towards the contralateral side. Both studies found differences between planned and unplanned tasks, with higher loadings in the unplanned tasks. Cowling and Steele[40] recorded an increase in muscle activation when the performer was required to catch a ball, compared with a normal landing. However the majority of laboratory investigations using landing tasks have used tasks that are not necessarily ecologically valid, such as drop jumps/landings,[67, 91, 105, 107, 108, 112, 151, 182, 198, 220] vertical jumps[106, 122, 171] and stop jumps.[33, 35, 88, 226] Results from these studies nonetheless still provide valuable information as to the neuromuscular biomechanical causes of non-contact ACL injury.

2.5.2.2 Knee Joint Loading

Within the literature external knee moments have been used as a surrogate measure of non-contact ACL injury risk.[14, 33, 36, 113, 119, 150, 182, 204, 209] Nevertheless it should be highlighted that the moments are not equivalent to residual joint loads or ACL load. In this regard, firstly some of the measured external moments may be supported by the musculature crossing the joint, subsequently the residual load directly applied to "muscle-less" joint maybe different.[131] Secondly, some muscle activation patterns may result in the muscles increasing residual loading. Finally, some of the loading not absorbed or generated by the muscles may be absorbed by other structures in the knee.[131] However, externally applied moments are the best surrogate measure of non-contact ACL injury currently available in the laboratory setting.

Besier et al.[14] compared two sidestep cutting tasks with both straight running and crossover cutting. They identified that sidestep cutting tasks had higher valgus and internal rotation moments when compared with both the other tasks in early stance. Valgus moments were of up to six times greater than the varus moment found in straight running. Similarly, internal rotation moments were up to four times greater in the sidestep cuts compared with running tasks. There were no differences found for flexion moments during the same time periods. As both valgus and internal rotation moments load the ACL, the authors argued that as non-contact ACL injuries usually occur during sidestep cutting, and not running and crossover cutting, that it is the increases in these moments which increase the risk of injury during sidestep cuts. While Besier et al.[13, 14] used mean values across three different phases, results from Landry and colleagues[119, 120] from the same cohort published over two studies reported similar differences in peak values for valgus loading. Hewett et al.[91] in a prospective design reported that females, who suffer an ACL injury during a season recorded increased valgus moments in landing tasks undertaken at the start of the season compared with injury-free athletes. Again there were no differences between groups of knee flexion moment. Similar results have been reported when comparing females post-ACL reconstruction to uninjured athletes.[182]

2.5.2.2.1 Modifiers of Joint Moments

As previously mentioned joint moments have been shown to increase when sidestep cutting and landing tasks are performed in unplanned conditions. Peak valgus and internal rotation moments respectively increase by 50% and up to 129% in sidestep cutting when compared with running.[13] Unplanned drop jump tasks show an increase in both flexion and valgus moments compared with the planned situation.[204] These reflect injury scenarios, where the need to suddenly react to other athletes has been demonstrated.[24, 56, 168]

The one study reporting the impact on knee moments of carrying sporting implements in sidestep cutting demonstrated that this simple, common sporting task can increase valgus moments compared with situations where no implement was carried. Chaudhari et al.[36] found that when a ball was held one handed in the ipsilateral arm to the support leg, there was a significant increase in the valgus moment compared with the no ball situation. However, interestingly this was not the case when the ball was held in the contralateral arm. The authors attributed this to the requirement to carry the ball in the ipsilateral arm reducing its ability to stabilise the body in the frontal plane. This constraint is not present when the ball is carried in the contralateral arm. This suggests that upper body kinematics are also related to knee joint loading. Ford and colleagues[68] found that during drop vertical jumps the use of an overhead target, consisting of a suspended basketball, increased the knee flexion moment.

Fatigue has been shown to affect knee joint moments. In landing tasks it has been shown to increase the valgus (or decrease varus) moments, increase internal rotation moments and decrease knee flexion moments.[34, 113, 151] The increase in valgus and internal rotation moments has the potential to increase the load on the ACL and therefore the risk of injury. Conversely the reduction in flexion moment suggests a decrease in applied anterior drawer, reducing the risk of injury. In sidestep cutting, fatigue has been shown to increase the knee flexion moment with no change in valgus or internal rotation moments.[200] This has the potential to increase the risk of injury however further research is needed. In order to account for this effect of fatigue on knee moments, during this thesis all tasks were presented to participants in random order during testing sessions.

2.5.2.2.2 Male/Female Differences

Comparisons between males and females performing sidestep cuts have demonstrated that females consistently have higher peak valgus moments than their male counterparts.[119, 150, 209] Sigward and Powers[209] also reported a difference in flexion moment for this task. This study also found increased quadriceps activation and suggested that females may be more at risk of anterior tibial translation loading the ACL. Within the landing phases of drop jump and stop jump tasks, females have been shown to record higher valgus moments compared with males.[33, 151] However, this difference was not observed by Kernozek and colleagues[113] when using drop landings, which may be due to the very controlled nature of drop landings. McLean et al.[151] found that the internal rotation moment was increased for females during landing tasks. These results appear to demonstrate that females exhibit increased joint moments that are known to load the ACL.

2.5.2.3 Joint Kinematics

There have been numerous studies investigating the kinematics of sidestep cutting and landing tasks. These have ranged from descriptive studies in field situations[4] to studies linking measured kinematics to loading and injury risk.[91, 150] The vast majority of studies have used the joint postures at initial foot contact to describe the kinematics of the tasks. As such this was the approach taken in this thesis.

2.5.2.3.1 Varus/Valgus and Internal/External Rotation Angles at the Knee

In both sidestep cutting and landing studies a number of researchers have reported knee varus/valgus and internal/external rotation angles at the knee,[26, 35, 67, 91, 99, 108, 121, 136, 146, 150, 182, 204, 209, 210] however the reliability of measuring these variables is low. A review by McGinley et al.[144] found that across 15 studies the average coefficient of multiple correlations within assessors was 0.74 for varus/valgus angles and 0.54 for internal/external rotation angles compared with 0.96 for flexion/extension angles. Reported varus/valgus and internal/external rotation angles are also lower than reported errors associated with such angles.[12, 16, 110, 144, 189] As such this thesis is not utilising these angles and they have been excluded from this review.

2.5.2.3.2 Joint Postures Associated With High Loading and Injury

Hewett et al.'s[91] study investigating the relationship between laboratory measures of a drop landing and injury, found that athletes going onto suffer an injury demonstrated lower maximal knee flexion angles, but no change in angle at initial foot contact. During sidestep cutting tasks McLean and colleagues[150] found that increased valgus moments during stance were associated with increased hip flexion and internal rotation postures, at initial foot contact. Sigward and Powers[210] compared the kinematics of subjects with high peak valgus loadings to those with low valgus loadings. They found that the high loading group demonstrated a more internally rotated foot and greater hip abduction and internal rotation joint posture at initial foot contact. This is similar to joint posture seen in video analysis of injury and may suggest that these postures should be avoided.

2.5.2.3.3 Male/Female Differences

A number of studies have found that women demonstrated decreased hip and particularly knee flexion during landing tasks.[47, 102, 121, 172, 199] However within this group of studies two found no differences in hip flexion angle[47, 121] with two further studies[41, 151] finding no differences between either hip or knee flexion between genders. Further, work by Fagenbaum and Darling[58] found women had higher knee flexion angles at initial foot contact and 200 ms post initial contact. Kernozek et al.[113] also demonstrated females landed with increased hip flexion. Similar results for hip and knee flexion have been found in sidestep cutting tasks. While some studies have identified decreases in knee flexion[136, 148] others have found no differences.[119, 146] Hip flexion has also been shown to be reduced in female athletes during sidestep cutting tasks.[119, 148] It would however appear that females tend to have a more extended lower limb posture during sporting tasks. As females have an increased risk of ACL injury, this is in agreement with the increased ACL loading at more extended knee postures.

Various studies have also demonstrated differences in other joint postures between males and females. It has been consistently shown that females land with greater ankle plantar flexion than their male counterparts.[47, 112, 151] In sidestep cutting task females have been shown to have less hip internal rotation[148] and greater hip external rotation.[119] Conversely in landing tasks, Lephart et al.[121] found females had greater hip internal rotation, though other studies using different landing tasks found no differences.[148] Females have also been shown to have decreased hip abduction during sidestep cutting.[148] This is opposite to what would be expected based upon joint position in injury data, then again this result has only been demonstrated in one study. Cowling and Steele[41] reported no differences in trunk flexion angles between males and females in landing tasks.

2.5.2.3.4 Modifiers of Joint Kinematics

The requirement to catch a ball has been show to modify both hip and trunk kinematics, but not knee angle during landing tasks.[40] This study used 2D video analysis and the authors noted that the changes may have been within measurement error. While the results may be questionable, it is an area of potential research and using 3D measurement techniques should be able to provide more reliable data.

As with kinetics, the performance of tasks in an unplanned situation modifies the kinematics. During sidestep cutting knee flexion angle has been shown to increase in early stance when compared with straight running.[13] During walking sidestep cutting in ACL deficient patients full body kinematic differences have been identified between pre-planned and unplanned conditions.[100, 101] Investigations in unplanned landing tasks have also identified changes in lower limb kinematics.[26, 204] There is still a paucity of research in this area that should be addressed, as unplanned tasks reflect injury scenarios.

Kernozek et al.[113] and Borotikar et al.[26] have both demonstrated that hip flexion/extension is affected by fatigue in drop jumps, while McLean et al.[151] reported no change. Both these studies have found no change in knee flexion angle, while Chappell et al.[34] identified decreases in knee flexion angle following fatigue. Conversely in sidestep cutting knee flexion angle has been shown to increase following fatigue.[200] With the limited research available it is difficult to draw conclusions and further work is needed. As discussed in regards to joint kinetics during this thesis all tasks were presented to participants in random order during testing sessions to eliminate this as a confounding factor.

In an interesting study participants were required to perform a sidestep cut with and without a plastic skeleton placed just past the force plate to represent a static defender.[148] Participants were found to increase both knee and hip flexion and hip abduction with the "defender" present. To date this is the only study to attempt this, and further research could be extremely beneficial, as this represents the injury situation.

2.5.2.4 Muscle Support at the Knee

As stated previously co-contraction of the muscles crossing the knee has been shown to reduce ACL loads in cadaveric studies.[124, 141] During the performance of sporting tasks in the laboratory this co-contraction has been observed.[15, 37, 183] Co-contraction has been indentified to increase in response to increased loads from more demanding tasks.[15] This increase in co-contraction has been found to be both general and specific.[15, 183]

Females have been identified as having inappropriate or insufficient muscle activations during sporting tasks, and this has been identified as a potential cause of the increased risk of non-contact ACL injury.[94, 119, 155, 209] Recent work has identified that inappropriate activation patterns are associated with increased risk of suffering a non-contact ACL injury.[232] There is a large amount of work still required to be completed on the effect of muscle activation on the support of loads at the knee, however it was decided to focus this thesis on the relationship between joint kinematics and knee kinetics.

2.5.2.5 Control of the Upper Body

Work by Zazulak et al.[230, 231] has demonstrated that deficits in trunk stability in both genders and trunk proprioception in females are predictive of ACL injury. This suggests that when assessing sidestep cutting and landing tasks one should examine torso positioning as well as the lower limb. To date there has been very little work in this area and should be a high priority for future research.

2.5.2.6 Summary of Laboratory Analysis

It would appear from laboratory research that increases in valgus and internal rotation moments are linked to increased risk of ACL injury. The lower body postures of an extended lower limb, internally rotated and abducted hip also appear to be associated with increased risk of this injury. While there has been significant research in the area, more, well designed, work is needed to better understand injury risk.

2.5.3 Summary of Neuromuscular Biomechanical Causes

Both video analysis of injury and laboratory work suggest that valgus and internal rotation moments at the knee are associated with non-contact ACL injuries. There appear to be common body postures observed during injury, specifically; an extended leg, abducted hip causing a wide foot placement outside the knee. Athletes may also have an externally rotated foot and misaligned torso. There are reflected in the joint kinematics associated with higher loading and displayed by females, known to have a greater risk of injury.

2.6 Rational for Technique Modification to Reduce Non-Contact ACL Injury

As moderation of neuromuscular biomechanical risk factors is the main aim of prevention programs and they can be used to assess if interventions aimed at reducing the risk of non-contact ACL injury, the next step in the process is to identify the ideal design for injury prevention. Lloyd[129] suggested that intervention programs should contain balance or neuromuscular, plyometric and technique components. Interventions to date have focussed on two of these factors; balance,[31, 159, 214] and plyometric tasks.[86, 90, 137, 187] However, many of the training programs have had some features of other components. In fact it has been thought that the "…most effective and efficient programs appear to require a combination of components…"[93] However, studies which have included a technique component, have to date only focused on improving landing within the plyometric tasks.[90, 137, 187]

While most of the above mentioned studies have been successful in reducing non-contact ACL injury rates they have not been able to identify features within the protocols that were associated with the reduction in injury risk. It has been recommended that training protocols are examined in the laboratory prior to being applied in the field.[62, 129] There have now been a number of studies which have investigated how balance and plyometric training protocols affect kinematics and kinetics of landing and sidestep cutting tasks.[37, 88, 89, 98, 105, 184] Yet to date there has not been a study that has investigated the use of technique training on joint kinematics and knee moments in the context of reducing the risk of non-contact ACL injuries.

So why should technique be investigated as a potential avenue for non-contact ACL injury prevention? As previously stated there are specific joint postures which are associated with injury and increases in joint moments that are known to increase the load on the ACL. However the relationship of other joint postures, in particular torso postures, to knee moments has yet to be undertaken. Athletes performing sporting manoeuvres with postures associated with higher knee moments have greater potential to load the ACL and therefore will have an increased risk of non-contact ACL injury.

Technique modification may be able to reduce the knee moments being experienced by these high loading athletes and therefore reduce their risk of non-contact ACL injury.

Technique may be able to modify lower limb joint loadings by changing the accelerations and positions of the body segments. Sigward and Powers[210] hypothesised that the difference in joint moments seen at the knee was due to increased hip abduction increasing the moment arm of the vertical ground reaction force on the knee (Figure 2-2). Segmental accelerations of the upper body will also be different for differing joint postures and these will cause varied loading of the knee joint.

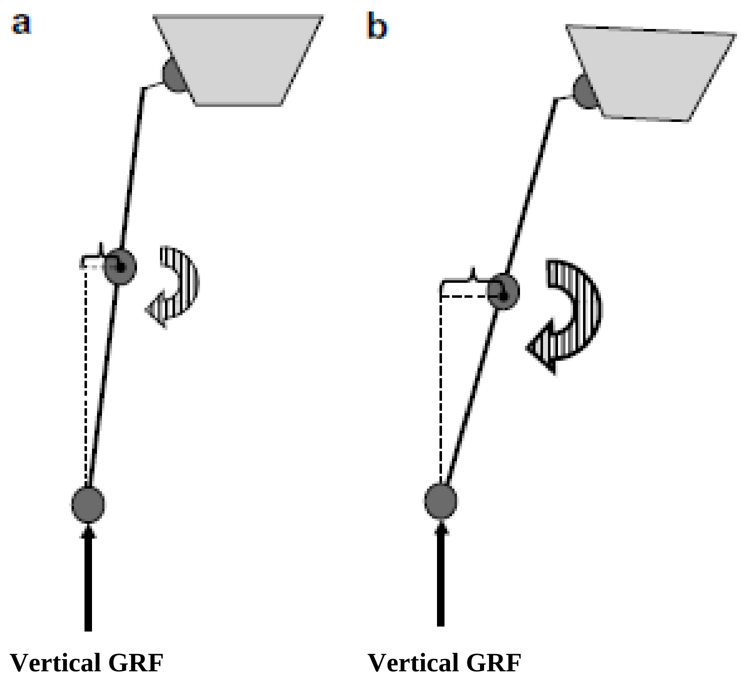

Figure 2-2 The contribution of hip abduction to the calculation of the frontal plane knee moment. Increased hip abduction moves the centre of pressure laterally with respect to the centre of mass of the tibia thereby creating a larger moment arm for the vertical ground reaction force intersegmental force (From Sigward and Powers[210]).

Can technique be varied during sporting task? Numerous studies have shown that technique modification, with its associated kinematic changes, can be achieved in one testing session.[42, 153, 171, 173, 195] A study by Scase et al.[202] investigated the effect of training on landing and falls technique in Australian football. They discovered that there was greater change of the beneficial technique over the training period in the intervention group compared with the control group. This was reflected in the intervention group demonstrating decreased injury risk.

2.6.1 Previous Intervention Studies Utilising Technique Modification

Two previous studies have attempted to modify technique in an endeavour to reduce the risk of ACL injury. Ettlinger and colleagues[57] used videos of injuries in association with key technique points to teach ski instructors to recognise and avoid dangerous postures. Although the study was successful in reducing ACL injury rates, the design cannot be readily transferred to the field sport setting, as skiing has a vastly different injury mechanism to field sports that involve sidestep cutting tasks.[22]

Henning[79, 87] taught field sport athletes to avoid using sidestep cuts and sharp decelerations, instead using crossover cuts. Interestingly, crossover cuts have since been shown to produce knee moments that possibly unload the ACL,[13, 14] when compared with sidestep cuts, and multi-step decelerations. Although this study was also successful in reducing ACL injury rates, the protocol required substantial changes to the 'standard' technique usually employed in change of direction tasks during match play and therefore may not be readily accepted by the sports community.

2.6.2 Summary of Technique Change

Technique modification has been suggested to be included in ACL injury prevention protocols with two studies to date having investigated technique modification for non-contact ACL injuries. However, they are inappropriate for general application to field sports because of the large modification from the standard technique seen in field sports, or differences in aetiology between skiing injuries and field sport injuries. No laboratory study has investigated the effect of technique modification in sporting tasks on knee joint loadings.

2.7 Summary

Due to both the severity and incidence of injury non-contact ACL injuries need to be prevented in sporting settings. This requires the development and refinement of prevention programs. The most appropriate avenue for prevention programs appears to be modification of the neuromuscular biomechanical characteristics of sidestep cutting and landing tasks. Analysis of injury situations and laboratory analysis of sidestep cutting and landing tasks has suggested that there may be techniques which increase an athlete's risk of suffering a non-contact ACL injury. While it has been suggested that prevention programs include technique components, to date there has yet to be a laboratory based study of technique modification as the central theme of an injury prevention protocol.

CHAPTER 3 GENERAL METHODS

3.1 Introduction

As this thesis is presented as a series of papers the methods are described within each of Chapters 4-8. Therefore the majority of the methods utilised will not be discussed within this chapter. However the technique modification program was developed and implemented to train both sidestep cutting and landing within one training session. As such this chapter will provide information on how the technique modification program was implemented. It will also presents where the biomechanical model utilised is described within the thesis.

3.2 Biomechanical Model

The biomechanical model utilised for this thesis was a combination of the UWA Lower and Upper Body Models. The UWA Lower Body Model is described in more detail by Besier and colleagues[16] while the UWA Upper Body Model is described in more detail by Lloyd and colleague.[128] The marker set required for both models were combined to form one marker set which is described in the methods of Chapter 4 (Figure 4-2). Chapters 5 and 6 describe the addition of a knee path rotation angle to the UWA Lower Body Model. The VICON BodyBuilder (VICON Peak, Oxford, UK) code for both the UWA Upper and Lower Body Models is provided in Appendix E.

3.3 Training Program

The technique modification program was designed to induce changes in both an athlete's sidestep cut and landing technique. It was hypothesised that this would then result in changes in knee joint moments, resulting in reduced risk of non-contact ACL injuries. The technique modification program was designed as a six week intervention during which performance tasks progressed from being classified as a closed skill to an open skill. [135] This progression required participants to move from performing the skill in a predictable environment at a time of the participant's choosing (closed skill) to performing the skill in an unpredictable environment where the execution of the skill was cued by external factors (open skill). This has been shown to produce better outcomes than only practicing a skill in an open environment.[85] The length of the program was set as six weeks, similar in length to other interventions aimed at reducing non-contact ACL injuries which have focused on pre-season training.[31, 86, 90, 187]

During sidestep cutting participants were trained to bring their stance foot closer to the midline of the body, ensure the stance foot was neither turn in nor turn out, and to maintain an upright torso, with the torso facing in the direction of travel. During landing the technique modification program aimed to bring participants' torsos facing forward and upright at initial foot contact, while increasing their knee flexion angle throughout the entire landing.

Participants attended training twice a week at either the School of Sport Science, Exercise and Health, UWA or immediately prior to team training at their sporting club. All training was undertaken in groups of one to two participants and instruction provided by the same trainer. The structure of the training session was:

1. Warm-up;
2. Sidestep cutting training;
3. Landing training.

The warm up consisted of short run followed by a number or plyometric based task to simulate the requirements of the sidestep cutting tasks. Figure 3-1 contains two examples of the warm up tasks.

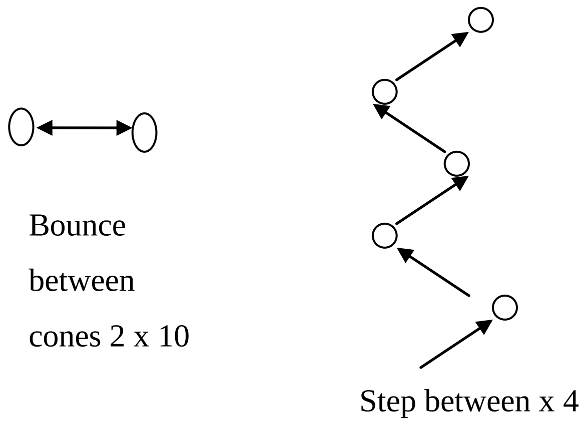

Figure 3-1 Examples of the warm up tasks. Circles indicate cones while lines indicate the direction of travel.

Following the warm up participants undertook the sidestep cutting and landing technique modification. This was constructed around weekly goals, described in Table 5-1 and Table 8-1, which then drove the development of the drills for each week (Table 3-1). During training participants were given both oral and visual feedback on their performance. Exemplar videos were used to both demonstrate the required drills and to provide comparisons for the visual feedback. Video feedback and exemplars were displayed using TimeWARP (SilconCOACH, Dunedin, NZ). These exemplar videos are available in Appendix C. To assist in providing feedback on foot placement during the sidestep cutting task three lines were painted on the ground 30 cm apart, representing the midline and extreme ranges of acceptable foot placement. As the technique changes in sidestep cutting were focused in the frontal plane the set up in Figure 3-2 was utilised. During landing tasks the camera was focused on the sagittal plane as this allowed for the capture of both knee angle and torso rotation (Figure 3-3).

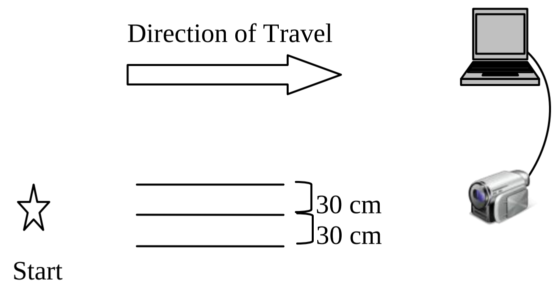

Figure 3-2 Training set up for sidestep cutting.

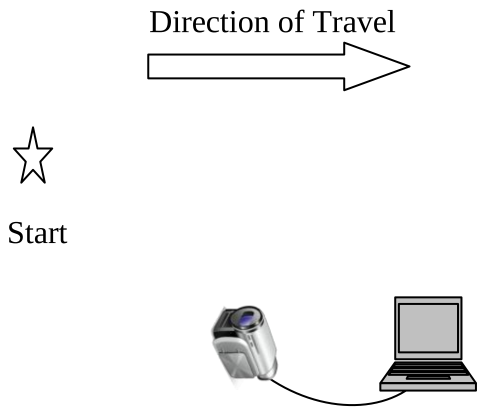

Figure 3-3 Training set up for landing

Table 3-1 Weekly training sessions

Week	Time	Tasks
1	0-2	Warm Up Drills
	2-12	• Perform self selected sidestep cut at ½ pace • Receive feedback based upon required changes • Initially receive feedback on torso angle, second session during the week they will receive information on foot position • Repeat performance with modified sidestep cut • Continue to receive feedback and perform modified sidestep cut and slowly increase pace
	12-20	• Perform one legged land from a box • Receive feedback on knee angle • Repeat
2	0-2	Warm Up Drills
	2-12	• Perform required sidestep cut at ¾ pace • Receive feedback based upon required changes • Should be able to perform the sidestep cut correctly by the end of the second session
	12-20	• Perform take off and one legged land • Receive feedback on knee angle and torso positioning • Repeat • Should be able to perform task correctly by the end of the second session

Continuation of Table 3–1 Weekly training sessions

Week	Time	Tasks
3	0-2	Warm Up Drills
	2-12	• Perform required sidestep cut at full pace working to: ◦ Performing required sidestep cut with ball • Receive feedback based upon required changes
	12-20	• Perform landing task while receiving a ball thrown straight at participant • Receive feedback based upon required changes
4	0-2	Warm Up Drills
	2-12	• Perform the required sidestep cut at ¾ to full pace • Trainer will indicate to subject if they are required to step left, right or run through using arm cues. Cues will start early and progressively get later across two training sessions • Receive feedback based upon required changes
	12-20	• Perform landing task while receiving a ball thrown to the left, right or directly to participant • During this stage balls will be thrown from the waist and early to allow the participant the best possible chance of picking up the direction early • Receive feedback based upon required changes
5	0-2	Warm Up Drills

	2-12	• Continuation of trainer directed movement direction
		• Start of defender directed movement direction
		  ◦ Defender to initially stand and then move left or right with attacker to move the other way working to:
		    ▪ Defender moving towards attacker then changing direction with attacker to go the other way
		• Receive feedback based upon required changes

	12-20	• Continuation of week 4 drills • Start of unanticipated ball direction
6	0-2	Warm Up Drills
	2-12	• Perform task successfully every time • Feedback for any required changes
	12-20	• Perform task successfully every time • Feedback for any required changes

CHAPTER 4 THE EFFECT OF TECHNIQUE CHANGE ON KNEE LOADS IN SIDESTEP CUTTING

Based on the following paper published in *Medicine and Science in Sports and Exercise*

Dempsey AR, Lloyd DG, Elliott BC, Steele JR, Munro BJ, Russo KA. The effect of technique change on knee loads during sidestep cutting. *Medicine and Science in Sports and Exercise*. 2007; 39(10):1765 - 1773.

4.1 Introduction

Injuries to the ACL are serious, costly and unfortunately common in many different sports including; basketball, soccer, lacrosse, European handball and Australian football.[38, 154, 159] In order to return to sport from a ruptured ACL, an injured athlete usually requires surgery, followed by nine to twelve months of rehabilitation.[161] The approximate cost of an ACL reconstruction is US$17,000, with the total cost of all ACL reconstructions in a given year in the United States estimated at US$850,000,000.[77] Individuals who have suffered an ACL injury also have significantly increased risk of developing knee joint osteoarthritis by the age of 50 years.[46]

Anterior cruciate ligament injuries can be classified into two broad groups; contact and non-contact. Across various sports non-contact injuries have been found to make up between 50% to 80% of ACL injuries.[6, 24, 38] As a large percentage of injuries are non-contact this indicates there is potential to reduce the number of ACL injuries occurring in sports. This may be achieved with appropriate training to change how the person performs the injury prone manoeuvres. Lloyd[129] stated that training programs to prevent ACL injuries should include balance, plyometric and technique components. Although there have been several studies examining the effect of balance and plyometric training on the risk of non-contact ACL injury,[31, 90, 98, 159] only a few recent studies have investigated changing participants' performance techniques on knee loading, and these have been restricted to landing tasks.[42, 173] As more ACL injuries occur during sidestep cutting, compared with landing, changing technique in this manoeuvre has greater potential to reduce non-contact ACL injury rates.[38, 168]

Injuries to the ACL occur when the loads being applied to the ligament are larger than the ligament's capacity to sustain them. The ACL's primary function is to prevent anterior tibial translation, but cadaveric studies have shown that the ligament is also loaded by valgus and internal rotation moments at the knee.[82, 140, 224] Previous laboratory studies have shown that when compared with running, the knee has larger valgus and internal rotation moments during sidestep cutting, the authors suggesting that the valgus and internal rotation moments are major contributing factors to ACL injury.[13, 14] Results from a prospective study of landing by Hewett and colleagues[91] supports this, finding females who had large peak valgus loads where at a greater risk of suffering an ACL injury. Video analyses in several sports have also reported that when the ACL ruptures during sidestep cutting, the knee usually collapses into valgus.[24, 38, 168] Recently it has been shown that the knee also gives way in internal rotation when the ACL ruptures during Australian football games.[38] Collectively, these results suggest that high valgus and internal rotation moments are the main cause of non-contact ACL injuries during sidestep cutting and should be reduced if injury risk is to be lowered.

Cadaveric studies have found that the resultant strain experience at the ACL in knees for anterior forces, rotation and abduction/adduction moments is modified by the knee flexion angle.[82, 140] In general terms as knee flexion angle increases there is a reduction in the resultant strain at the ACL. This appears to be reflected *in vivo*. Studies of actual injuries have found that athletes tend to have knee flexion angle of less than 30º at foot strike.[38, 168] It would therefore appear that increasing knee angle may reduce the resultant load on the ACL for the same applied load at the knee, therefore reducing the risk of injury.

Previous studies have indicated that there are differing techniques employed to perform a sidestep cut. Besier and colleagues[13, 14] identified two groupings within their subjects, one exhibiting mean valgus moments and one exhibiting mean varus moments during the weight acceptance phase of sidestep cutting. McLean and colleagues[145] observed inter-subject variability in knee angles during sidestep cutting, but did not report knee loads. It has been shown that by constraining arm movements during sidestep cutting, valgus loads at the knee are increased.[36] Increased valgus loads have also been linked to increased hip flexion, hip internal rotation and knee abduction angles.[150] However, no study has investigated the effect of imposing a range of different sidestep cutting techniques on knee loads. Therefore, the aim of this study was to identify if modifying sidestep cutting technique creates substantial and functionally important changes to knee loading. It was hypothesised that varus/valgus and internal/external rotation moments, and knee flexion angle, would be affected by changes in sidestep cutting technique.

4.2 Methods

4.2.1 Participants

Fifteen healthy, male, experienced amateur team sport athletes, with no history of major lower limb injury volunteered to participate in this study (height 182.5 ± 7.1 cm, mass 73.3 ± 10.4 kg). Experienced team sport (Australian football, rugby union and soccer) athletes were selected to ensure that they had sufficient skill in performing a sidestep cut. Our previous work comparing the differences between planned and unplanned sidestep cutting revealed effect sizes of about 0.80.[13] In the current study design to achieve similar effect sizes, which represented substantial functional differences, seven subjects were required for an 80% power and alpha of $p<0.05$. For the same power and alpha we decided to recruit 15 subjects, which gave us the power to detect a smaller effect size of 0.65. All test procedures were approved by the Human Research Ethics Committee at the UWA, and prior to data collection, written informed consent was obtained from all subjects.

4.2.2 Experimental Design

All trials were performed on a 20 m x 15 m runway and markers tracked by a 12 camera VICON MX motion analysis system operating at 250 Hz (VICON Peak, Oxford, UK), with ground reaction forces synchronously recorded at 2000 Hz from a 1.2 m x 1.2 m force plate (Advanced Mechanical Technology Inc., Watertown, USA). Subjects were asked to perform repeated trials of both normal and nine imposed sidestep cutting tasks during one testing session. Prior to commencing trials, subjects selected the preferred foot with which they would perform the sidestep cut. This foot was determined by subjects performing a sidestep cut with each leg and selecting their preferred side.

Subjects were required to perform five successful trials of each sidestep cut, which was to 45° ± 5 from the approach direction, with all subjects running at 4.5 ± 0.2 m/s during the stride before the force plate. This speed was monitored using VICON Workstation (VICON Peak, Oxford, UK) to identify the average linear velocity of a marker on the left posterior superior iliac spine across the final approach stride. Cut angle was monitored through tape markings on the ground signifying 45º ± 5, with subjects required to land with their next foot contact within these markings. All subjects performed their normal sidestep cut (NS), then sidestep cuts with nine different imposed techniques, categorised into four extreme postural groupings (Figure 4-1):

Torso lean: leaning in the same direction (T_{Same}) and leaning in the opposite direction ($T_{Opposite}$) to the direction of the sidestep cut;

Knee: knee straight ($K_{Straight}$) (as close to full extension as possible) and knee flexed (K_{Flexed}) (as flexed as possible);

Frontal plane foot placement: foot placed close to the body (F_{Close}) and foot placed away from the body (F_{Wide}); and

Transverse plane foot placement: foot turned in (F_{In}) and foot turned out (F_{Out}).

In addition, we had one extra technique modification involving the trunk rotating in the opposite direction ($T_{Rotated}$), to which we found it was not possible to have a functional opposite for this posture. The NS was performed first followed by the imposed tasks presented in random order within the functional groupings.

The imposed postures were demonstrated to the subjects using a previously prepared video (Appendix B) and standard instructions. A trial was then captured using a digital video camera and subjects were given both visual and auditory feedback on their performance. This step was repeated until the subject could successfully perform the imposed sidestep cut. This was assessed by same experimenters for each subject, using demonstration video as a reference. Once capable of performing the imposed sidestep cut, subjects undertook the trials immediately. After undertaking the trials the subject was then trained and tested on the next imposed posture. This step was repeated until all imposed postures had been completed.

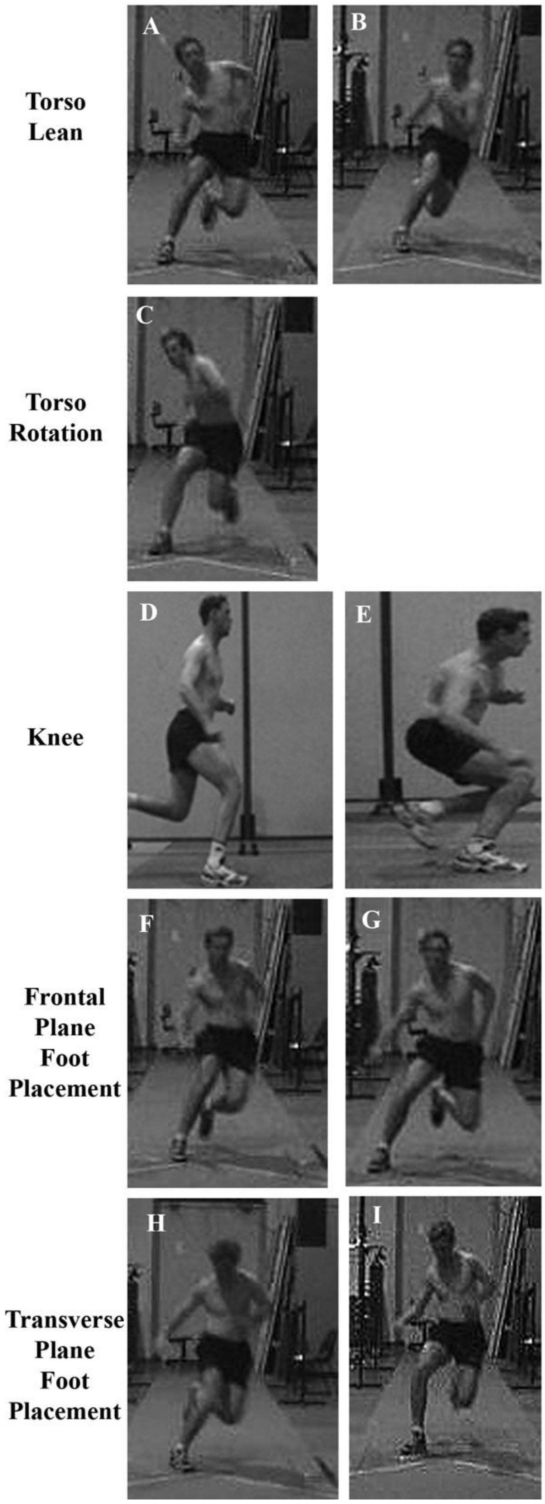

Figure 4-1 Screen shots at heel strike from the videos used to demonstrate the imposed postures to subjects. The subject is stepping off the right foot and travelling left. A) leaning in the opposite direction ($T_{Opposite}$); B) leaning in the same direction (T_{Same}); C) trunk rotating in the opposite direction ($T_{Rotated}$); D) knee straight ($K_{Straight}$); E) knee flexed (K_{Flexed}); F) foot placed close to the body (F_{Close}); G) foot placed away from the body (F_{Wide}); H) foot turned in (F_{In}); and I) foot turned out (F_{Out}).

A trial was considered successful if the subject performed the required sidestep cut with the appropriate technique, achieved a cut angle of 45° ± 5 with the foot of the leg of interest landing on the force plate and did not target the force plate. Subjects were aware of the location of the force plate but to avoid targeting they were instructed to look ahead during their approach run. Targeting was identified by either a "stutter step" during approach or "reaching" towards the force plate with the last stride. To assist in this a run up marker was used to modify the approach distance to ensure the correct foot was striking the force plate.

4.2.1 Data Collection and Analysis

To facilitate the motion analysis, retro-reflective markers were affixed to the whole body to conform to requirements of the UWA Full Body Marker Set[16, 128] (Figure 4-2), which consisted of 50 markers placed on either bony landmarks or as part of three-marker clusters. Single markers were placed on the left and right forehead, left and right rear head, left and right acromion process, sternal notch, spinous process of cervical vertebrae 7 and thoracic vertebrae 10, xiphoid process, left and right anterior superior iliac spines, left and right posterior superior iliac spines, left and right head of first and fifth metatarsal, left and right head of third metacarpal, and left and right calcaneus. Three-marker clusters were placed on the upper arm, forearm, thigh and leg and a two marker cluster on the dorsal surface of the hand. In addition, the ankle, wrist and shoulder joint centres were respectively defined using markers on the left and right medial and lateral malleoli, left and right radial and ulnar styloid processes and left and right anterior and posterior shoulder. These markers were removed during the dynamic trials. A six marker pointer was used to identify 3D location of the medial and lateral humeral epicondyles of both elbows, and medial and lateral femoral epicondyles of both legs.[16] Functional knee and hip tasks were carried to identify knee joint and hip joint centres, as was a trial with the subject standing on a foot calibration rig.[16] The latter trial was used to establish the position of the foot markers and to measure foot abduction/adduction and rear foot inversion/eversion angles.[16]

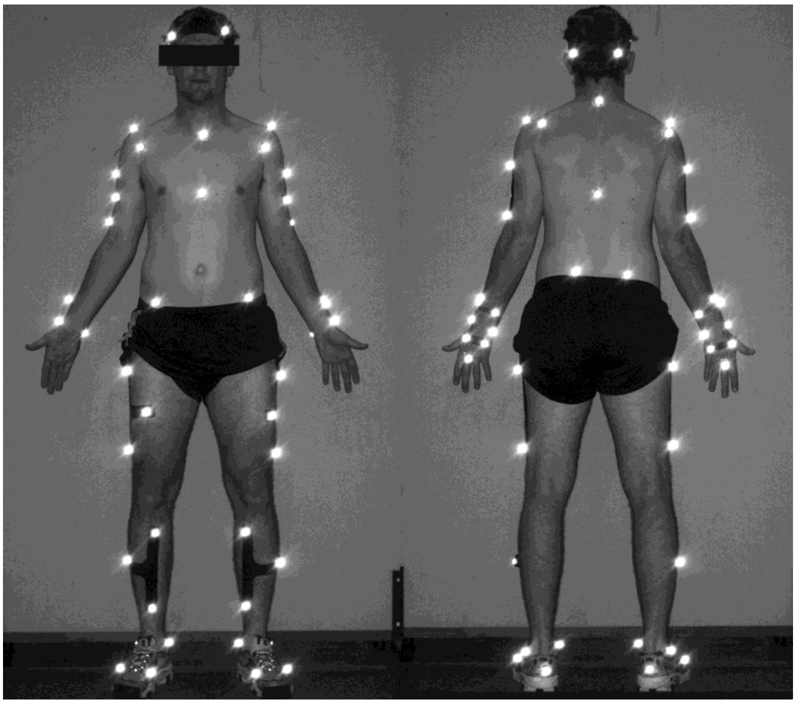

Figure 4-2 A participant showing the University of Western Australia (UWA) Full Body marker set.

Kinematic and inverse dynamic calculations were performed in VICON Workstation and Bodybuilder (VICON Peak, Oxford, UK) using the UWA Full Body Model, a combination of the UWA Upper[128] and Lower Body Models.[16] Prior to modelling, both the ground reaction force and position data were filtered using a 4^{th} order 18 Hz zero-lag low-pass Butterworth filter, the filter frequency selected by performing a residual analysis and visual inspection of the data. The UWA Lower Body Model uses a functional method to identify both the knee joint and hip joint centres.[16] The knee joint axis was located by calculating a mean helical axis using a custom MATLAB (Mathworks Inc., Natick, USA) program, with the knee centre identified as the midpoint of the femoral epicondyles along this line.[16] Spheres were fitted to each thigh marker trajectory to find a hip joint centre relative to the pelvis anatomical coordinate system, constraining it to within a 100 mm cube around a regression calculated hip joint centre.[16] The foot coordinate system was established using the data from the foot calibration rig trial, which overcame errors in placing markers while incorporating the person's measured foot abduction/adduction and rear foot inversion/eversion angles.[16] External moments were calculated with inverse dynamics[16, 109] using the body segment parameters calculated based on values in de Leva.[44]

A custom MATLAB program was used to identify a weight acceptance phase during stance. This phase was from initial foot contact to the first trough in the unfiltered vertical ground reaction force (Figure 4-3). Although the UWA group has previously analysed multiple phases of the sidestep cut, weight acceptance was selected as the sole phase to analyse in this study as the maximum magnitude valgus and internal rotation moments were found within this phase, indicating that this may be the period of high injury risk (Figure 4-4).[13-15]

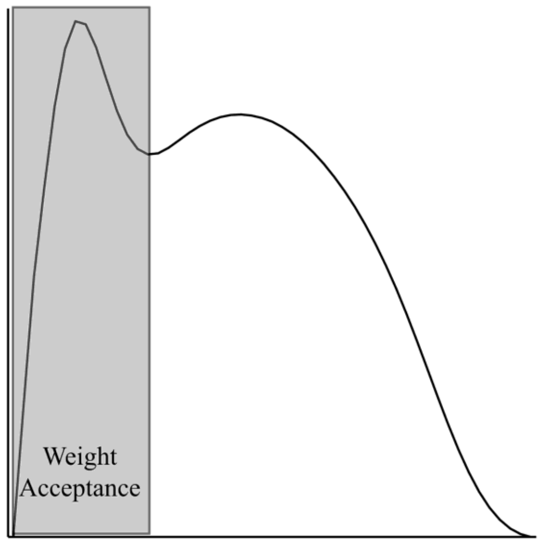

Figure 4-3 Vertical ground reaction force with the weight acceptance phase indicated.

Peak valgus, peak internal rotation and mean flexion/extension moments were identified within the weight acceptance phase. Peak valgus and internal rotation moments, rather than means, were chosen as peaks in both moments were exhibited during weight acceptance (Figure 4-4). Large peaks may constitute dangerous loading patterns. When analysing the loads experienced in sidestep cutting other groups have also used peak valgus moments.[91, 150] Mean flexion/extension moments were used as there was no definite peak within the weight acceptance phase. Knee flexion angle was identified at initial foot contact for all tasks. Joint angle data representing the imposed technique performed in the trial were determined and analysed at initial foot contact to ensure that the subjects had successfully achieved each required technique. If this was not the case the trial was rejected. In all cases three or four trials for each technique were available for analysis. A subject average was calculated from these trials.

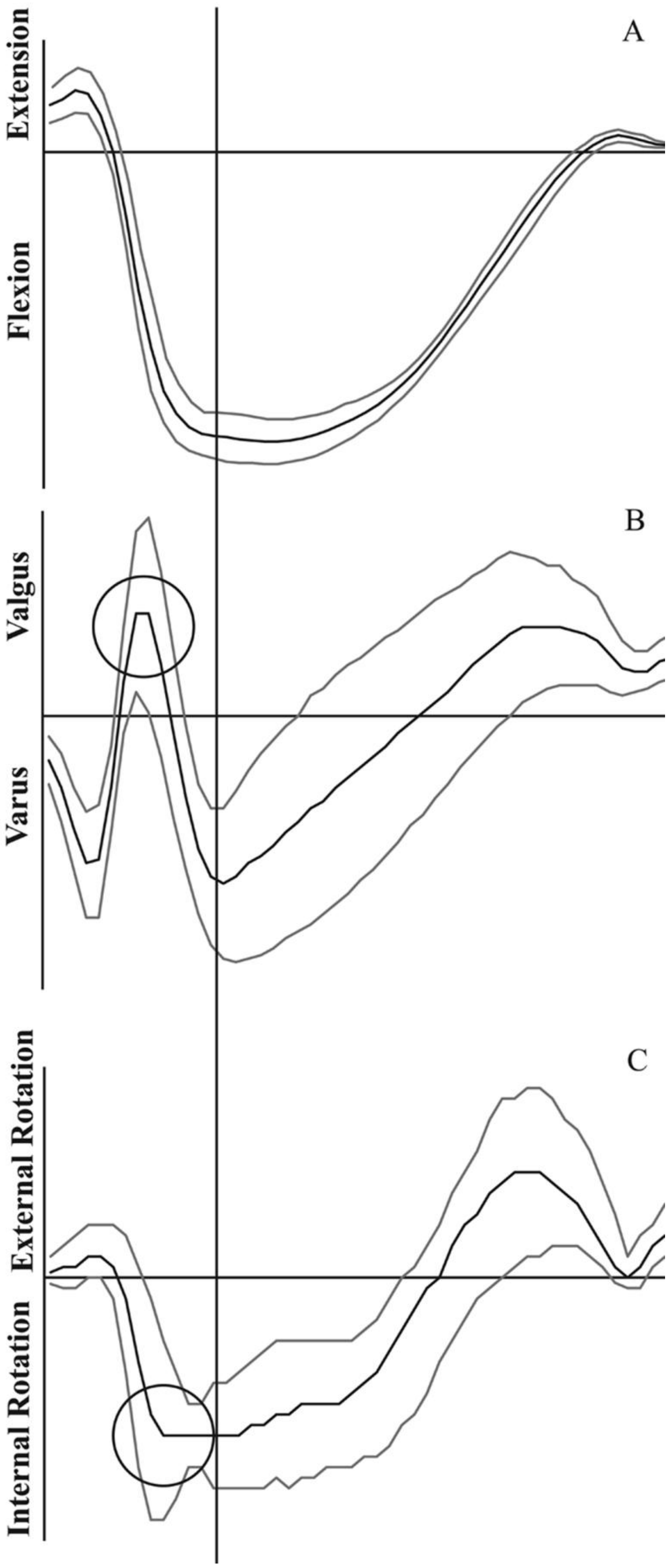

Figure 4-4 Average knee flexion/extension (A), varus/valgus (B) and internal/external rotation moments (C), averaged across all techniques. The circles indicate the peaks, whereas the vertical line indicates the end of the weight acceptance phase.

As we were interested in comparing the differences in knee moments and flexion angle between the extreme postures within each technique group and with the NS, a one way repeated measures ANOVA was performed on the following groupings: Torso lean: $T_{Opposite}$ -NS- T_{Same}, Knee: K_{Flexed} -NS- $K_{Straight}$, Transverse plane foot placement: F_{In} -NS- F_{Out}, and Frontal plane foot placement: F_{Wide} -NS- F_{Close}. Since the $T_{Rotated}$ did not have an extreme opposite posture it was only compared with NS using a paired t-test. For the paired t-test and the four ANOVAs we use an alpha level of $p < 0.05$ with no correction as all comparisons were specified a priori. However, in the post hoc comparisons within the four ANOVAs a Sidak correction applied to an original alpha level of $p < 0.05$, in preference to Bonferroni corrections which can be very conservative. To examine if relevant segment posture's angles were changed in the extreme postural groupings, we compared posture angles across all tasks using a repeated measure ANOVA for each variable utilising the same procedure described above. All statistical procedures were performed using SPSS 14.0 (SPSS Inc., Chicago, USA).

4.3 Results

There were significant differences in the relevant position data between each of the extreme postural groupings (Table 4-1). This indicates that the positions represent the extremes of a particular posture. In addition to this, four techniques also reported values significantly different to the NS: $T_{Opposite}$ had greater trunk lateral flexion away from the direction of sidestep cutting, $T_{Rotated}$ had greater trunk rotation in the opposite direction to the sidestep cut, K_{Flexed} had greater knee flexion, and F_{Wide} returned a greater foot distance from pelvis.

All tasks returned a mean flexion/extension moment with a value in the flexion range. The F_{Wide} condition returned a mean flexion/extension moment (-0.94 ± 0.36 $Nm \cdot kg^{-1} \cdot m^{-1}$) with the highest flexion value (Figure 4-5). This was significantly greater than the F_{Close} (-0.72 ± 0.38 $Nm \cdot kg^{-1} \cdot m^{-1}$, $p = 0.024$) technique. The mean flexion/extension moment displayed during the NS (-0.78 ± 0.44 $Nm \cdot kg^{-1} \cdot m^{-1}$) was significantly greater than the F_{In} (-0.59 ± 0.37 $Nm \cdot kg^{-1} \cdot m^{-1}$, $p = 0.021$) and the mean flexion/extension moment displayed during the F_{In} was also significantly smaller than its pair task of F_{Out}

(-112.96 ± 39.29 Nm·kg^{-1}·m^{-1}, p = 0.001). All other pairs produced moment values of similar magnitude except for T_{Same}, which tended to generate lower moments than during both the NS and $T_{Opposite}$.

Table 4-1 Mean (standard deviation) pertinent posture angles at heel strike for the different imposed postures

	Trunk Lateral Flexion (°)	Trunk Rotation (°)	Knee Angle (°)	Foot Rotation In/Out (°)	Foot Distance from Pelvis (cm)
NS	7.7 (8.2)	-9.7 (8.7)	17.6 (5.5)	-10.4 (14.4)	34.4 (4.6)
$T_{Opposite}$	28.6 (8.2) *#				
T_{Same}	3.1 (9.8) *				
$T_{Rotated}$		-60.0 (8.5) #			
K_{Flexed}			22.7 (7.1) *		
$K_{Straight}$			13.8 (6.7) *		
F_{In}				1.2 (10.9) *	
F_{Out}				-23.8 (6.3) *	
F_{Close}					30.7 (3.2) *
F_{Wide}					49.1 (4.1) *#

* Significantly different pair; # significant difference from NS (p <0.05).
Positive values indicate: trunk lateral flexion, leaning right; trunk rotation, left shoulder back; knee angle, knee flexion; foot rotated in/out, toe in.

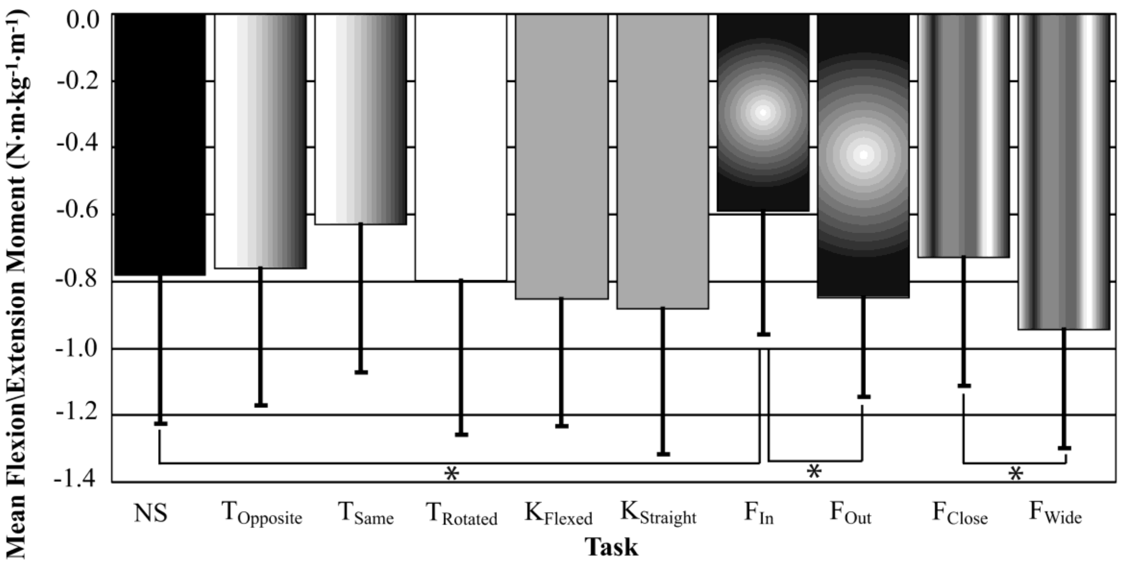

Figure 4-5 Mean flexion moment. Tasks with the same pattern were compared with each other and all tasks were compared with NS. (See Figure 4-1 for positions) Tasks that have been linked with a line and an * are significantly different at $p < 0.05$.

The highest peak valgus moment (Figure 4-6) was again returned by the F_{Wide} condition (0.79 ± 0.38 Nm·kg^{-1}·m^{-1}), which was significantly higher than both NS (0.45 ± 0.32 Nm·kg^{-1}·m^{-1}, *p* = 0.000) and F_{Close} (0.51 ± 0.37 Nm·kg^{-1}·m^{-1}, *p* = 0.003) techniques. The peak valgus moment generated during the $T_{Opposite}$ was significantly higher than its paired T_{Same} (0.65 ± 0.36 Nm·kg^{-1}·m^{-1} vs. 0.47 ± 0.36 Nm·kg^{-1}·m^{-1}, *p* = 0.030), and tended to be greater than the NS. All other pairs returned moment values of similar magnitude to each other.

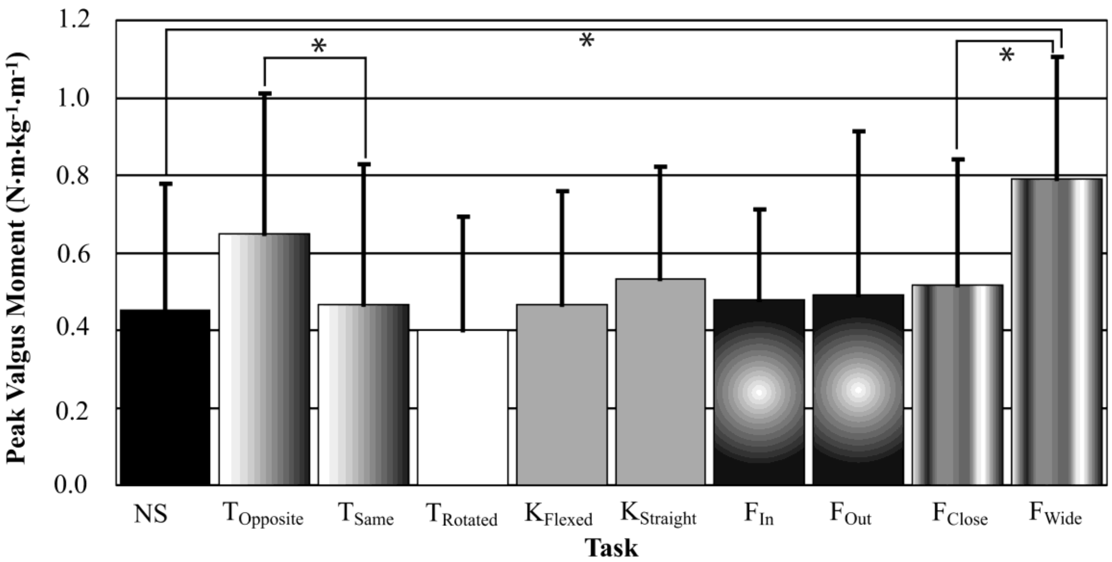

Figure 4-6 Peak valgus moment. Tasks with the same pattern were compared with each other and all tasks were compared with NS. (See Figure 4-1 for positions) Tasks that have been linked with a line and an * are significantly different at p < 0.05

Two techniques produced high peak internal rotation moments in relation to the other tasks (Figure 4-7). As with the peak valgus and mean flexion/extension moments, the F_{Wide} (-0.33 ± 0.23 Nm·kg^{-1}·m^{-1}) technique resulted in the highest peak internal rotation moment, significantly greater than the NS (-0.19 ± 0.10 Nm·kg^{-1}·m^{-1}, *p* = 0.048). The NS also generated significantly lower peak internal rotation moments than the $T_{Rotated}$ (-0.29 ± 0.10 Nm·kg^{-1}·m^{-1}, *p* = 0.001). All other techniques returned peak internal rotation moment values of similar magnitude.

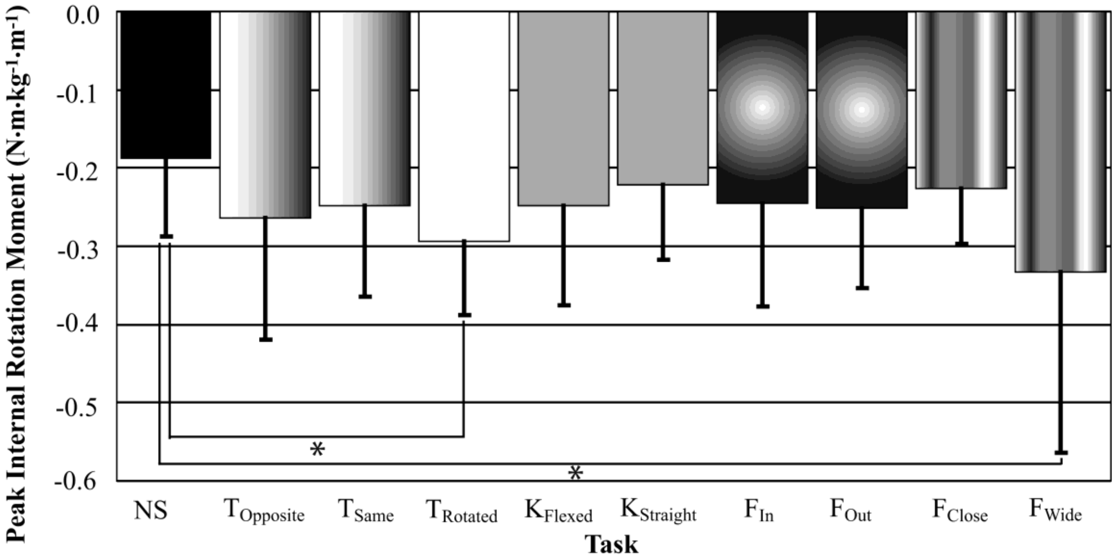

Figure 4-7 Peak internal rotation moment. Tasks with the same pattern were compared with each other and all tasks were compared with NS. (See Figure 4-1 for positions) Tasks that have been linked with a line and an * are significantly different at p < 0.05.

As can be seen from (Table 4-1) there was a significant difference in knee flexion angle between K_{Flexed} and $K_{Straight}$ (p = 0.000) as well as between K_{Flexed} and NS (p = 0.006). There were also significant larger knee flexion angle recorded in the $T_{Rotated}$ technique (23.6 ± 6.5º) compared to the NS condition (17.6 ± 5.5º, p = 0.010) (Table 4-2). The T_{Same} technique (22.3 ± 1.7º) retuned a knee angle that was significantly larger to both NS (p = 0.010) and $T_{Opposite}$ (18.2 ± 1.7º, p = 0.004). All other groupings returned similar values.

Table 4-2 Mean (standard deviation) posture angle representation common injury position at heel strike for techniques that returned high knee loads and normal sidestep cut (NS)

	Trunk Lateral Flexion (°)	Trunk Rotation (°)	Knee Angle (°)	Hip Abduction/Adduction(°)	Foot Rotation In/Out (°)
NS	7.7 (8.2)	-9.7 (8.7)	17.6 (5.6)	-10.6 (8.0)	-10.4 (14.4)
F_{Wide}	9.3 (7.9)	-6.9 (9.8)	17.3 (6.7)	-23.0 (15.2)	-22.9 (10.3)
$T_{Rotated}$	22.6 (9.0)	-60.0 (8.5)	23.6 (6.5)	-16.8 (10.6)	4.3 (9.0)
$T_{Opposite}$	28.6 (8.2)	-10.5 (9.6)	18.2 (6.7)	2.4 (9.3)	-9.9 (11.3)

Positive values indicate: trunk lateral flexion, leaning right; trunk rotation, left shoulder back; knee angle, knee flexion; hip abduction/adduction, adduction; foot rotated in/out, toe in.

4.4 Discussion

The aim of this study was to identify if modifying sidestep cutting technique creates substantial and functionally important changes to knee loading. It has been shown that externally loading the knee with valgus and internal rotation moments results in high loading of the ACL.[140] Two of the imposed postures F_{Wide} and $T_{Opposite}$ in the present study resulted in significantly higher peak valgus moments compared to their functional pair, with F_{Wide} also significantly higher than NS. In peak internal rotation moments there were no techniques that were significantly greater than its functional pair. However, F_{Wide} and $T_{Rotated}$ were significantly higher than NS. Markolf and colleagues[140] found that the combination of the two aforementioned loading directions significantly increased the strain being experienced by the ACL. Both peak moments occur in close to the same time point during the weight acceptance phase across the techniques (Figure 4-4), therefore, F_{Wide} is the technique most likely to endanger the ACL, as it returned significantly greater peak valgus and peak internal rotation moments.

For all three moments there was a general increase in magnitudes when compared to the normal sidestep cut. The average effect sizes for all moments were 0.48 for peak valgus, 0.57 for peak internal rotation and 0.45 for mean flexion/extension. However, in the tasks where a significant difference was identified there was large effect size with mean value of 0.81. The smaller increases may not be “bad” in terms of ACL injury but rather a reflection of the subjects being inexperienced at the new task. A large significant difference between a pair of tasks indicates that a functionally important increase may have been caused by the body posture, and therefore the technique that produced the high loading should be avoided.

With reference to body posture three conditions were significantly different from NS, F_{Wide}, $T_{Opposite}$, and $T_{Rotated}$. The normal sidestep cut always occurs at some point between the two extreme postures, which are always significantly different from each other. Non-significant positional change may limit the ability to identify if technique changes modify the knee moments, but as all the extremes are significantly different it is possible to identify the moment changes from these positions.

There is currently some debate as to whether a high external flexion moment is good or bad in terms of ACL injury. A high external flexion moment, as exhibited in the F_{Wide} technique, indicates a high level of quadriceps activation to prevent the knee from flexing. Some groups argue that this increase in quadriceps activation is bad as it will increase anterior translation at the knee and therefore increase ACL load.[77] The other argument is that an increase in quadriceps contraction will protect the ACL as the quadriceps have moment arms which provide support for the knee in varus/valgus and internal/external rotation.[15, 130] In addition, McLean[147] showed that when modelling sidestep cuts, the level of quadriceps action causing anterior translation of the tibia was not sufficient to rupture the ACL. The stated reasons for this were that the quadriceps were not strong enough, and the action of quadriceps was counteracted by the action of the hamstrings and posteriorly directed forces on the tibia resulting from the deceleration experienced during the first half of stance. Nevertheless, when the anterior translation produced by the quadriceps is combined with valgus and internal rotation moments, this probably represents the loading condition that constitutes the greatest risk of non-contact ACL injury.

Knee flexion angles have been shown to alter the resultant ACL strain for the same load in cadaveric studies.[82, 140] In the current study the significantly increased peak internal moment found for the $T_{Rotated}$ may not be as “bad” for the ACL as it first appears since the resultant load on the ligament may be lowered by the significant increase in knee flexion. However whether the 6º of increased knee flexion is sufficient to reduce ACL loads is unknown. The lateral hamstrings support of applied internal rotation loads at knee angles of less than 30º can reduce applied ACL load, therefore it would be expected that increased knee flexion will moderate the increased peak internal moment.[141] However the loads occurring at the knee are in three dimensions. The resultant ACL load from a valgus load increases to 30º of knee flexion, even with muscular support.[70, 124] Therefore while the peak valgus moment is of similar magnitude to NS (Figure 4-6) the resultant load at the ACL caused by the peak valgus moment may cancel out the reduction in peak internal moment due to the increased knee flexion. With the present position of the literature it is difficult to draw a conclusion as to the moderating impact of knee flexion.

Previous research investigating possible relationships between techniques and ACL injury has used video analyses of injuries occurring during games.[24, 38, 168] One major drawback in this type of analysis is there is no information about the loads being experienced at the knee, which can be assessed in laboratories studies. However, the limitation of laboratory analysis is that, while the knee loads can be calculated, they cannot be clearly linked to the actual injury. While a prospective studies laboratory, such as Hewett and colleagues',[91] allows for better links between the laboratory results and actual injury the positions achieved in the laboratory do not necessary reflect those which occur during the injury. Coupling the results from the laboratory studies and in-game injury analysis can overcome these limitations. Video analyses have suggested that an abducted hip, straight leg, foot rotated out, rotated torso and lateral torso flexion are often characteristic of non-contact ACL injuries.[24, 77, 103, 168] Three of these postures are represented in the high loading techniques identified in this study: F_{Wide} – abducted hip, $T_{Opposite}$ – lateral torso flexion and $T_{Rotated}$ – rotated torso. During F_{Wide} the foot was also turned out more than in NS, with $T_{Rotated}$ also having more lateral flexion and hip abduction than NS (Table 4-2), consistent with the postures causing ACL injury suggested by video analyses. Therefore, the current work supports the previous video analyses of ACL injury and provides the actual knee loads that may be related to the injury. It is recommended that sidestep cutting techniques that exhibit these postures should be avoided in order to reduce the risk of injury.

Athletes do not suffer an injury each time that they perform a sidestep cut, evident by the fact that no injuries were sustained during the present testing. This is the result of the external knee loads being supported by the muscles crossing the knee.[15, 130] This study did not analyse the effect technique had on muscular support and is an area of future research. Previous work has found that when sidestep cutting tasks are performed under an unanticipated condition the loads experienced at the knee in both valgus and internal rotation increase significantly with possible compromised muscular support.[13, 15] Unanticipated sidestep cuts are common during team sports, often to avoid a defender, a task which has been shown to change the kinematics of a planned sidestep cut.[148] During the current protocol all sidestep cuts were performed in anticipated conditions. Should an individual perform an unanticipated sidestep cut with a F_{Wide}

technique the knee loads experienced may be even higher and place the athlete at a high risk of injury. However, this notion requires further investigation.

Having identified sidestep cuts with techniques that may highly load the ACL the next step is to identify whether athletes can be trained to avoid using these techniques. If technique modification is successful in changing technique and reducing knee loads it can be added to current training protocols aimed at non-contact ACL injury reduction. However, in order to be accepted by the sporting community it would also need to be shown that the technique modification is not detrimental to the ability of an athlete to use their sidestep cut to avoid or intercept the opposing player. There also needs to be a long term prospective randomised control study similar to those performed by Caraffa et al.,[31] Hewett et al.,[90] and Myklebust et al.[159] to identify whether technique changes aimed at reducing ACL injuries are successful or have any effect on other injuries. Athletes are unlikely to accept training that will increase their risk of another injury as there are other training protocols that have been shown to be effective at preventing ACL injuries and do not carry this risk.[31, 90, 98, 159] If a technique modification study is unsuccessful it may also be appropriate to look at the ability to modify the technique of young, developing athletes. The motor patterns of adult, particularly elite, athletes may be harder to change, especially in unanticipated situations. This may not be true of younger, developing athletes.

4.5 Summary

In summary, sidestep cutting techniques have a significant effect on peak valgus, peak internal rotation and mean flexion/extension moments at the knee. With the identification of high risk techniques it be can speculated that it may be possible to develop training protocols that modify an athlete's sidestep cutting technique, specifically by bringing the foot to the midline and keeping the torso upright with no rotation, to reduce their knee loads and therefore *potentially* their risk of ACL injury.

CHAPTER 5 CHANGING SIDESTEP CUTTING TECHNIQUE REDUCES KNEE VALGUS LOADING

Based on the following paper accepted for publication in the *American Journal of Sports Medicine:*

Dempsey AR, Lloyd DG, Elliott BC, Steele JR, Munro BJ. Changing sidestep cutting technique reduces knee valgus loading *American Journal of Sports Medicine.* 2009;37(11):2194-2200.

5.1 Introduction

In many team sports ACL injuries are unfortunately common, with the vast majority requiring reconstructive surgery and extensive rehabilitation, prior to athletes returning to pre-injury activities.[48] Even with surgery, sufferers of an ACL injury are at increased risk of developing osteoarthritis later in life, a disease with its own significant associated cost, both financially and in terms of quality of life.[133] In the team sport settings 50% to 80% of ACL injuries occur in non-contact situations.[6, 24, 38] From an injury prevention perspective this is beneficial, as it indicates that modifying the characteristics of an individual may be sufficient to reduce the risk of ACL injury.

The first step in developing a prevention protocol is to identify the aetiology of injury. Numerous anatomical studies have shown that, although the ACL's primary function is to prevent anterior tibial translation, it is also loaded by both valgus and internal rotation moments.[139, 140, 224] Modelling work by McLean et al.[147] found that, during landing and sidestep cutting tasks, anterior drawer loads in isolation were not sufficient to rupture the ACL and that valgus and internal rotation loads were essential. Therefore, *in vivo* loading in one plane may not be sufficient to rupture the ACL and rather an interaction and/or combination of loading from more than one plane increases the likelihood of injury, although there is still debate within the field in regards to this view.[149, 217]

The effects of all three knee moments on ACL load have been shown to be altered by knee angle. In general terms, as knee flexion angle increases there is a reduction in the resultant strain on the ACL.[82, 140] However, when compared to anterior drawer in isolation, the application of both an anterior drawer and internal rotation load to the knee below 10° of knee flexion causes an increase in the resultant strain on the ACL.[140] The same is seen with a combination of valgus and anterior drawer from 10° to 50° of knee flexion.[140]

In a sport setting, non-contact ACL injuries often occur during sidestep cutting tasks,[38] which have increased valgus and internal rotation moments at the knee compared with straight line running.[13, 14] Furthermore, ACL injuries often occur during an unplanned or "spur of the moment" sidestep cut, which has been shown to produce higher knee loads than those that occur during a planned maneuver.[13] In a prospective study, Hewett et al.[91] found that female athletes, who went on to suffer an ACL injury, recorded higher valgus loads when performing a jump landing in the laboratory. Analysis of ACL injuries occurring during sports such as European handball and Australian football have also shown that at the point of injury, the knee tends to collapse into valgus.[24, 38, 168]

Video analysis has provided further clues to the mechanisms of ACL injury where athletes have exhibited similar body postures during sidestep cutting tasks that resulted in ACL injury. Specifically, at initial contact, these postures have been an abducted hip, extended knee joint, externally rotated foot and laterally flexed or rotated torso.[24, 38, 104, 116, 168] The study described in Chapter 4 imposed sidestep cut techniques on athletes in a laboratory setting and found that the three postures; 1) wide foot placement, 2) torso leaning away from the direction of the sidestep cut, and 3) torso rotating away from the direction of the sidestep cut, increased valgus and/or internal rotation moments.[51] However, a more extended knee joint in isolation did not result in significantly increased moments. Other studies linking body posture with knee loading during sidestep cutting tasks have also reported similar results.[150, 210] With this knowledge the question then arises; can we use technique modification to reduce non-contact ACL injuries?

Two previous studies have attempted to modify technique in an endeavour to reduce the risk of ACL injury. Ettlinger and colleagues[57] used videos of skiing injuries in association with key technique points to teach ski instructors to recognise and avoid dangerous postures. Although the study was successful in reducing ACL injury rates it cannot be readily adopted in the team sport setting as skiing has a vastly different injury mechanism to team sports that involve sidestep cutting tasks.[22] There is not sufficient time after initial foot contact for an athlete to modify their technique prior to the injury occurring. Henning[87] taught team sport athletes to avoid using sidestep cuts and sharp decelerations, instead using cross over cuts, which have since been shown to produce knee moments that unload the ACL when compared to sidestep cuts,[2, 3] and multi-step decelerations. Although this study was successful in reducing ACL injury rates, Henning's protocol requires substantial changes to the 'standard' technique usually seen in change of direction tasks during match play. It may not therefore be readily accepted by the sports community.

The aim of this study was to examine whether changes to sidestep cutting technique could reduce knee loading. The chosen technique was based upon the results presented in Chapter 4 ,[51] so that athletes performing a sidestep cut were trained to bring the stance foot closer to the midline of the body and position the torso, such that it was upright and facing in the general direction of travel. It was hypothesised that during sidestep cutting participants would display significant changes in the selected technique variables with accompanied reductions in the three-dimensional knee moments from pre- to post-training.

5.2 Methods

5.2.1 Participants

Twelve male non-elite team sport (Australian football, rugby union, and soccer) athletes (height 184.3 ± 5.4 cm, mass 80.2 ± 12.5 kg) who were experienced in performing a sidestep cut and who had no history of major lower limb injury or disease were recruited as participants. Nine participants completed the study with the three withdrawals caused by participants' external time constraints. Participants were recruited through contact with sporting clubs and from the university. A power analysis conducted on our previous work[13] that revealed significant differences between planned and unplanned sidestep cuts indicated that for 80% power with the alpha set at p=0.05, seven subjects were required. Ethics approval was obtained from The University of Western Australia Human Research Ethics committee and written, informed consent was obtained from all participants prior to data collection.

5.2.2 Experimental Design

Participants were tested twice, immediately prior to and following six weeks of technique modification training, which progressed from closed to more open skills practice. This progression required participants to move from performing the skill in a predictable environment at a time of the participant's choosing (closed skill) to performing the skill in an unpredictable environment where the execution of the skill was cued by external factors (open skill).[135] This has been shown to produce better outcomes than only practicing a skill in an open environment.[85] Training was performed in small groups (1-2 participants), twice a week with each session lasting 15 minutes. Each week, designated technique training goals determined the structure of the drill set for that week (Table 5-1 and Table 5-2) and prescribed drills. During training, which was performed by the one instructor, participants were given both oral and visual feedback for the designated technique goal. The visual feedback used TimeWARP (SilconCOACH, Dunedin, NZ) to provide immediate feedback on their sidestep cut technique together with reference videos (Appendix C) of athletes performing cuts using the desired technique. Participants aimed to gradually bring the stance foot closer to the midline of the body, ensure the stance foot was neither turned in nor turned out, and to maintain an upright torso, with the torso facing in the direction of travel (Figure 5-1). To guide participants in bringing their foot closer to the midline, markings were painted on the ground to indicate the outer limits of acceptable foot placement.

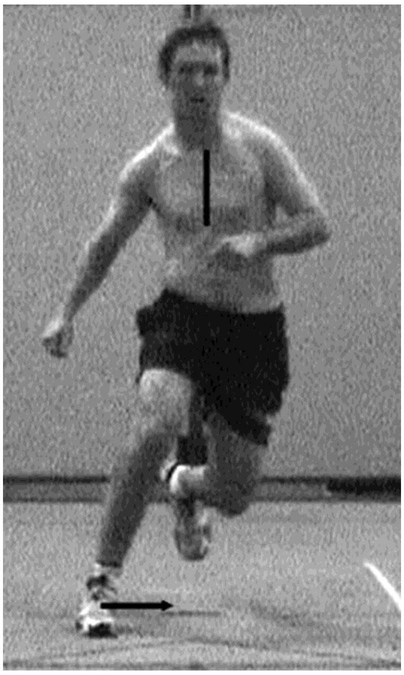

Figure 5-1 The whole body technique. Note the close placement of the stance foot relative to the coronal plane midline of the pelvis, the neutral

foot alignment, the upright torso posture and the torso facing the direction of travel.

Table 5-1 Weekly goals on which the sidestep cutting training program was based

Week	Training Aims
1	Can attain all three individual postures (stance foot closer to midline of body, torso upright, and torso facing in direction of travel)
2	Can do the full task with the required technique
3	Can do the full task while carrying a ball
4	Can start to do the task with trainer directed unanticipated sidestep cut
5	Can start to do the task with an unanticipated defender
6	Can perform the task consistently both pre-planned and unanticipated

Table 5-2 Sidestep cutting training program

Week	Tasks
1	• Perform self selected sidestep cut at ½ pace • Receive feedback based upon required changes • Initially receive feedback on torso angle, second session during the week they will receive information on foot position • Repeat performance with modified sidestep cut • Continue to receive feedback and perform modified sidestep cut and slowly increase pace
2	• Perform required sidestep cut at ¾ pace • Receive feedback based upon required changes • Should be able to perform the sidestep cut correctly by the end of the second session
3	• Perform required sidestep cut at full pace working to: • Performing required sidestep cut with ball • Receive feedback based upon required changes
4	• Perform the required sidestep cut at ¾ to full pace with ball • Trainer will indicate to subject if they are required to step left, right or run through using arm cues. Cues will start early and progressively get later across two training sessions • Receive feedback based upon required changes

5	• Continuation of trainer directed movement direction with ball
	• Start of defender directed movement direction with ball
	    • Defender to initially stand and then move left or right with attacker to move the other way working to:
	        o Defender moving towards attacker then changing direction with attacker to go the other way
	• Receive feedback based upon required changes

6	• Perform task successfully every time • Feedback for any required changes

During testing, all trials were performed on a 20 m x 15 m runway and recorded using a 12 camera VICON MX motion analysis system sampling at 250 Hz (VICON Peak, Oxford, UK). Ground reaction forces were synchronously recorded at 2000 Hz from a 1.2 m x 1.2 m force plate (Advanced Mechanical Technology Inc., Watertown, USA). Before commencing trials, participants selected the preferred foot with which they would perform the sidestep cut.

The testing protocol was similar to that used previously by the UWA group.[13, 14, 51] After adequate warm up and task familiarisation, the participants were required to perform at least four successful trials of three manoeuvres; a straight run, a sidestep cut and a cross over cut, under two different conditions; planned and unplanned. The sidestep cut, which along with the crossover cut, was to 45° ± 5, the angle selected to permit comparisons with the literature.[91, 150, 210] For this study only the sidestep cut trials were analysed, with the other trials retained to avoid anticipation of this manoeuvre during the unplanned tasks. Using a target board with three high intensity light emitting diodes, participants were given cues for one of the three tasks in both the planned and unplanned conditions. For the planned trials participants received the cue prior to the trial commencing. During unplanned trials participants were cued approximately 400 ms prior to reaching the force plate, the actual cue time was based upon their approach speed, the latter being monitored using infrared timing gates linked to custom software.

A trial was considered successful if the subject performed the required sidestep cut at 5.2 ± 0.5 m/s and achieved a cut angle of 45° ± 5, based on marks on the floor, with the foot of the leg of interest landing centrally on the force plate. Participants were aware of the location of the force plate but, to avoid targeting, they were instructed to look ahead.[76, 185, 223] To assist in this a marker was placed at the start of the approach and moved to adjust the approach distance to ensure the desired foot contacted the force plate. Trials were also rejected if the subject clearly targeted the plate. This was identified by either a “stutter step” during approach or “reaching” towards the force plate with the last stride.

5.2.3 Data Collection and Analysis

Participants were fitted with retro-reflective markers as per the UWA Full Body Model,[51] a combination of the UWA Upper[128] and Lower Body Models [16] (Figure 4-2). Kinematic and inverse dynamic calculations were performed in VICON Workstation (VICON Peak, Oxford, UK) using the UWA Model, which employs custom code written in MATLAB (Mathworks, Natick, MA, USA) and VICON BodyBuilder (VICON Peak, Oxford, UK). This code uses data collected from functional methods to identify knee axes and hip joint centres and is described in more detail by Besier et al.[16] External moments were calculated with inverse dynamics[16, 109] using the body segment parameter values based on de Leva.[44] Prior to modelling, both the ground reaction force and position data were filtered using a 4th order 18 Hz zero-lag low-pass Butterworth filter. The filter frequency selected by performing a residual analysis and visual inspection of the data.

Using the UWA Full Body Model reduces many of the errors introduced by poor marker placement as both the knee axis and hip joint centre are located utilising functional methods. This has been shown to produce more reliable kinetic and kinematic data than utilising markers placed on anatomical landmarks.[16] However, as the model does have some markers placed on anatomical landmarks and intra-tester reliability is higher than inter-tester reliability,[144] a single experianced researcher undertook marker placement in both pre- and post-testing sessions.

A custom MATLAB program was used to identify the weight acceptance phase in stance, which was defined as from initial foot contact to the first trough in the ground reaction force trace during the sidestep cutting task. Peak valgus and peak internal rotation moments were identified at the knee because these peaks are well defined in weight acceptance.[51] Mean flexion/extension moments were also determined in this phase, the mean being used because there is no peak in the flexion/extension moment in weight acceptance.[51] The moments were normalised to each subject's height (m) multiplied by their mass (kg).[36, 51, 91] To identify technique changes as a result of technique modification training, the following joint posture data were determined at initial foot contact: lateral torso flexion, torso rotation and foot distance from mid pelvis. Knee flexion angle at initial foot contact and mean knee flexion angle across the weight acceptance phase was also calculated to allow a better understanding of the effects of knee moments on ACL load. Mean velocity across the task and cut angle were calculated for the pelvic centre to assess the performance characteristics of each sidestep cut. Cut angle was calculated as:

$$CutAngle = \tan^{-1}\left(\frac{y_i - y_{i-10}}{x_i - x_{i-10}}\right) \textit{ where i = mid-swing following heel strike}$$

As we *a priori* specified which way the pre- to post-training changes would occur, we used a one-tailed repeated measures two-way ANOVA design with two within factors to identify any significant ($p < 0.05$) main effects of testing session (pre- versus post-training) or condition (planned verses unplanned) on knee loading and sidestep cutting technique. When there were significant interaction effects within each ANOVA, a *post hoc* test was performed using a Sidak correction. All statistical procedures were performed using SPSS 15.0 (SPSS Inc., Chicago, IL). In order to link changes in knee load with changes in specific technique modifications a correlation was performed between moments reporting a significant difference between pre- and post-training and those postural variables reporting similar changes.

5.3 Results

After six weeks of technique modification training there was no significant change in the mean flexion moment or the peak internal rotation moment (Table 5-3). However, there was a significant 36% reduction in the peak valgus moment ($p = 0.034$) after training (Table 5-3). There were no significant planned or unplanned condition effects or any interaction effects between condition and testing session for any of the knee moments.

Neither knee flexion at initial foot contact nor mean knee flexion angle across weight acceptance was significantly different between pre- and post-training (Table 5-4). There were also no significant main effects of condition for knee flexion at initial foot contact. However, there was increased mean knee flexion across weight acceptance for the unplanned sidestep cuts compared to the planned manoeuvres (p = 0.038). Neither measure of knee flexion returned any significant interaction effects.

Table 5-3 Mean (standard deviation) knee joint moment data (Nm•kg^{-1}•m^{-1}) during sidestep cutting.

	Pre		Post	
	Planned	Unplanned	Planned	Unplanned
Mean Flexion/Extension	0.97 (0.33)	0.91 (0.23)	0.85 (0.30)	0.87 (0.31)
Peak Valgus	-0.38 (0.26)	-0.40 (0.23)	-0.24 (0.22)*	-0.26 (0.11)*
Peak Internal Rotation	0.17 (0.07)	0.26 (0.18)	0.19 (0.07)	0.21 (0.13)

* indicates a difference from pre- to post-training.

Table 5-4 Mean (standard deviation) of the different postures and performance variables.

	Pre		Post	
	Planned	Unplanned	Planned	Unplanned
Knee Flexion (°) (IC)‡	14.0 (5.4)	15.4 (5.2)	12.0 (3.3)	15.1 (3.8)
Mean Knee Flexion (°) (WA)‡	29.7 (4.8)	32.1 (2.8)†	30.0 (5.5)	32.9 (4.4)†
Foot from Pelvis (cm)	36.9 (4.0)	36.6 (1.7)	34.6 (4.4)*	34.4 (5.1)*
Torso Lateral Flexion (°)	7.4 (3.2)	12.2 (4.9)†	3.9 (3.2)*	11.6 (3.5)†*
Torso Rotation (°)	-15.9 (6.0)	-11.8 (5.9)	-14.3 (5.7)	-14.4 (9.8)
Cut Angle (°)	32.1 (4.7)	29.8 (5.1)†	31.3 (4.3)	27.9 (4.4)†
Velocity (m.s^{-1})	5.7 (0.4)	5.1 (0.3)†	5.4 (0.5)	5.2 (0.3)†

‡ IC = initial foot-ground contact; WA = weight acceptance
* indicates a significant difference from pre- to post-training
† indicates a significant difference between the planned and unplanned sidestep cuts.
For the posture variables positive values indicate the following: knee angle – knee flexion; torso lateral flexion – leaning right; torso rotation – left shoulder back.

Participants significantly reduced (p = 0.039) foot distance from mid pelvis from pre- to post-training (Table 5-4). However, there were no significant main effects of condition or any interactions for foot distance from mid pelvis. There was a significant reduction in torso lateral flexion from pre- to post-training (p = 0.005, Table 5-4). Planned sidestep cuts were performed with less torso lateral flexion than unplanned sidestep cuts

(p = 0.003), however there were no interaction effects (Table 5-4). There were no main or interaction effects for torso rotation.

As there was a significant difference in the peak valgus moment and foot distance from mid pelvis, a correlation was performed on the two variables, revealing a significant between-variable correlation of r = -0.468 (p = 0.025). The same procedure was followed for the differences in peak valgus moment and torso lateral flexion resulting in a non-significant correlation of r = -0.377 (p = 0.135).

There were no pre- to post-training effects or interaction effects for cut angle. However, during the unplanned sidestep cuts there was a lower cut angle compared to the planned events (p = 0.006, Table 5-4). Unplanned sidestep cuts were also performed more slowly than the planned sidestep cuts (p = 0.001). There was no difference in approach speed between pre- and post-testing and no interaction effects.

5.4 Discussion

Following technique modification training, the participants displayed a significant change in their sidestep cutting technique at initial foot contact, specifically in foot placement distance from the pelvis and torso lateral flexion. Both of these technique variables changed in the desired manner as these technique modifications were the focus of the training program. Importantly, these technique changes were accompanied by a 36% reduction in peak valgus moment during the weight acceptance phase of the sidestep cut. In addition, there were correlations with pre- to post-training reduction in foot distance from the pelvis and torso lateral flexion with the reduction in peak valgus moment.

When using external knee moments as a surrogate measure of non-contact ACL injury risk, it should be highlighted that the moments are not equivalent to joint loads or ACL load. Initially, some of the measured external moments are supported by the musculature crossing the joint, subsequently the moment directly applied to “muscle-less” joint maybe different.[132] Secondly, some of the loading not absorbed by the muscles will be absorbed by other structures in the knee. However, externally applied moments are a good surrogate measure of non-contact ACL risk and have be used commonly in the literature.[14, 150, 210]

The knee flexion angle at initial foot contact and during weight acceptance is important in terms of valgus loading and its reduction post-training. Markolf et al.[140] showed that when compared with anterior tibial draw alone, ACL loading was increased when valgus moments were applied with 10° to 50° of knee flexion. With knee angles in this range the probability of suffering an ACL injury would certainly be increased if an athlete experiences high valgus loading, when in combination with anterior draw from quadriceps extension and/or internal rotation moments. Therefore, when assessing the non-contact ACL injury risk, both knee angle and knee loading are important. The present technique modification training resulted in a reduction in the valgus loading but no modification to the knee angle, either at initial foot` contact or during weight acceptance. Therefore, the lowering of the valgus moments due to the technique modifications would likely reduce the ACL loading, and therefore injury risk.

Results from this study support the incorporation of whole body technique modification to reduce knee valgus loading and in turn, reduce non-contact ACL injury risk. However, despite reducing torso lateral flexion, the component of the training program encouraging participants to face the direction of travel, was unsuccessful. This lack of change in torso rotation may have been due to the participants being experienced team sports athletes or alternatively, the required postural technique changes may have represented minor modifications to participants who have well established sidestep cut technique. Therefore, a longer, more intense or more focused training program may be required to elicit changes in torso rotation. Applying the training program to younger, less experienced athletes may also be more appropriate to elicit the desired changes in technique. The failure to modify the peak internal rotation moment may also be due to the lack of change in torso rotation. The results presented in Chapter 4 found that there was an increased peak internal rotation moment when sidestep cuts were performed with extreme torso rotation and wide foot placement.[51] It may be the case that, to cause any changes in the peak internal rotation moments, prior to an intervention an athlete would need to reflect these postures. This was not the case for the current cohort.

Unplanned sidestep cuts are often associated with non-contact ACL injuries.[38, 168] It was possible that training would only be effective in altering sidestep cutting technique in the planned condition, where the player had time to "setup" their body posture prior to the manoeuvre. However, the results showed that participants were also able to change their sidestep cutting technique in the unplanned condition, where they had very little time to adjust their body posture prior to performing the sidestep cut. As most injuries appear to occur when a subject is off balance or unprepared for the task, this is an extremely important finding.[168]

The one previous study to report differences between the performance of planned and unplanned tasks in running activities found that unplanned sidestep cuts elicited higher valgus moments during weight acceptance when compared to planned sidestep cut tasks.[13] During the current study, although we found technique and performance differences, we found no differences in knee loading between planned and unplanned sidestep cuts. This discrepancy may be due to differences between the studies in selecting the cue time between participants receiving the light stimulus and performing the sidestep cut. In the Besier et al.[13] study, the delay was adjusted for each subject, and set to the point where the participant could only just perform the task, while one set time period was used in the current study for all participants. It may have been that for some individuals the delay was insufficient to produce a true unplanned sidestep cut. Nevertheless, the unplanned condition in the current study was a very difficult task as the participants performed the unplanned sidestep cuts 7% slower with a 9% smaller cut angle than in the planned manoeuvres , similar to that seen in Besier et al.[13] Another study which examined the performance of unplanned sidestep cuts while walking observed varus moments compared to a valgus moment for planned sidestep cuts in early stance, suggesting movement speed may be an important factor influencing knee loading.[100] There was a speed difference of approximately 2 m/s between the two studies, which may account for the between-study discrepancy. The current study's high running speeds may be expected to produce larger loading differences than those in the Besier et al.[13] study, although it could be at higher running speeds unplanned versus planned differences are reduced. Further investigation is warranted to investigate this discrepancy in results and impact of technique modification training on knee loads in unplanned sidestep cuts where a difference in load is observed between conditions.

In the current study the basic performance characteristics of the sidestep cuts were maintained from pre- to post-training. That is, the participants undertook the sidestep cut with the same running speed and cut angle in both testing sessions. This indicates that loading changes were not due to changes in overall sidestep cut performance characteristics. The apparent failure of participants to achieve the cut angle required (Table 5-4) is due to this value not measuring the same factors as during the testing session. During testing, participants were required to place their foot within a 10° range, and were all successful in achieving this. Conversely, the angle reported is that of the pelvic centre over the 10 frames prior to mid-swing post heel strike. Interestingly, there is only one series of published papers which have examined differences in cut angle[13, 14] and no published studies have investigated the impact of speed in running sidestep cuts. As there was no change in the sidestep cut performance characteristics post-training, it appears that the technique modifications do not adversely affect performance, an important feature if the technique is to be accepted by the wider sporting community. However, there is a need for further analyses to examine the effectiveness of the modified sidestep cut technique in actual game conditions.

This is in part due to the component of attacking sidestep cutting tasks of deceiving defending players. This is often achieved by moving the torso in the opposite direction to that the attacking player wishes to travel, an example of two of the postures resulting in high knee loading. However in planning to perform a sidestep cut to fake a defender athletes are likely activate a muscular support strategy to support these high loads.[15] Therefore any assessment in actual game conditions will need to assess: i) if the task was planned; ii) the kinematics of the sidestep cut; iii) the muscle activation if possible; and iv) the success of the sidestep cut.

This study attempted to ascertain whether sidestep cutting technique could be modified over a period of time, and whether these technique modifications were successful in reducing knee loads during sidestep cutting. Now that it is established that we can modify sidestep cutting technique and reduce the accompanying knee loads, further research is recommended to compare the technique modification training to other non-contact ACL injury prevention protocols which have been shown to be successful in the laboratory, such as balance training,[37] or as suggested by the literature, increasing knee flexion angle.[38, 104, 212] Further investigation is also required into whether the modified technique is maintained post training period, both in the short term (e.g. remainder of a sporting season) and long term (e.g. subsequent sporting seasons). The technique modification program also needs to be trialled in a team setting to ensure that the effects are maintained when being applied to a large group.

The ability to alter sidestep cutting technique needs also to be considered in the game situation. Results from this study are laboratory based and, while they show that valgus loading was reduced, this does not necessarily lead to a reduction in ACL injuries in the field. It is therefore recommended that the technique modification program should be trialled in a competition setting, utilising a large subject cohort to ascertain whether this training type can reduce ACL injuries in competition and training. In order to ensure that the reduction in the incidence of ACL injury is due to factors controlled by the research design, laboratory testing should be included alongside the epidemiology testing, at least on a subset of the participants; a factor that has been ignored in most epidemiology studies.[31, 90, 159, 170]

Previously it has been suggested that training programs for ACL injury prevention should include balance, plyometric and technique components.[78, 129, 197] In fact, most intervention studies that have reported a significant reduction in ACL injuries have used multiple components.[93] A training program that provides specific sidestep cutting technique training combined with landing, balance and plyometric training may be the most effective at lowering ACL injury and should be examined in a prospective study.

5.5 Summary

Whole body technique training that focused on foot placement close to the midline of the body and the torso being in a more upright posture was effective in reducing the peak valgus moments of the knee during sidestep cutting. This reduction in knee loading might, in turn, reduce risk of injury to the ACL. The technique modification training examined in this research now needs to be compared to other ACL injury prevention training protocols both in the laboratory and in the field to ensure intervention strategies to reduce ACL are effective.

CHAPTER 6 HOW DOES BALL MOVEMENT DIRECTION AFFECT KNEE LOADS AND FULL BODY KINEMATICS IN AN ECOLOGICALLY VALID LANDING TASK?

Based on the following paper submitted to the *American Journal of Sports Medicine*

Dempsey AR, Lloyd DG, Elliott BC, Munro BJ, Steele JR. How does ball movement direction affect knee loads and full body kinematics in an ecologically valid landing task? *American Journal of Sports Medicine.* (Submitted).

6.1 Introduction

The two primary sporting manoeuvres observed during non-contact ACL injuries are landing and sidestep cutting.[38] As such, there has been extensive research attempting to better understand what characteristics of these manoeuvres are associated with non-contact ACL injuries. The focus of much of this work has been directed at mechanisms that cause or support high valgus and internal rotation moments at the knee,[13, 15, 40, 151] as these variables have been shown to be related to ACL loading.[65, 140, 224] Should the resultant strain on the ACL from application of these loads become too high ligament damage occurs. At more extended knee angles, the extension moment generated through quadriceps activation also loads the ACL through anterior tibial draw.[140] While different groups have argued that either anterior drawer,[50] or valgus load[147] are required to cause ACL injury, in fact, combined loading has been shown to produce higher ACL forces than single plane loading.[140]

Specific techniques used to perform landing and sidestep cutting tasks have been linked with non-contact ACL injuries. These relationships have been found from both simple visual analysis of video of actual injuries,[24, 38, 116, 168] and in laboratory studies that have linked specific techniques to increased knee load.[51, 150, 210] Laboratory testing has also found differing techniques between males and females exhibited through different lower limb postures during landing tasks.[47, 58, 113] These differences have been proposed as the reason for higher injury rates of females compared to males.[6] Specifically, it appears that lower body postures of an extended lower limb, internally rotated and abducted hip appear to be associated with increased risk of injury. The relationship of technique to knee load is not limited to the lower body. In sidestep cutting tasks, increased torso rotation and lateral flexion away from the stance leg have been linked to higher internal rotation and valgus moments respectively.[51]

One of the major differences between the laboratory based studies of sidestep cutting and landing has been how closely the laboratory tasks reflect the sporting manoeuvres that cause injuries. During their laboratory studies of sidestep cutting tasks, Besier and colleagues[13] introduced unplanned sidestep cutting tasks in an attempt to better mimic injury situations. They found that unplanned tasks resulted in an increase in both the valgus and internal rotation moments, when compared with planned sidestep cuts. Unplanned sidestep cuts have now been incorporated in several studies investigating the relationship between non-contact ACL injuries and sidestep cutting.[52, 100, 119, 192] Further McLean and colleagues[148] found that the addition of a static 'defender' altered participant kinematics in planned sidestep cutting tasks. However, in landing tasks, the majority of the research has used tasks that are not necessarily ecologically valid, such as drop jumps,[108, 151, 198] vertical jumps[122, 171] and stop jumps.[35, 226]

With the majority of non-contact ACL injuries occurring in attacking situations, it is highly likely that a team sport athlete suffering an injury will have had some interaction with the ball during flight.[168] During planned sidestep cutting, Chaudhari et al.[36] required athletes to perform this manoeuvre without a ball and then with a ball in either the ipsilateral or contralateral arm relative to the support leg, in a randomised design. Increased peak valgus moments during stance relative to a sidestep cut without a ball were observed during the ipsilateral condition but not the contralateral condition. The authors identified changes in arm positioning as the cause of the increase in valgus moment.

Ford and colleagues[68] found that during drop vertical jumps, use of an overhead target, consisting of a suspended basketball, caused participants to display increased knee flexion moments during the landing phase compared to performing the same tasks with no overhead target. During single leg landings, Cowling and Steele[40] found that requiring an athlete to catch a ball during flight altered hip and trunk but not knee sagittal plane kinematics during landing, although they did not investigate joint postures in other planes. It would therefore appear that the requirement to catch a ball, has the potential to alter landing kinematics and kinetics. However, it is still unknown whether the position of the ball relative to the direction of travel of a player affects joint kinetics in landing.

The aim of this paper was to investigate the effect ball movement, in an ecologically valid landing task, would have on knee loading and joint kinematics. It was hypothesised that variations in ball movement would result in differing knee joint moments, which would be accompanied by a change in kinematics. Should a specific ball movement condition produce knee moments thought to increase the risk of non-contact ACL injury, the paper's secondary aim was to identify joint postures, which are related to the increase in joint moments. It was also hypothesised that any higher loading task would display joint postures previously associated with increased knee moments or with non-contact ACL injury.

6.2 Methods

6.2.1 Participants

Twenty five healthy male team sports athletes were recruited to participate in this study (height 181.8 ± 7.1 cm, mass 78.0 ± 12.1 kg). All participants were experienced in performing functional landing tasks through their respective team sport (Australian football, rugby union or soccer). Participants were excluded if they had a history of major lower limb injury (any ACL injury or other lower limb injury in the last 12 months). Ethics approval was obtained from UWA Human Research Ethics committee and written, informed consent was obtained from all participants prior to data collection. Subject numbers were based upon a power analysis performed using effect sizes reported in Chapter 4 [51] and a power of 0.80 and $p = 0.05$.

6.2.2 Experimental Design

All testing was undertaken at the UWA Sports Biomechanics Laboratory with the movement of markers affixed to the participants recorded using a 12 camera VICON MX motion analysis system sampling at 250 Hz (VICON Peak, Oxford, UK). Ground reaction forces were synchronously recorded at 2000 Hz from a 1.2 m x 1.2 m force plate (Advanced Mechanical Technology Inc., Watertown, USA). Before commencing trials participants selected their preferred support leg for both take off and landing.

A ball movement rig was developed, which was attached to a gantry above the force plate (Figure 6-1). This rig allowed the same trained experimenter to release a ball to fall, under gravity, either towards or away from the participant's support leg. The initial height of the ball was set to the participant's maximal one leg vertical jump height.

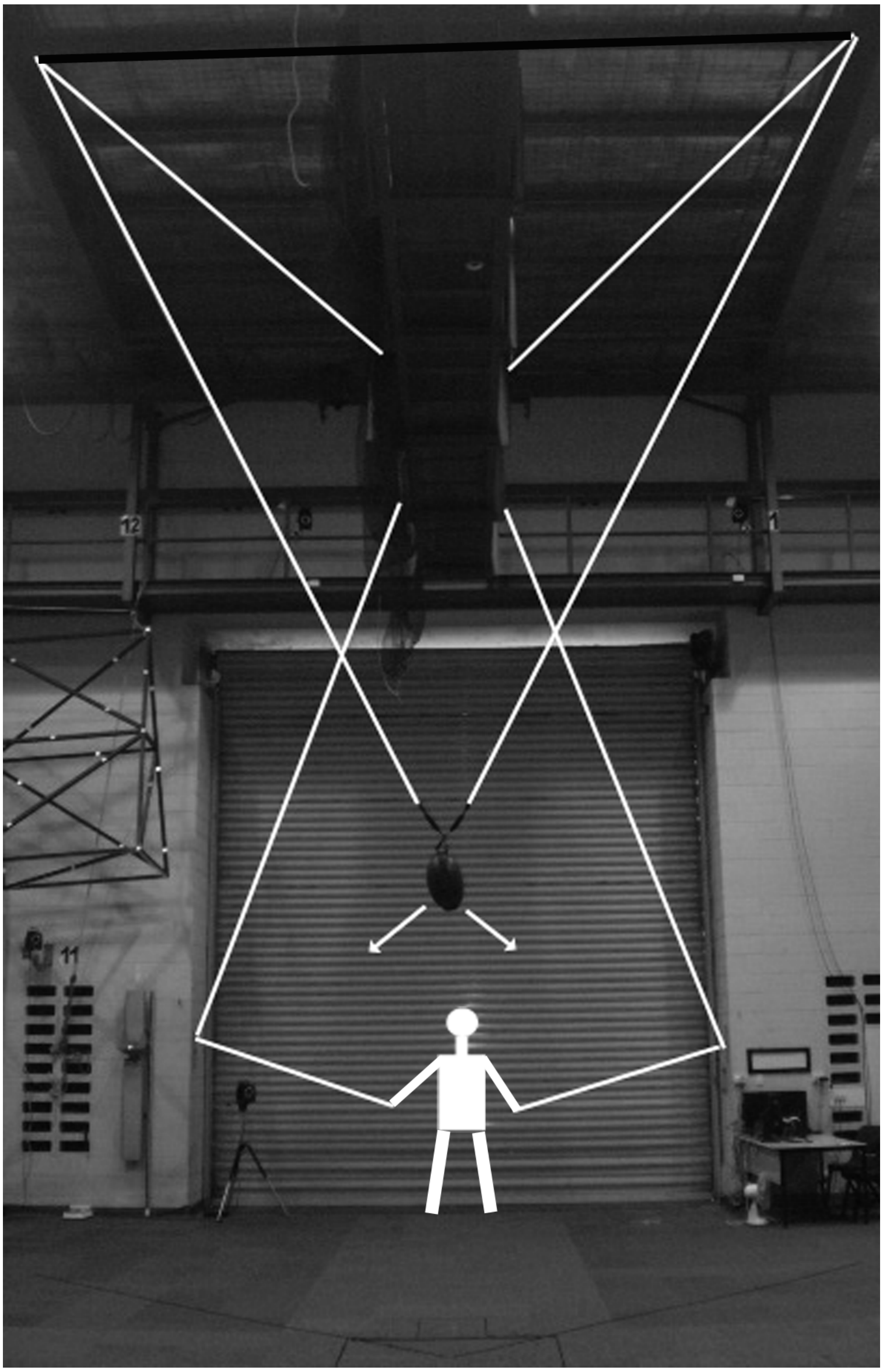

Figure 6-1 Ball movement rig. The ball was suspended from a gantry above the force plate and released by the same experimenter for each participant. Release of the right catch caused the ball to fall to the left

During the testing session participants performed four landing tasks: ball moving toward the support leg early in approach (TE), ball moving toward the support leg late in approach (TL), ball moving away from the support leg early in approach (AE) and ball moving away from the support leg late in approach (AL) (Appendix D). During TE and AE the ball approached a maximum lateral movement of about 0.6 m with the ball released one step prior to take off, while the TL and AL displayed reduced lateral movement with the ball released immediately prior to take off. At the commencement of each trial the participants were unaware of which direction the ball would fall.

Participants were required to perform three successful trials of each landing task. Tasks were presented in random order until sufficient successful trials had been performed. A successful trial involved participants undertaking a five step approach, taking off and landing on their preferred foot and successfully taking possession of the suspended ball. The landing was required to be on one foot and on the force plate; however, there was no restriction on landing technique following the initial foot contact.

6.2.3 Data Collection and Analysis

Participants were fitted with retro-reflective markers as per the UWA Full Body Model,[51] a combination of the UWA Upper[128] and Lower Body Models.[16] Kinematic and inverse dynamic calculations were performed in VICON Workstation (VICON Peak, Oxford, UK), using the UWA Model, which employs custom code written in MATLAB (Mathworks, Natick, MA, USA) and VICON BodyBuilder (VICON Peak, Oxford, UK). The UWA Full Body Model uses functional methods to identify knee axes and hip joint centres and is described in more detail by Besier et al.[16] Prior to modelling, both the ground reaction force and position data were filtered using a 4th order 18 Hz zero-lag low-pass Butterworth filter, the filter frequency selected from residual analysis and visual inspection of the data. Inverse dynamics were used to calculate external joint moments,[16, 109] using the body segment parameters reported by de Leva.[44]

A landing phase was identified based upon the vertical ground reaction force. Previously *in vivo* studies have shown that the peak ACL load occurs close to the peak vertical force.[32] As such, we defined the landing phase from initial foot contact to double the time from this point to the peak vertical ground reaction force, this period being similar to that used by Decker and colleges.[47] To this end, a custom MATLAB

(Mathworks Inc., Natick, MA) program was used to identify the start and end time points of the landing phase and an ensemble average was created of the three joint moments of the support leg over this phase (Figure 6-2). For the flexion/extension and internal/external rotation curves there was one major flexion and internal rotation peak that could be respectively identified. However, there were obvious differences within the varus/valgus trace, with a first valgus peak in all trial types and a second valgus peak in the TE and TL tasks, while AE and AL tasks displayed a varus trough. However, it was decided to select the largest peak valgus moment occurring during the entire landing phase for analysis as it is this moment that would reflect the time point where this moment places an athlete at greatest risk of injury.[65, 91, 140] The moments were normalised to each subject's height (m) multiplied by their mass (kg).[36, 51, 91, 151, 226] Maximal knee flexion angles were also identified within the landing phase.

To characterise the body posture at landing the values of the following kinematic variables were determined at initial foot contact of the support limb: foot rotation, ankle plantar/dorsi flexion, ankle inversion/eversion, knee flexion/extension, hip flexion/extension, hip abduction/adduction, hip internal/external rotation, torso flexion/extension, torso lateral flexion and torso rotation. In order to identify the orientation of the knee relative to the direction of travel, a knee-path rotation angle was calculated. This was defined as the rotation of a knee coordinate system around the y-axis of the direction-of-travel coordinate system. The knee coordinate system was defined with the origin at the knee joint centre; the z-axis being the helical knee axis, positive being left to right; the y-axis, being a vector along the plane defined by the knee joint centre and hip joint centre orthogonal to the z-axis, positive inferior to superior; and the x-axis being orthogonal to the z-y axis, positive posterior to anterior. The direction-of-travel coordinate system was defined with the origin being the global origin; the x-axis being the vector running from the x and z position of the mid-pelvis point 20 frames prior to the current frame to the x and z components of the mid-pelvis point 20 frames after the current frame, positive travel direction; y-axis being the unit vector of the global y-axis, positive going up; and the z axis being orthogonal to x-y axis, positive going left to right. Negative numbers indicated that the medial aspect of the knee was pointing in the direction of travel (external rotation).

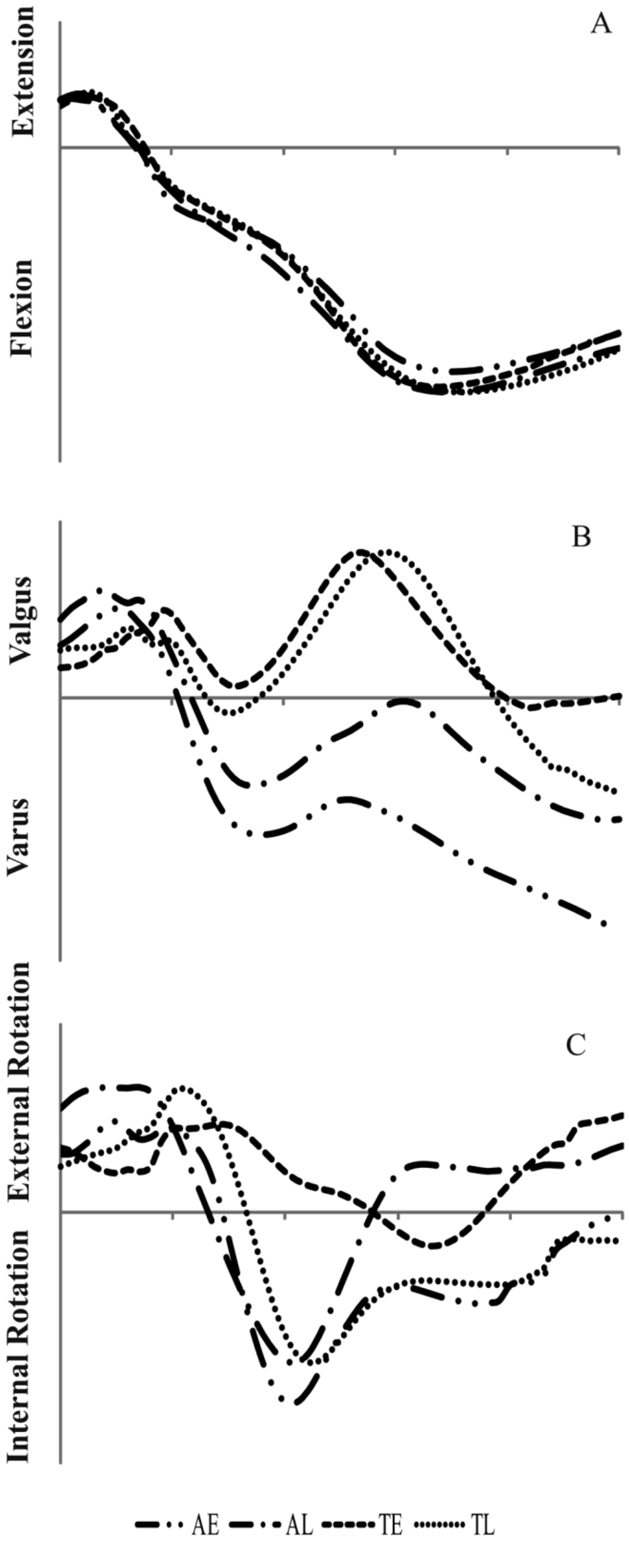

Figure 6-2 Ensemble averages across the landing phase of the four landing tasks for the knee flexion/extension (A), varus/valgus (B) and internal/external rotation moments (C). TE - ball moving toward the support leg early in approach; TL - ball moving toward the support leg late in approach; AE - ball moving away from the support leg early in approach; AL - ball moving away from the support leg late in approach

All moments and joint postures were compared across tasks using one way repeated measures ANOVA with significance set a $p < 0.05$. When there were significant interaction effects within each ANOVA, a *post hoc* test was performed using a Sidak correction. All statistical procedures were performed using SPSS 17 (SPSS Inc., Chicago, IL).

6.3 Results

There was no significant difference between any of the four landing tasks for either the maximal flexion moment ($p = 0.270$) or peak internal rotation moment ($p = 0.441$) of the support limb during the landing phase. However, there was a significant difference between task for the peak valgus moment ($p = 0.001$). The *post hoc* test showed that TE had a significantly greater valgus moment than both AE ($p = 0.001$) and AL ($p = 0.005$), but not TL ($p = 0.171$). TL was also significantly higher than AE ($p = 0.001$), but not AL ($p = 0.726$) (Table 6-1).

Table 6-1 Mean (standard deviation) knee joint moment data ($Nm \bullet kg^{-1} \bullet m^{-1}$)

	AE	AL	TL	TE
Flexion	-2.08 (0.48)	-2.19 (0.54)	-2.09 (0.55)	-2.08 (0.57)
Valgus	0.23 (0.17)*^	0.31 (0.16)*	0.36 (0.21)	0.43 (0.24)
Internal Rotation	-0.17 (0.12)	-0.15 (0.08)	-0.17 (0.10)	-0.14 (0.10)

* Significantly different from TE
^ Significantly different from TL
TE - ball moving toward the support leg early in approach; TL - ball moving toward the support leg late in approach; AE - ball moving away from the support leg early in approach; AL - ball moving away from the support leg late in approach

Between tasks there was a significant difference in knee flexion angle at initial foot contact ($p = 0.001$). At initial foot contact the knee flexion angle for AE was significantly lower than both TL ($p = 0.027$) and TE ($p = 0.001$), however there was no difference between AE and AL ($p = 0.155$) (Table 6-2). *Post hoc* testing reviled no other significant differences. There was also no significant between task differences in the maximum knee flexion achieved during the landing phase ($p = 0.589$).

Table 6-2 Mean (standard deviation) for knee flexion angle (°) at heel strike and maximum angle during weight acceptance

	AE	AL	TL	TE
Heel Strike	5.3 (7.2)*^	6.6 (6.2)	7.0 (6.9)^	7.9 (6.8)*
Max	53.6 (10.3)	54.5 (10.3)	54.4 (12.0)	55.7 (12.5)

* Significantly different from TE
^ Significantly different from TL
TE - ball moving toward the support leg early in approach; TL - ball moving toward the support leg late in approach; AE - ball moving away from the support leg early in approach; AL - ball moving away from the support leg late in approach

There were significant between task differences identified for the following position variables at initial foot contact: foot rotated in (p = 0.001), hip flexion\extension (p = 0.001), hip abduction\adduction (p = 0.001), hip internal\external rotation (p = 0.001), torso lateral flexion (p = 0.001) and torso rotation (p = 0.001) (Table 6-3). Specifically when the ball moved towards the support leg participants had more externally rotated feet. TE also had more hip flexion than all three other tasks, and torso lateral flexion back towards the support leg. Reflecting the nature of the task TL and TE, where the ball was swung towards the support leg, both had increased torso rotation back towards the support leg, compared to AL and AE where the ball was swung away from the support leg. Finally AE had increased hip external rotation when compared to the other three tasks.

There was also a significant between task difference in the knee-path rotation angle (p = 0.001). TE (-46.6 ± 25.6°) was significantly more externally rotated than AE (-24.2 ± 22.1°, p = 0.001) and AL (-33.8 ± 25.4°, p = 0.008), whereas TL (-43.4 ± 22.1°, p = 0.001) was significantly more externally rotated than AE. AE was also significantly less externally rotated than AL (p = 0.001).

Table 6-3 Mean (standard deviation) of joint positions (°) at heel strike

	AE	AL	TL	TE
Foot Rot In\Out	-16.4 (12.0)*^	-21.7 (12.9)*^	-31.9 (15.1)	-33.9 (20.6)
Ankle PD Flex	-23.1 (14.2)	-22.3 (15.6)	-24.0 (14.3)	-23.8 (15.0)
Ankle Inv\Ev	2.6 (4.5)	1.5 (4.9)	2.4 (5.3)	3.1 (6.2)
Hip Flex\Ext	23.0 (9.0)*	22.3 (9.4)*	23.7 (8.5)*	27.5 (9.3)
Hip Abd\Add	-16.1 (4.9)^	-14.9 (5.3)^	-12.2 (5.6)	-14.1 (6.1)
Hip Int\Ext Rot	-14.2 (8.2)*^+	-11.7 (8.8)^+	-7.9 (8.7)*	-10.5 (9.0)
Torso Flex\Ext	1.5 (7.3)	0.8 (6.5)	-0.4 (7.5)	1.0 (9.6)
Torso Lat Flex	0.3 (5.2)*	3.0 (4.2)*	3.4 (4.8)*	8.2 (7.8)
Torso Rot	3.2 (20.6)*^ +	-13.5 (25.2)*^	-37.0 (20.3)	-43.3 (20.8)

* Significantly different from TE
^ Significantly different from TL
+ Significantly different from AL
TE - ball moving toward the support leg early in approach; TL - ball moving toward the support leg late in approach; AE - ball moving away from the support leg early in approach; AL - ball moving away from the support leg late in approach. Variables are as follows with positive direction in brackets: Foot Rot In\Out –rotated in\out (toe in); Ankle PD Flex – plantar\dorsi flexion (plantar flexion); Ankle Inv\Ev – inversion\eversion (inversion); Hip Flex\Ext – flexion\extension (flexion); Hip Abd\Add – abduction\adduction (adduction); Hip Int\Ext Rot – internal\external rotation (internal); Torso Flex\Ext – flexion\extension (flexion); Torso Lat Flex – lateral flexion (leaning right); Torso Rot – rotation (left shoulder back).

6.4 Discussion

Previously it has been identified that the inclusion of a ball into the performance of sporting tasks can create altered joint moments.[36, 68] In sidestep cutting tasks it has been shown that knee valgus moment may be modified as a function of the position the ball is carried.[36] However, no research has examined knee kinetics in landing after a jump, where the positioning of a ball required to be caught during the jump was varied. The investigation of this relationship, in the context of identifying ball positioning that resulted in an increased risk of non-contact ACL injury, was the main aim of this study. Landings, where the ball was swung towards the support leg (TE and TL), displayed increased peak valgus moment at the knee, when compared with landings where the ball was swung in the opposite direction. As previously shown increases in valgus moment at the knee have been associated with ACL injury,[91] we speculate that the increased valgus moments associated with the TL, and in particular the TE task, indicate that the ball swinging towards the support leg carries increased risk of ACL injury.

The work by Chaudhari et al.[36] identified increases in valgus loading when the ball was carried in the arm on the same side as the support leg in sidestep cutting tasks. These results are similar to those in this study, where gathering the ball on the same side as the support leg increased the knee joint moments. In sidestep cutting tasks, the authors identified that the requirement to bring the support side arm closer to the body reduced its ability to provide stabilisation.[36] However, they also stated that this change only partially explained the variation in joint moments, with trunk stability suggested as another potential cause of change. Variations in trunk and lower limb joint postures have been previously associated with modification in knee loading during sidestep cutting tasks, with the results of these studies revealing "risky" postures that are consistent with those observed during ACL injury.[24, 38, 51, 116, 150, 168] Postural variations between tasks may therefore explain the variation in peak valgus moments identified within this study.

Together with the identified changes in knee moments, the various ball positions resulted in different joint postures. It was hypothesised that the joint postures displayed by any high loading landing tasks would reflect these joint positions previously identified to be related to injury.[24, 38, 51, 116, 150, 168] The greatest difference in knee moments occurred between the TE and AE tasks. Therefore, we analysed the data from the landing tasks performed with these two extreme ball positions to highlight the significant differences in the segment and joint postures that may be associated with an increased risk of ACL injury. During the TE task, the subjects displayed more flexion at the hip and knee, less external rotation at the hip, but a greater degree of toe out at the foot compared to during the AE task. There was also greater trunk lateral flexion and rotation towards the support leg at landing during the TE task.

Knee flexion angle has been shown to change how the knee moments are transmitted to the ACL.[140] In general terms, the resultant load on the ACL is greatest at more extended knee postures. However, the application of valgus loads in conjunction with anterior drawer or internal rotation has been shown to increase ACL loading between

10° and 50° of knee flexion, peaking about 20° to 30°.[18, 140] In addition, with the knee in more flexed postures the support of varus and valgus moments by the hamstring and quadriceps muscles is compromised.[130] Contrary to this, more extended knee postures have been identified as common during actual injuries.[24, 38, 116, 168]

In the TE task, the knee was significantly more flexed than during the AE task at initial foot contact. However, the maximal knee flexion angle displayed during these tasks was of similar magnitude. Studies investigating the difference between male and female kinematics during landing have had differing results in terms of knee angle. Some studies have found females display higher knee flexion angles relative to their male counterparts,[47, 121, 199] some no differences between the genders[41, 151] and one study reported males to display higher knee flexion angles.[58] A prospective study by Hewett et al.[91] did not identify any difference in knee angle between athletes who went on to suffer an ACL injury compared to those who remained uninjured. Contrary to this, females who suffered an ACL injury have been shown to display greater knee flexion angles at initial contact. than their male counterparts.[116] Therefore, it is difficult to draw conclusions as to the relationship between knee angle in isolation and risk of ACL injury.

During an actual injury, the knee flexion angles at initial foot contact, while still close to full extension, have been identified to be of a magnitude greater than those occurring in all four of our landing tasks.[116] Therefore, the small difference in knee flexion, 2.6°, between the TE and AE tasks evident in the present study, may not be functionally relevant for the reduction or increase of injury risk. Investigations in sidestep cutting have found that modification of knee angle at initial foot contact is not associated with changes to any early stance moments.[51] In the TE condition, as the peak valgus moment occurred later in the weight acceptance phase compared to during the AE task (Figure 6-2), and therefore the initial knee angle at initial foot contact may not be the best measure of risk. Valgus moments produce the highest ACL loading when applied in conjunction with anterior drawer or internal rotation moments and when knee flexion is between 10° and 50°. The maximal knee flexion angle for all our tasks was in the range of 53.6° - 55.7°. This knee posture and loading state seems to have occurred for TE and TL ball positions and may be mechanical conditions that increase the risk of ACL injury. As better techniques develop to analyse footage of injuries,[117] the identification of the knee flexion angle at the estimated point of rupture should be investigated to better understand this relationship.

During the TE task there was increased external rotation in the knee-path rotation angle, which meant the medial aspect of the knee was facing the direction of travel. Increased valgus moments may arise from landing in this posture as the posteriorly directed ground reaction force, or breaking force, will be acting to force the knee into valgus (Figure 6-3). To date there has been no investigation into the positioning of the body in relation to the direction of travel in injury scenarios. However, in a series of still images presented by Olsen et al,[168 - Figure 2] the injured athlete appears to travel from left to right, with the medial aspect of the knee facing right at initial foot contact. Therefore, this is an area worthy of further investigation.

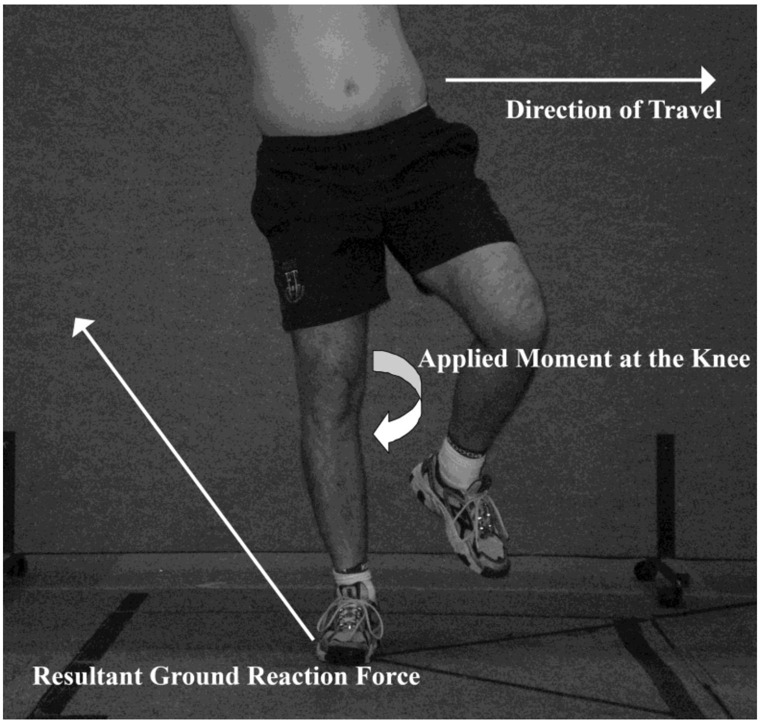

Figure 6-3 How external rotation of the knee relative to the direction of travel may increase knee valgus moment. The action of the posteriorly directed resultant ground reaction force relative to the direction of travel will cause a valgus moment at the knee, when the medial aspect of the knee is facing the direction of travel

Increased hip flexion, decreased hip external rotation and increased turn out of the foot were also associated with the TE landing task when compared to the AE task. Both reduced hip external rotation (moving to internal rotation) and externally rotated foot have been associated with ACL injury or increased risk of ACL injury.[24, 104] While this study found increased hip flexion in the higher loading task, the literature consensus is that a more extended hip places athletes at an increased risk of ACL injury.[24, 104] However, as with knee angle, all values for hip flexion are within a similar range to those observed during actual injury.[116] It may again be that while there is a significant difference, it was not a functional difference. Further work is recommended to investigate the impact of hip flexion angle on both the loads occurring at the knee and the ability of, in particular, bi-articular muscles crossing both joints to support any such loading.

Deficits in control of the upper body have been shown to be predictive of ACL injuries.[230] Previously we have identified that variations in trunk positions are related to joint loading in sidestep cutting tasks.[51, 52] In particular, increased torso lateral flexion over the support leg increases peak knee valgus moments and torso rotations towards the support leg increase peak internal rotation moments at the knee. Video analysis of injury identified that, particularly in landing tasks, the trunk is often out of alignment with the lower limb.[24] The trunk postures observed in the high loading TE task appear to be consistent with the literature. Based upon sidestep cutting results it would be expected that increased torso rotation would also lead to increased internal rotation moments.[51] The lack of difference in the peak internal rotation moment may be due to a reduced requirement to move the torso to face a new direction in the current landing tasks, thereby reducing the need to produce rotation moments.

Having established that the postures displayed during the TE task are associated with an increased risk of a non-contact ACL injury, it is necessary to establish how these results can be used. Technique has been identified as an important component of prevention programs for non-contact ACL injury, and technique modification focused prevention programs have been successful in reducing knee loads in sidestep cutting tasks.[52, 129] It should be established if a technique modification program, that focuses on moving athletes away from at risk postures, is capable of reducing knee loads during the TE task. Should this be successful, the program should then be assessed to determine whether it can reduce injury rates in a sporting setting.

In order to further our understanding of the complex nature of non-contact ACL injuries the tasks we utilise in our laboratory testing should reflect those of injury scenarios. The landing tasks utilised within this study were designed to reflect the natural variations to a sporting task, specifically an overhead mark in Australian football, during which non-contact ACL injuries are known to occur.[38] During an overhead mark, players run forward, jump and catch a ball overhead that has been kicked to them from a distance greater than 15 m. The ball movement from side to side reflects an inaccurate kick, or deflections from opposing players. However, the main features of the task; a jump and landing followed by catching an oncoming ball above the head; are common in sports such as basketball or American football

6.5 Summary

Ball positioning during landing tasks affects both knee joint loading and joint positioning. Specifically, moving the ball towards the landing leg increased the peak knee valgus moment. During the TE task the resultant joint postures appear to reflect those that have been previously associated with increased risk of actual non-contact ACL injuries. Further research needs to be undertaken to identify whether modifying landing technique during these dynamic landing tasks is capable of reducing knee loading and, subsequently, reducing the risk of non-contact ACL injuries.

CHAPTER 7 ASSOCIATIONS BETWEEN WHOLE BODY POSITIONING AND KNEE LOADS DURING FUNTIONAL LANDING TASKS

Based on the following paper submitted to the *American Journal of Sports Medicine*

Dempsey AR, Lloyd DG, Elliott BC, Munro BJ, Steele JR. Association between whole body positioning and knee loads during functional landing tasks. *American Journal of Sports Medicine.* (Submitted).

7.1 Introduction

Anterior cruciate ligament injuries are an unfortunate reality for too many athletes participating in a wide range of team sports. Over 50% of these injuries are non-contact, indicating that there is the potential to reduce the incidence of injury through some form of intervention focused on modifying the individual athlete.[6, 24, 38, 116] These non-contact injuries most often occur during sidestep cutting and landing tasks[24, 38, 116, 168] which, in laboratory testing, have been shown to be associated with high valgus and internal rotation moments at the knee.[13, 14, 53, 204] High valgus and internal rotation moments at the knee are known to load the ACL, particularly when applied simultaneously.[140] As such interventions aimed at reducing non-contact ACL injury rates have been focused on modifying the neuromuscular performance characteristics of athletes to either increase their muscular support and/or reduce these moments.[31, 90, 98] It has been suggested that technique modification should also feature in such training programs.[129] While it has been investigated briefly on its own,[52, 87] and as a non-task specific component of plyometric based interventions,[90] a better understanding of the relationship between technique and loading is required to develop best practice technique modification interventions.

Analysis of videos of ACL injury episodes has revealed common joint postures are evident at initial foot contact. At initial foot contact, athletes suffering an ACL injury tend to have an extended knee, abducted hip, wide foot placement outside the line of the knee, and may also have an externally rotated foot and misaligned torso.[24, 38, 116, 168] Research in sidestep cutting has identified specific techniques which are associated with increases in both valgus and internal rotation moments at the knee. Specifically, increased foot internal rotation,[210] hip internal rotation,[150] hip abduction,[51, 210] hip flexion,[150] and lateral torso flexion toward the stance leg[51] have been associated with increased valgus moments. Increased internal rotation moments have been associated with increased hip abduction and the rotation of the torso towards the stance leg.[51] Hewett et al.[91] identified in a prospective study that athletes who went on to suffer an ACL injury displayed reduced peak knee flexion angles during a landing task. However, there is yet to be a study investigating the relationship between whole body technique and knee joint moments in landing tasks.

As females have a high risk of suffering ACL injuries[6, 80, 154] comparisons of males versus females have identified kinematic characteristics that may increase the risk of injury in landing tasks. For example, several studies have demonstrated that women have decreased hip flexion and, in particular, decreased knee flexion during landing tasks relative to their male counterparts.[47, 102, 121, 172, 199] However, two of these studies found no differences in hip flexion angle[47, 121], and two additional studies[41, 151] revealed no differences in either hip or knee flexion between genders. Further, work by Fagenbaum and Darling[58] found women had higher knee flexion angles at initial foot contact and 200 ms post initial contact than males during a drop jump task. Kernozek et al.[113] demonstrated females landed with increase hip flexion when performing a drop jump task. It has been consistently shown than females land with greater ankle plantar flexion than their male counterparts.[47, 112, 151] Lephart et al.[121] found females had greater hip internal rotation, though other studies using different landing tasks found no between-gender differences.[148] Cowling and Steele[41] reported no differences in trunk flexion angles between males and females in landing tasks. These gender differences strengthen the argument that technique is related to injury risk in landing task. However they also indicate that there is still not consistent consensus within the literature.

Current knowledge suggests that landing technique is related to knee joint loading and therefore risk of non-contact ACL injury. However, to date there is yet to be a study systematically investigating the relationship between full body kinematics and knee joint loads in landing tasks. Should specific techniques be related to high loads, it may be possible to design technique modification programs that are able to reduce the risk of injury either in isolation or as a supplement to current training programs known to be successful in reducing injury rates. Therefore, the aim of this study was to identify what full body joint postures at initial foot contact are associated with peak loadings. By combining the data from both peak internal rotation and peak valgus moments it may be possible to identify technique parameters that are important for reducing knee joint loading and, in turn, the risk of non-contact ACL injury. It is expected that joint postures associated with increased load will be similar to those seen during actual injury.

7.2 Methods

7.2.1 Participants

Twenty five healthy male team sport athletes were recruited to participate in this study (height 181.8 ± 7.1 cm, mass 78.0 ± 12.1 kg). All participants were experienced in performing functional landing tasks through their respective team sport (Australian football, rugby union or soccer). Participants were excluded if they had a history of major lower limb injury (any ACL injury or other injury in the last 12 months). Ethics approval was obtained from UWA Human Research Ethics Committee and written, informed consent was obtained from all participants prior to data collection.

7.2.2 Experimental Design

During testing, all trials were performed on a 20 m x 15 m runway and the movement of retro-reflective markers affixed to the participants was recorded using a 12-camera VICON MX motion analysis system sampling at 250 Hz (VICON Peak, Oxford, UK). Ground reaction forces were synchronously recorded at 2000 Hz from a 1.2 m x 1.2 m force plate (Advanced Mechanical Technology Inc., Watertown, USA). Before commencing trials, participants selected their preferred foot with which they would perform the landing task.

We utilised the landing test described in Chapter 6 .[53] Briefly, the test required participants to catch a ball that was falling, under gravity, either towards or away from their support leg (Appendix D). The ball fell from a starting height that the participants attained during a maximum one leg vertical jump. The ball was released by the same trained examiner for each participant, being released either early or late in the approach run, which, respectively resulted in the catch position of the ball being far from or close to the run direction.

Subjects were required to perform three successful trials of each landing task. Tasks were presented in random order until sufficient successful trials had been performed. A successful trial involved participants taking off and landing on their preferred foot and successfully taking possession of the ball. The landing was required to be on one foot and on the force plate; however, there was no restriction on landing technique post initial foot contact.

7.2.3 Data Collection and Analysis

Participants were fitted with retro-reflective markers as per the UWA Full Body Model,[51] a combination of the UWA Upper[128] and Lower Body Models.[16] Kinematic and inverse dynamic calculations were performed in VICON Workstation (VICON Peak, Oxford, UK) using the UWA Model, which employs custom code written in MATLAB (Mathworks, Natick, MA, USA) and VICON BodyBuilder (VICON Peak, Oxford, UK). This code uses data collected from functional methods to identify knee axes and hip joint centres and is described in more detail by Besier et al.[16] External moments were calculated with inverse dynamics[16, 109] using the body segment parameter values based on de Leva.[44] Prior to modelling, both the ground reaction force and position data were filtered using a 4th order 18 Hz zero-lag low-pass Butterworth filter, the filter frequency selected by performing a residual analysis and visual inspection of the data.

A landing phase was identified based upon the vertical ground reaction force. This phase ran from initial foot contact to double the time from initial foot contact to the peak vertical ground reaction force, this period being similar to that used by Decker and colleges.[47] A custom MATLAB (Mathworks Inc., Natick, MA) program was used to identify this time point. Within this phase, the peak valgus and peak internal rotation moments were identified. Flexion/extension moments were not analysed as they have been shown to be of similar magnitude for variations of the same task and, as such, it is changes in valgus or internal rotation moments that probably increase the risk of ACL injury.[14, 53, 147] The moments were normalised to each subject's height (m) multiplied by their mass (kg).[36, 51, 91, 150]

To characterise the body posture at landing the following kinematic variables were identified at initial foot contact: foot rotation, ankle plantar/dorsi flexion, ankle inversion/eversion, knee flexion/extension, hip flexion/extension, hip abduction/adduction, hip internal/external rotation, torso flexion/extension, torso lateral flexion and torso rotation. In order to identify the orientation of the knee relative to the direction of travel, a knee-path rotation angle was calculated. This was defined as the rotation of the knee around the y-axis of the direction-of-travel coordinate system. The knee was defined with the origin at the knee joint centre; the z-axis, being the knee flexion/extension helical axis, positive being left to right; the y-axis, being a vector along the plane defined by the knee joint centre and hip joint centre orthogonal to the z-axis, positive inferior to superior; and the x-axis being orthogonal to the z-y axis, positive posterior to anterior. The instantaneous direction-of-travel coordinate system was defined with the origin being the global origin; the x-axis, being the vector running from the x and z position of the mid-pelvis point 20 frames prior to the current frame to the x and z components of the mid-pelvis point 20 frames after the current frame, positive travel direction; the y-axis being the unit vector of the global y-axis, positive going up; and the z axis being orthogonal to x-y axis, positive going left to right. Negative numbers indicated that the medial aspect of the knee was pointing in the direction of travel (external rotation).

Data from the four landing conditions were pooled for all participants. Intra-participant correlations were performed for all positional data at initial foot contact and the normalised peak valgus and peak internal rotation moments. The slopes of all correlations were submitted to a one sample *t*-test to identify whether the mean slope values were significantly different from zero in SPSS 15.0 (SPSS Inc., Chicago, IL).[150] Statistical significance was set using an alpha of $p \leq 0.05$. Effect sizes were calculated using G*Power.[59] In recognition of the exploratory nature of the study and to improve functional relevance, variables approaching significance with a moderate ($d = 0.41$) or higher effect size[216] were considered to be relevant in terms of reducing knee loads and therefore potentially reducing ACL injury risk.

7.3 Results

The joint angles of knee flexion/extension ($p = 0.005$, $d = 0.65$), torso lateral flexion ($p = 0.001$, $d = 0.80$), torso rotation ($p = 0.0015$, $d = 0.66$) and foot rotation ($p = 0.001$, $d =$

1.20) were correlated to the peak valgus moment with slopes that were significantly different from zero (Table 7-1). Hip flexion/extension (*p* = 0.05, *d* = 0.46) was not significantly correlated to the peak valgus angle but displayed a medium effect size. Functionally, an increased valgus moment was associated with increased knee flexion, increased hip flexion, increased torso lean over the support leg, increased torso rotation towards the support leg and an externally rotated foot (Figure 7-1). Knee/path rotation (*p* = 0.004, *d* = 1.0) also returned slopes significantly different to zero (Table 7-1). Higher valgus moments were associated with having the knee externally rotated relative to the direction of travel (Figure 7-1). The strongest relationships were for knee/path rotation (r^2 = 0.27 ± 0.20), torso rotation (r^2 = 0.27 ± 0.20), and foot internal/external rotation (r^2 = 0.26 ± 0.20),.

Table 7-1 Mean (standard deviation) of the slopes between position data at initial contact and the peak valgus moment with the associated p value, effect size (d) and r^2 value. Bolded values indicate significance difference for the slope.

	Slope	*p*	*d*	r^2
Knee Flexion/Extension	**0.015 (0.023)**	**0.005**	**0.65**	**0.14 (0.11)**
Hip Flexion/Extension	0.007 (0.015)	0.053	0.46	0.15 (0.16)
Hip Abduction/Adduction	-0.003 (0.014)	0.411	0.21	0.11 (0.11)
Hip Internal/External Rotation	0.004 (0.012)	0.148	0.33	0.14 (0.13)
Ankle Plantar/Dorsi Flexion	-0.007 (0.019)	0.088	0.36	0.13 (0.16)
Ankle Inversion/Eversion	0.002 (0.037)	0.832	0.05	0.17 (0.16)
Foot Internal/External Rotation	**-0.006 (0.005)**	**0.001**	**1.20**	**0.26 (0.18)**
Torso Flexion/Extension	-0.001 (0.008)	0.289	0.12	0.10 (0.13)
Torso Lateral Flexion	**0.008 (0.010)**	**0.001**	**0.80**	**0.16 (0.16)**
Torso Rotation	**-0.002 (0.003)**	**0.001**	**0.66**	**0.27 (0.20)**
Knee Rotation relative to Path	**-0.004 (0.004)**	**0.004**	**1.00**	**0.27 (0.20)**

With reference to the peak internal rotation moment, the joint angles of hip abduction/adduction (*p* = 0.005, *d* = 0.60), hip internal/external rotation (*p* = 0.025, *d* = 0.57) ankle inversion\eversion (*p* = 0.012, *d* = 0.57) and torso lateral flexion (*p* = 0.023, *d* = 0.60), were correlated with slopes that were significantly different from zero (Table 7-2). Specifically, higher internal rotation moments were linked to less hip abduction, less hip external rotation, more ankle inversion and the torso leaning away from the support leg (Figure 7-2). Knee/path rotation (*p* = 0.034, *d* = 0.50) returned a slope

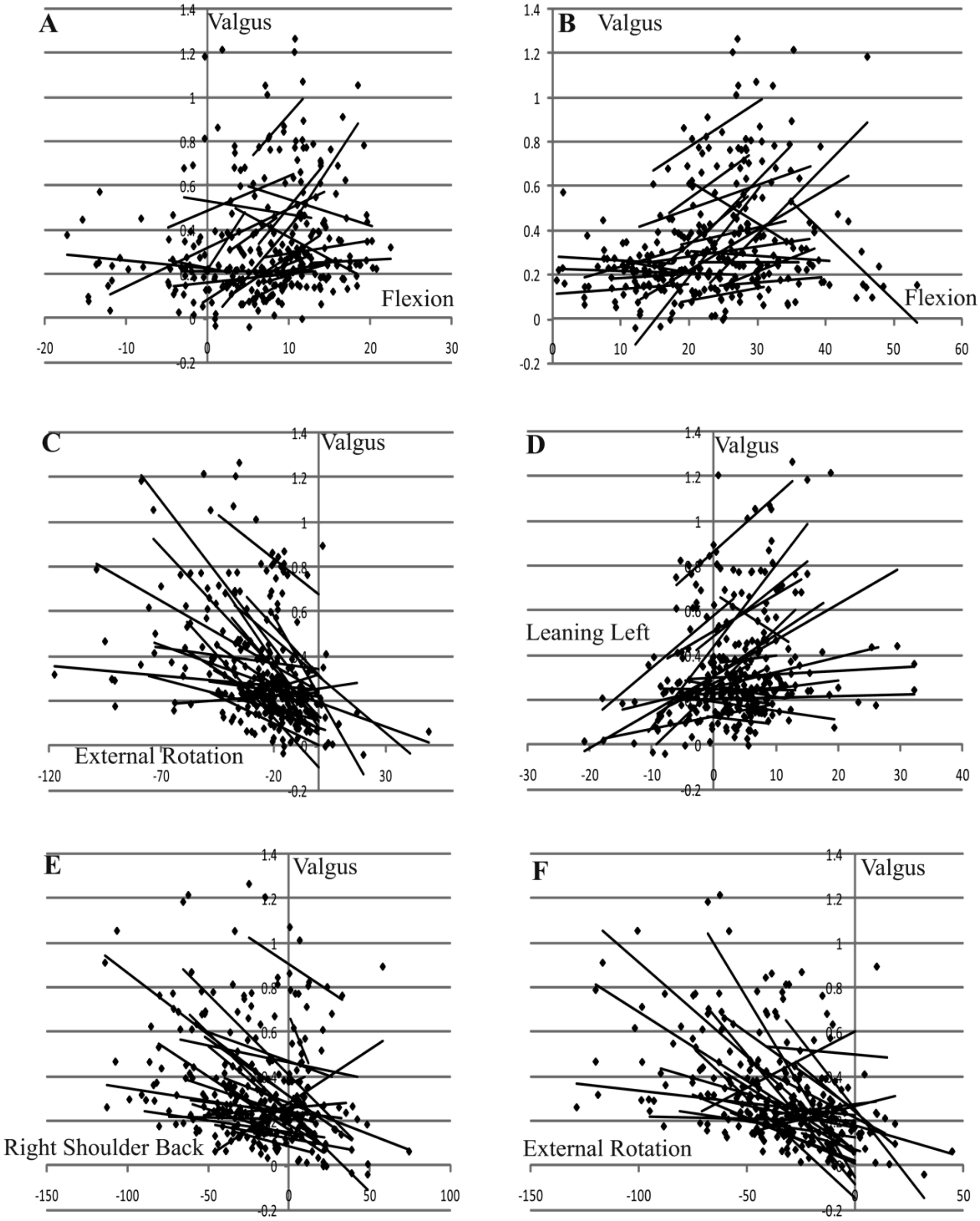

Figure 7-1 Scatter plots of position data versus peak valgus rotation moment for position variables with slopes significantly different from zero. Black lines are regression lines for each subject. A – knee flexion/extension; B – hip flexion/extension; C – foot internal/external rotation; D – torso lateral flexion; E – torso rotation; F – knee rotation relative to path. Vertical axis represents the varus/valgus moment in $Nm{\cdot}kg^{-1}{\cdot}m^{-1}$. Horizontal axis represents the joint angle in degrees.

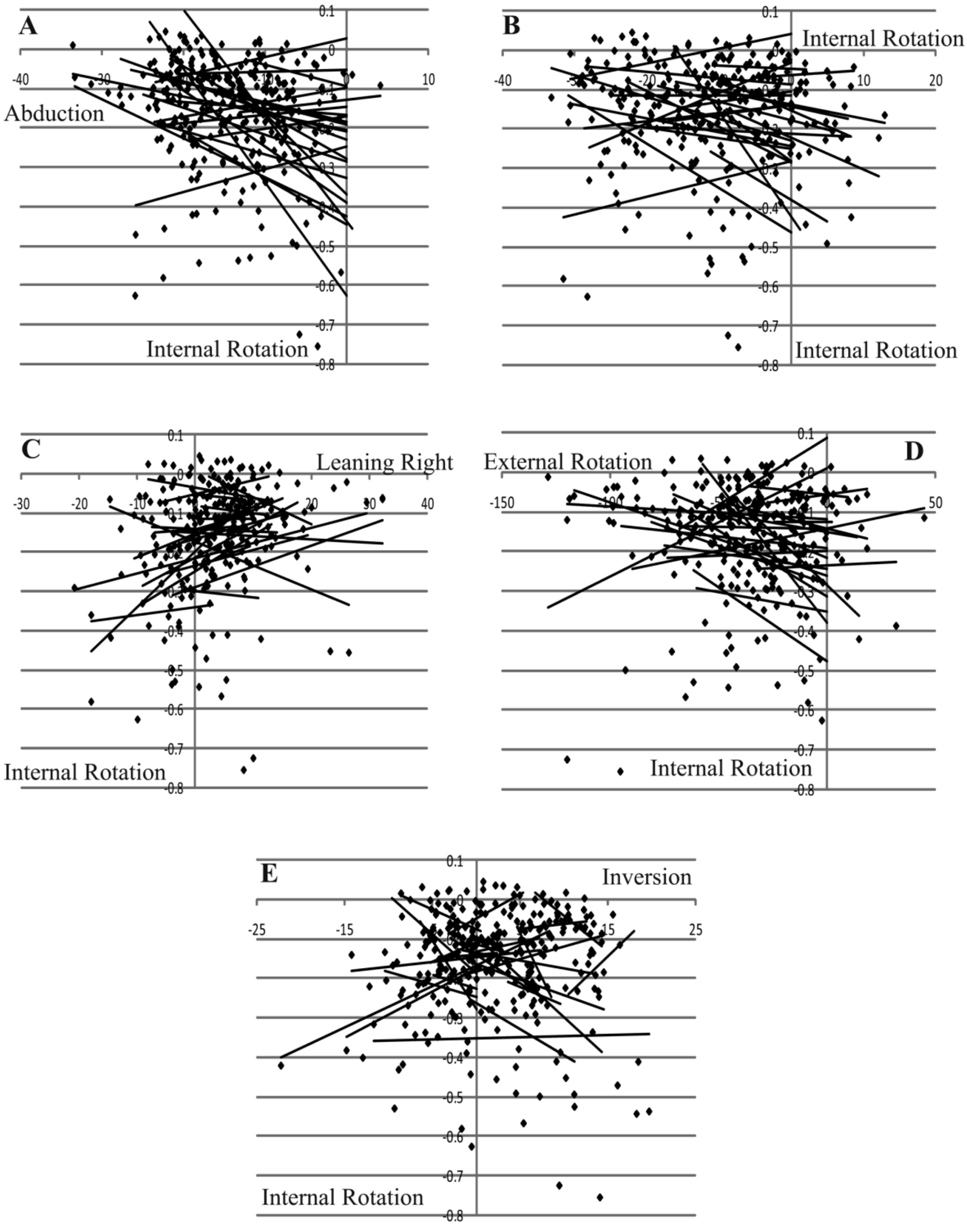

Figure 7-2 Scatter plots of position data versus peak internal rotation moment for position variables with slopes significantly different from zero. Black lines are regression lines for each subject. A – hip abduction/adduction; B – hip internal/external rotation; C – torso lateral flexion; D – knee rotation relative to path, E- ankle inversion\eversion. Vertical axis represents the varus/valgus moment in $Nm \cdot kg^{-1} \cdot m^{-1}$. Horizontal axis represents the joint angle in degrees

Table 7-2 Mean (standard deviation) of the slopes between position data at initial contact and the peak internal rotation moment with the associated p value, effect size (d) and r^2 value. Bolded values indicate significance difference for the slope.

	Slope	p	d	r^2
Knee Flexion/Extension	-0.003 (0.017)	0.456	0.18	0.15 (0.15)
Hip Flexion/Extension	-0.002 (0.008)	0.270	0.25	0.13 (0.16)
Hip Abduction/Adduction	**-0.006 (0.010)**	**0.005**	**0.60**	**0.14 (0.17)**
Hip Internal/External Rotation	**-0.004 (0.007)**	**0.025**	**0.57**	**0.08 (0.08)**
Ankle Plantar/Dorsi Flexion	0.007 (0.033)	0.303	0.21	0.14 (0.14)
Ankle Inversion/Eversion	**-0.008 (0.014)**	**0.012**	**0.57**	**0.14 (0.18)**
Foot Internal/External Rotation	-0.001 (0.003)	0.061	0.33	0.15 (0.14)
Torso Flexion/Extension	-0.003 (0.008)	0.137	0.38	0.14 (0.19)
Torso Lateral Flexion	**0.003 (0.005)**	**0.023**	**0.60**	**0.15 (0.17)**
Torso Rotation	-0.000 (0.002)	0.680	0.00	0.12 (0.15)
Knee Rotation relative to Path	**-0.001 (0.002)**	**0.034**	**0.50**	**0.14 (0.16)**

significantly different to zero. The knee being externally rotated relative to the direction of travel was correlated with higher internal rotation moments (Figure 7-2). Torso lateral flexion had a $r^2 = 0.15 \pm 0.17$ while hip abduction/adduction, ankle inversion/eversion and knee/path rotation all had a $r^2 = 0.14$.

7.4 Discussion

The main aim of this study was to identify full body postures that were correlated with valgus and internal rotation moments at the knee during landing tasks. It has been suggested that one of the components of non-contact ACL injury prevention programs should be technique modification, and while indirect technique modification has been incorporated in prevention programs utilising plyometrics,[129, 137, 159] there is no study associating full body landing techniques with high knee joint loadings.[129, 137, 159] The identification of postures associated with high loading of the knee will allow for better design of training protocols aimed at preventing non-contact ACL injuries.

Having the knee externally rotated relative to the direction of travel was associated with both high valgus and high internal rotation moments at the knee. The increase in valgus moment is most likely due to the braking force at landing having a greater ability to cause a valgus moment at the knee, if the knee is perpendicular to the force. As an externally rotated knee is also correlated with higher peak internal rotation moments, it would appear that instructing athletes to land with the knee pointing in the direction of travel would be beneficial. The correlation of an externally rotated foot with peak valgus moment may also be explained in the same manner. This position of external foot rotation is commonly seen in injury and is one of the body postures in the "position of no return" described by Ireland.[24, 104, 168]

While it has been argued in the literature that an increase in knee flexion during landing tasks would be beneficial for reducing ACL injury risk,[47, 104, 113] the current study found that an increase at initial ground contact was associated with increased valgus moments. However, this increase in moment may not cause an actual increase in strain on the ACL. The externally measured moment is only an indirect measure of the load applied to the ACL, which is moderated by increased knee flexion angles. In addition, valgus and internal rotation moments can be supported by the musculature crossing the knee joint.[132].

Knee flexion angle at initial contact may not be as important as the movement of the knee during early stance following initial contact, particularly as the peak occurs later in stance. It may be that athletes who make initial contact with a more extended knee joint and then move into flexion increase the time over which the force is absorbed and, therefore, reduce peak loading. Reduced maximal knee flexion during landing tasks has previously been associated with an increased risk of suffering an ACL injury.[91] Therefore, there may be a compromise between the best knee flexion angle at initial contact where the level of flexion in early landing is sufficiently high to ensure low ACL strain from the applied load,[140] while still remaining sufficiently extended to allow sufficient flexion post landing. Further research is recommended to examine the relationship between knee flexion angle, valgus loading and ACL loading in functional landing tasks utilising tools such as neuromuscular modelling in order to better understand their relationship to non-contact ACL injuries.

While it has been suggested that a more extended hip posture is associated with an increased risk of ACL injury, results from studies comparing male and female technique differences have been inconclusive.[47, 113, 121, 199] The current study found that increased hip flexion was associated with increased valgus moments. Most hip flexion angles identified in this study are similar to those seen during actual injury episodes, suggesting that, while there is a relationship, it may not be related to injury risk.[116] However, the effect of hip flexion on the ability of the biarticular muscles crossing both the hip and the knee to stabilise the knee in face of the applied valgus and internal rotation moments needs further investigation.

The correlation of higher internal rotation moments at the knee with less hip abduction and less hip external rotation is again reflective of the "position of no return" described by Ireland.[104] Previously, plyometric-based intervention studies have used a "knee over toe" position as a teaching guide for good landing technique.[170] The higher loading joint postures identified in this study would place an athlete well away from this posture, with the reduced hip abduction and external rotation bringing the knee inside the externally rotated foot. Landing in a "knee over toe" posture should lead to a reduction in joint moments, and therefore, reduce the risk of non-contact ACL injury.

Torso rotations have been shown to impact on both peak valgus and peak internal rotation moments in sidestep cutting tasks.[51] Additionally, the ability to control the trunk, particularly after lateral perturbations, predicts future ACL injuries.[51, 230] It is therefore not surprising, that torso rotations were associated with high valgus and internal rotation loads during landing tasks. As high peak valgus moments were associated with leaning towards the support leg and the large internal rotation moments were associated with leaning away from the support leg, the recommendation would be to strive for an upright and forwards facing torso at initial foot contact.

As this is the first study to directly investigate the associations between full body kinematics and knee loads in landing tasks further investigation should be undertaken to confirm the results and clarify the relationship of loading to knee and hip flexion. There are several methodological considerations that should be undertaken when designing subsequent studies. Firstly, the landing task should be reflective of game scenarios. The task utilised in this study was designed to mimic an overhead mark in Australian football. It has been shown that ball positioning affects both the kinematics and kinetics of both landing and sidestep cutting.[36, 53] Therefore, variations in task may cause different results and conclusions. Secondly, the methodology of identifying variations needs to be considered. In the current study variability was introduced by using different ball movements to induce changes during the same task. McLean et al.[150] utilised natural variation within sidestep cutting, while in Chapter 4 [51] directly assessed the impact of technique modification within sidestep cutting. The application of the McLean et al. and the approach used in Chapter 4to a basic landing task would allow for better understanding of the relationship between technique and loading.

7.5 Summary

The current study showed body postures at initial contact were associated with increased valgus and internal rotation loads at the knee. Specifically, landing with an externally rotated foot, with the knee also externally rotated to the direction of travel, an abducted and internally rotated hip and a laterally flexed or rotated torso would appear to be associated with an increased risk of injury. Teaching athletes to avoid these postures may lead to a reduction loading of the ACL. Increased knee and hip flexion were also associated with increased knee valgus moments, differing from current literature findings. Further work is needed to better understand these angle relationships to non-contact ACL injury.

CHAPTER 8 CAN TECHNIQUE MODIFICATION TRAINING REDUCE KNEE LOADING IN LANDING TASKS?

Based on the following paper submitted to the *American Journal of Sports Medicine*

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8.1 Introduction

Anterior cruciate ligament (ACL) injuries are a serious and all too common injury occurring in team sports. As most ACL injuries occur in non-contact situations, particularly during sidestep cutting and landing tasks, there is large scope for interventions aimed at modifying physical characteristics and/or movement techniques of athletes to reduce the risk of injury.[24, 38, 116, 168] It has been suggested that effective ACL injury prevention training programs should include balance, plyometric and technique training components.[129] There have been several laboratory-based studies assessing changes induced by plyometric and balance programs.[88, 89, 98, 105, 184] Recent work investigated the effect of technique modification training on sidestep cutting and found it was possible to reduce knee valgus moments through six weeks of training that emphasised foot placement and torso positioning.[52] However, no study has comprehensively investigated the effect of a technique modification program in landing tasks on knee joint loading. Technique modification training may reduce knee loading associated with non-contact ACL injury risk, in landing following catching a ball.

Knee joint moments have been used as a surrogate laboratory based measure of ACL load and, in turn, risk of non-contact ACL injury.[14, 33, 36, 150, 182, 204] The ACL is known to be loaded when the knee experiences anterior tibial drawer, internal rotation moments or valgus moments.[65, 140] Additionally, strain on the ACL is increased when these loads are applied simultaneously compared to when the loads are applied in isolation.[140] While various authors have argued that either anterior drawer[50] or the valgus moment[147] is more important in causing injury, for this paper it will be assumed that it is a combination of all applied loads that most likely causes injury.[140] As anterior drawer occurs when internal knee extension (external flexion) moments are generated while the knee is extended, it follows that changes in any of the applied knee flexion, valgus or internal rotation moments has the potential to modify the risk of non-contact ACL injury.

Knee flexion posture alters the transmission of all three knee moments load to loading of the ACL. In general terms, as knee flexion angle increases, the resultant load on the ACL decreases.[70, 72, 140] This is exhibited with the greatest transmission of a combination of internal rotation and anterior drawer loads occurring below 10° of knee flexion.[140] However, high ACL loads from a combination of valgus moments and anterior tibial drawer can occur at up to 50° of knee flexion, peaking around 20° to 30° of flexion.[140] Increased ACL loading at more extended knee postures is consistent with results from video analysis of injuries that have shown that at initial foot contact there is a trend for athletes' knees to be in an extended posture.[24, 38, 116, 168] Lin and colleagues[127] found that in simulations of stop jumps where sufficient ACL loads were produced to cause its rupture, the knee was more extended than when the loads were insufficient to cause ACL rupture. Raising the knee flexion angle also increases the potential of the biceps femoris to support internal rotation moments, with increases in the internal rotation moment arm increasing approximately fourfold from full extension to 50° of knee flexion.[28] All these findings support the recommendation that athletes should land with increased knee flexion to reduce the risk of non-contact ACL injury[104] and a number of plyometric based interventions have included cues to increase knee flexion within their drills.[90, 137, 159, 170] However, increased knee flexion has yet to be associated with reduced knee moments in either sidestep cutting or landing.[51, 54, 150]

Deficits in torso control have also been shown to be related to ACL injuries.[230] During laboratory investigations, increased torso lateral flexion and rotation towards the support leg have been shown to be related to increased valgus and internal rotation moments in both landing and sidestep cutting tasks.[51, 54] During actual injuries Boden and colleagues[24] described the leg and torso to be "…out of sync…". Technique training to control torso posture in landing may modify knee loading and reduce risk of ACL injury.

Therefore, the aim of this current study was to investigate the effect of a landing technique modification program on knee moments. The program was designed to train athletes to land with an upright and forward facing torso at initial foot contact, while increasing knee flexion angle throughout the entire landing. It was hypothesised that modification of these postures would result in reduced peak internal rotation and peak valgus knee moments during landing tasks. The results of this study will provide further information needed to develop intervention protocols that reduce the risk of non-contact ACL injury in sports involving landing tasks.

8.2 Methods

8.2.1 Participants

Twenty two male team sports athletes were recruited to participate in this study (height 180.5 ± 6.6 cm, mass 78.1 ± 14.2 kg). All participants were experienced in performing functional landing tasks through their respective team sport (Australian football, rugby union or soccer). Participants were excluded if they had a history of major lower limb injury. Five participants withdrew from the study, citing external time constraints. Ethics approval was obtained from UWA Human Research Ethics committee and written, informed consent was obtained from all participants prior to data collection. Subject numbers were based upon a power analysis performed using effect sizes reported in Chapter 5 [52] and a power of 0.08 and p = 0.05, inflated to account for dropout.

8.2.2 Experimental Design

The technique modification program was based on the one described in Chapter 5 for sidestep cutting.[52] It consisted of a six week program, containing two sessions per week, with weekly training tasks based upon weekly goals (Table 8-1 and Table 8-2). As the six weeks progressed, training drills moved from closed (controlled) to open (game-like) tasks; a progression shown to produce better skill acquisition outcomes than practice with just open skills.[85] Training was undertaken in small groups of 1-2 participants, with all sessions taken by the same instructor. During each training session, participants were given both oral and visual feedback. The visual feedback used TimeWARP (SiliconCOACH, Dunedin, NZ) to provide immediate feedback on their landing technique together with reference videos (Appendix C) of athletes performing the landing task using the desired technique. Participants aimed to have their torso facing forward and upright at initial foot contact, while increasing their knee flexion angle throughout the entire landing. No one received training prior to baseline testing and subsequent landing training.

Table 8-1 Weekly goals on which the landing training program was based

Week	Aims
1	Start of increased flexion
2	Can do full task
3	Can perform task catching a ball thrown straight
4	Can perform task catching a ball thrown left or right
5	Can start to do the task with unanticipated ball direction
6	Can perform the task consistently both pre-planned and unanticipated

Table 8-2 Landing training Program

Week	Tasks
1	• Perform one legged land from a box • Receive feedback on knee angle • Repeat
2	• Perform take off and one legged land • Receive feedback on knee angle and torso positioning • Repeat • Should be able to perform task correctly by the end of the second session
3	• Perform landing task while receiving a ball thrown straight at participant • Receive feedback based upon required changes
4	• Perform landing task while receiving a ball thrown to the left, right or directly to participant • During this stage balls will be thrown from the waist and early to allow the participant the best possible chance of picking up the direction early • Receive feedback based upon required changes
5	• Continuation of week 4 drills • Start of unanticipated ball direction
6	• Perform task successfully every time • Feedback for any required changes

All testing was undertaken at the UWA Sports Biomechanics Laboratory with marker movement recorded using a 12 camera VICON MX motion analysis system sampling at 250 Hz (VICON Peak, Oxford, UK). Ground reaction forces were synchronously recorded at 2000 Hz from a 1.2 m x 1.2 m force plate (Advanced Mechanical Technology Inc., Watertown, USA). Before commencing the trials participants selected the preferred support leg on which they would both take off and land during the landing task.

The landing test described in Chapter 6 [53] was used for this study. Briefly, the test required participants to take possession of a ball that was falling, under gravity, with the ball starting from the same height that the subject attained in a maximum effort one leg vertical jump (Appendix D). Subjects had a five step running approach and took off from the preferred support leg. They were required to land initially on the support leg only, however there were no restrictions following this. The ball was released by the same trained examiner for each participant and was released to fall either towards or away from the support leg, either early or late in the approach run. Pilot work identified that the landing task producing moments most likely to increase the risk of non-contact ACL injury was the ball falling towards the support leg early in the approach run. As such, this was the only task analysed for this study. However, participants still performed all four tasks to maintain the efficacy of the landing test.

Participants were required to perform three successful trials of each of landing task. The types of tasks were presented in random order until sufficient successful trials had been performed. A successful trial involved participants taking off and landing on their preferred foot and successfully taking possession of the falling ball. The landing was required to be on one foot and on the force plate.

8.2.3 Data Collection and Analysis

Participants were fitted with retro-reflective markers as per the UWA Full Body Model,[51] a combination of the UWA Upper[128] and Lower Body Models.[16] Kinematic and inverse dynamic calculations were performed in VICON Workstation (VICON Peak, Oxford, UK) using the UWA Model, which employs custom code written in MATLAB (Mathworks, Natick, MA, USA) and VICON BodyBuilder (VICON Peak, Oxford, UK). The UWA Full Body Model uses functional methods to identify knee axes and hip joint centre and is described in more detail by Besier et al.[16] Prior to modelling, both the ground reaction force and position data were filtered using a 4th order 18 Hz zero-lag low-pass Butterworth filter, the filter frequency selected from residual analysis and visual inspection of the data. Inverse dynamics were used to calculate external joint moments,[16, 109] using the body segment parameters reported by de Leva.[44]

The portion of the landing phase used to compare knee moments was selected using the vertical ground reaction force data. Previously, *in vivo* studies have shown that the peak ACL load occurs close to the time of the peak vertical force.[32] As such, the landing phase was classified as the period from the point of initial foot contact to double the time from this point to peak vertical ground reaction force. Subsequently, a custom MATLAB program (Mathworks Inc., Natick, MA) identified the start and end time points of this landing phase, these points being similar to that used by Decker and colleges.[47] Within this phase, the peak knee flexion, valgus and internal rotation moments were selected for analysis as they have the greatest potential to load the ACL. The moments were normalised to each subject's height (m) multiplied by their mass (kg).[36, 51, 91, 151, 226] Maximal knee flexion angles, and knee flexion angles at the time of peak valgus and internal rotation moment were also identified within this phase. To characterise the body posture at landing the values of the following kinematic variables were determined at initial foot contact: knee flexion/extension, torso flexion/extension, torso lateral flexion and torso rotation.

All moments and joint postures were compared from pre- to post-training using paired *t*-tests with the alpha set at $p < 0.05$. All statistical procedures were performed using SPSS 17 (SPSS Inc., Chicago, IL). Effect sizes were calculated using G*Power.[59] To improve functional relevance of the study, changes approaching significance with a moderate ($d = 0.41$) or higher effect size were considered to be relevant for potentially reducing ACL injury risk.[216] Where significant or functional changes were identified in the knee moments, correlations were undertaken to see whether these were associated with kinematic changes identified as significant or functional. Changes were calculated, such that positive values indicated changes that were *a priori* identified as reducing risk of ACL injury.

8.3 Results

Subjects initially contacted the ground with a relatively extended knee of less than 10°of knee flexion (Table 8-3). There was no significant or functional increase in knee flexion angle at initial foot contact following the training ($p = 0.459$, $d = 0.20$). However, during the landing phase there was a significant increase in the maximum knee flexion angle of approximately 10° ($p = 0.010$, $d = 0.67$). There was also a significant increase in the knee flexion angle occurring at the peak internal rotation moment of approximately 15° ($p = 0.017$, $d = 0.65$), but not at the peak valgus moment ($p = 0.250$, $d = 0.29$).

Table 8-3 Mean (standard deviation) for knee flexion angle (°) at initial foot contact, maximum angle during weight acceptance and a peak valgus and peak internal rotation moments. *p* and *d* are the respective probabilities and effect sizes of the pre to post training differences.

	Pre	Post	*p*	*d*
Initial Foot Contact	6.8 (7.1)	8.0 (6.2)	0.459	0.20
Max	57.0 (14.5)	66.7 (17.9)*	0.010	0.67
Peak Valgus Moment	25.7 (10.5)	30.9 (15.6)	0.250	0.29
Peak Internal Rotation Moment	31.8 (9.9)	46.2 (21.1)*	0.017	0.65

* Significant difference at $p < 0.05$

Torso postures did not change after training (**Error! Reference source not found.**). here were no significant or functional changes for torso flexion/extension ($p = 0.639$, $d = 0.12$), lateral flexion ($p = 0.263$, $d = 0.29$) or rotation ($p = 0.213$, $d = 0.32$) following training. This is despite a 7° reduction in torso rotation in the post training testing session.

Table 8-4 Mean (standard deviation) of torso angles (°) at initial foot contact. *p* and *d* are the respective probabilities and effect sizes of the pre to post training differences.

	Pre	Post	*d*	*d*
Torso Flexion\Extension	1.3 (10.7)	0.3 (8.9)	0.639	0.12
Torso Lateral Flexion	8.2 (6.3)	5.4 (7.6)	0.263	0.29
Torso Rotation	-43.7 (23.1)	-36.0 (20.4)	0.213	0.32

* Significant difference at $p < 0.05$
A positive value indicates: Torso Flexion\Extension – flexion; Torso Lateral Flexion – leaning right; Torso Rotation – left shoulder back.

The altered joint kinematics did not result in changes to either the peak flexion ($p = 0.676$, $d = 0.10$) or peak valgus ($p = 0.244$, $d = 0.37$) moments recorded during the landing phase (Table 8-5). However, peak internal rotation moments increased following the training program (p = 0.042, d = 0.52). The increase in peak internal rotation moment was correlated with an increase in the maximal knee flexion angle (r = 0.613, p = 0.009), but was not correlated with change in knee flexion angle at the time of peak internal rotation moment (r = 0.073, p = 0.779).

Table 8-5 Mean (standard deviation) peak knee joint moment data ($Nm \cdot kg^{-1} \cdot m^{-1}$). p and d are the respective probabilities and effect sizes of the pre to post training differences.

	Pre	Post	*p*	*d*
Flexion	-2.07 (0.56)	-2.03 (0.39)	0.676	0.10
Valgus	0.41 (0.23)	0.32 (0.19)	0.244	0.37
Internal Rotation	-0.13 (0.05)	-0.20 (0.13)*	0.042	0.52

* Significant difference at $p < 0.05$

8.4 Discussion

The main aim of this study was to induce technique changes and observe the effect that these changes had on knee joint loading, characterised by knee moments. Specifically, the six week technique modification program aimed to increase knee flexion during landing and have athletes land with an upright forward facing torso. It should be noted that, although the technique modification program was successful in increasing maximum knee, with a 10° increase in maximal knee flexion angle, there was no change in either the knee flexion angle at initial contact or on in any of the torso angles.

The unexpected lack of change in knee flexion at initial foot contact may be a result of the methodology used in the training intervention. The current study utilised verbal and visual feedback to train the participants to increase knee flexion. Previous research has shown that verbal feedback is capable of increasing knee flexion angles at initial foot contact within a testing/training session,[42] although these changes are not always carried forward to follow up testing sessions.[215] Steele and Munro[215] demonstrated that the use of a biofeedback device providing instantaneous aural feedback to the athlete during landing training was successful in increasing both maximal knee flexion and knee flexion at initial foot contact at follow up testing after training with the device for six weeks. The integration of immediate biofeedback into the technique modification program described in this study may result in further increases in maximal knee flexion and knee flexion increases at initial foot contact.

While non-significant, there was a 17% reduction in torso rotation following technique modification training. However, further investigation revealed this reduction to be due to large changes in technique displayed by only three participants (Figure 8-1). The lack of change in the remainder of participants, and the lack of change in torso lateral flexion may be as a result of the requirement of the landing task to gather a ball located away from the body on the support leg side.

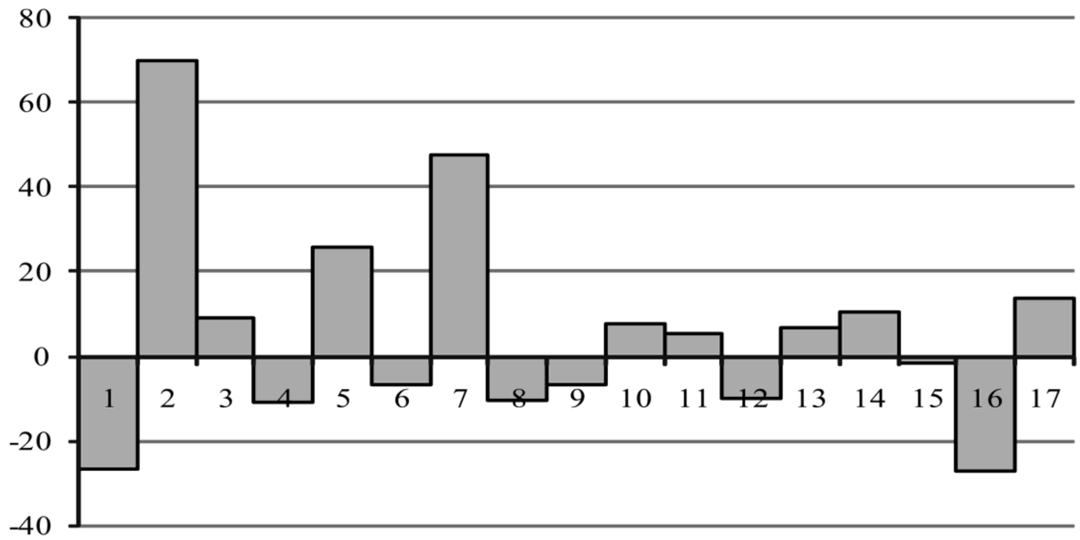

Figure 8-1 Individual participant changes in torso rotation from pre- to post-training. Positive changes indicate the desired change.

While the technique modification program was successful in modifying maximum knee flexion, it did not reduce the knee joint moments. There was no change in either the peak flexion or peak valgus moment during landing from pre- to post-technique modification training, although there was a significant increase in peak internal rotation moment. The strong correlation between the change in maximal knee flexion and change in knee internal rotation moment is indicative of some relationship between the two variables. Despite knee flexion angle not previously having been associated with knee internal rotation moments in studies investigating both sidestep cutting and landing,[51, 54, 150] the current finding suggests that increasing the maximum knee flexion angle in landing task causes an increase in the peak internal rotation moment. Therefore, increasing maximal knee flexion angle may increase the risk of injury, possibly making the current intervention inappropriate for reducing the risk of non-contact ACL injuries. However, other factors may alter this conclusion.

The increase in the peak internal rotation knee moment needs to be viewed with respect to the knee angles affect on this moment's transmission to the ACL and potential muscular support. Greatest transmission of internal rotation moments to the ACL occurs in conjunction with the application of anterior drawer below 10° of knee flexion.[140] While the initial contact knee angles are below 10° of knee flexion in the present study, the knee angle at peak internal rotation moment occurred well outside this range at both pre- and post-intervention. As the knee flexion angle at the time of the peak internal rotation moment increased by almost 15° after training, the increase in the magnitude of the moment may not have increased the load on the ACL as it is occurring further away from the joint angles where high load transmission are experienced. This 15° increase in knee flexion angle also increases the potential for the biceps femoris to support the internal rotation moment, with an approximate doubling of the external rotation moment arm of both heads of biceps femoris.[28] As we did not assess muscle activation during the landing we cannot identify actual increases in muscular support, however the increase in support potential, coupled with the reduction in transmission, suggest that the increased in knee internal rotation moment may not be as detrimental as first thought.

The increase in maximal knee flexion angle did not affect the knee angle occurring at the peak valgus moment. Peak transmission of valgus loading, applied in conjunction with anterior drawer loads, occurs around 20° to 30° of knee flexion.[140] In the current study the peak valgus moment was occurring at knee angles falling within this range. While increased knee flexion angles increase the potential for muscular support or internal rotation moments, the opposite is true for valgus moments.[130] As increasing knee flexion angles did not affect the angle at which the peak valgus moment was applied, and increased knee flexion decreases the potential for support, the value of increasing knee flexion angle to reduce the risk of injury from valgus loading is questionable.

The results of the present study suggest that the relationship between knee angle, knee loading and risk for non-contact ACL injury is complicated and further investigation is required. This investigation should utilise neuromuscular skeletal modelling tools to evaluate the impact of knee angle on knee moments and potential muscular support. Further, the results from such a study should be used to drive stochastic biomechanical models, such as those described by McLean et al.[147] and Lin et al.,[127] to estimate ACL loadings occurring under a variety of conditions. This will allow for the identification of the ideal landing technique to prevent ACL injury and the development of training programs to allow athletes to develop this technique.

Results and conclusions from this study should be viewed in context of the limitations of this study. The task selected in this study is reflective of an overhead mark in Australian football, a task during which ACL injures are known to occur.[37] ACL injures also occur during vastly different landing tasks such as shooting for goal in European handball.[168] The resultant technique and loading may be different, and therefore the impact of increasing knee flexion may be different. The results from the current study may not be applicable, and investigations should be undertaken into both the kinematic and kinetic profiles of varied landing tasks, and the impact of technique modification within each of these. The current study also only investigated one group and did not compare to controls. This should be undertaken in order to ensure that changes reported are not solely due to time effects and are the result of the technique modification program.

8.5 Summary

The technique modification program was only successful in changing maximum knee flexion during landing tasks following six weeks of training. This increase in maximal knee flexion during the landing phase was accompanied by increased internal rotation moments but with no change to either the flexion or valgus moments. Further research should be undertaken to investigate the effect of knee flexion angle on both joint moments and muscular support. This research should utilise new tools such as biofeedback technologies and neuromuscular skeletal modelling.

CHAPTER 9 GENERAL DISCUSSION

9.1 Conclusions

The overarching theme of this thesis was to identify how technique modifications in sporting tasks affected knee loading, particularly external valgus and internal rotation moments. This was undertaken in the context that technique modification may be able to reduce the risk of non-contact ACL injury, a serious, oft occurring injury within team sports. High external valgus and internal rotation moments at the knee have been shown to be related to non-contact ACL injury through a combination of cadaveric[140] and *in vivo*[65] studies, as well as biomechanical investigations into high risk manoeuvres[14, 91] and inferences from analysis of actual injuries.[38] Studies of actual injuries have identified that the high risk sporting tasks, in terms of non-contact ACL injury, are sidestep cutting and landing.[24, 38] Further similar joint postures have been observed at initial foot contact during actual injuries in both these tasks.[24, 38, 117, 168] This has led to the recommendation that interventions aimed at reducing the risk of non-contact ACL injury should include a technique modification component.[129] However, to date there has been a paucity of research investigating the relationship between knee moments and kinematics in either sidestep cutting or landing tasks, and none investigating the relationship between whole body kinematics and knee moments. Further there have been no studies investigating the effect of specific whole body technique modification on knee loads in either sidestep cutting or landing. Therefore the specific aims of this thesis were:

1. Identification of sidestep cutting techniques associated with high valgus and internal rotation moments;

2. Testing if a sidestep cutting technique modification program based upon avoidance of the identified "high loading" techniques is capable of reducing external valgus and internal rotation moments in sidestep cutting;

3. Identification of landing techniques associated with high valgus and internal rotation moments; and

4. Testing if a landing technique modification program based upon recommendations from the literature and joint posture linked to higher loading, is capable of reducing external valgus and internal rotation moments in landing.

To address these aims five studies were undertaken; a series of two focussing on sidestep cutting and aims one and two and a series of three focussing on landing and aims three and four. The first of the sidestep cutting studies required participants to perform both their normal sidestep cut followed by a series of trials where they were required to perform the manoeuvre with specified techniques. This series of nine imposed sidestep cutting techniques represented the extremes of postures achievable by differing body segments. Through comparisons between the extreme postures of each segment, i.e. torso leaning as far as possible in the same direction as the sidestep cut and torso leaning as far as possible in the opposite direction as the sidestep cut, it enables the identification of body postures that produced higher knee joint moments. Following the identification of these high loading postures it was possible to develop a six week technique modification program, which formed the basis of the second study investigating sidestep cutting. During this study participants were tested immediately prior to and following their participation in the six week technique modification program. This allowed for the identification of changes to both their full body kinematics and knee joint moments during the weight acceptance phase of the side step cutting manoeuvre.

In the first of the two studies (Chapter 4) on sidestep cutting it was shown that imposed sidestep cuts requiring wider stance foot placement (F_{Wide}) and torso lean in the opposite direction to the sidestep cut ($T_{Opposite}$) resulted in high valgus moments during the weight acceptance phase of the sidestep cut. Rotating the torso away from the direction of the sidestep cut ($T_{Rotated}$) and wider stance foot placement (F_{Wide}) caused high internal rotation moments. As these three joint postures resulted in increased knee moments known to load the ACL, it can be assumed that performing a sidestep cut with these joint postures would result in increased risk of non-contact ACL injury. Further these joint postures are similar to those observed during actual injuries, strengthening the argument that these should be avoided.

The second study (Chapter 5) identified that technique modification training was successful in reducing the width of foot placement and in bringing participants' torsos more upright. This was accompanied by a reduction in peak knee valgus moments. However, while there was no change in torso rotation or knee internal rotation moments, it does appear that technique modification can have positive effects on both full body kinematics and knee moments.

Within the series of three landing studies, two investigated the relationship between full body kinematics and knee loads, while the final study investigated the implementation of a six week technique modification program on full body kinematics and knee moments. The first study investigated the influence of varying the positing of a ball in the air that participants were required to take possession of, prior to performing a landing task. Further, it investigated whole body kinematics associated with the task producing the highest knee moments. Investigation of the association between the whole body kinematics and knee moments was expanded in the second study. This study identified joint postures associated with high valgus or internal rotation moments by analysing the average of the regression lines created for each participant based upon three trials of each of four ball positions. The final study investigated the effect of a 6 week technique modification program aimed at having the torso upright and forward facing at initial foot contact with a flexed knee joint on full body kinematics and knee kinetics. During this study participants were tested immediately prior to and following their participation in this six week technique modification program. Again this allowed for the identification of changes to both their full body kinematics and knee joint moments.

In the first of these studies (Chapter 6) it was identified that the ball falling towards the support leg resulted in increased peak valgus moments and therefore potential risk of non-contact ACL injury. In the second study (Chapter 7) it was shown that increased valgus and internal rotation knee moments on landing from a jump were associated with a number of different joint postures. These were; increased knee flexion at initial foot contact, increase hip flexion at initial foot contact, decrease in hip abduction and external rotation, the foot and knee turned out, ankle inversion and torso lateral flexion or torso rotation towards the support leg. The association of increased hip and knee flexion with increased valgus and internal rotation moments is contrary to that suggested by the literature. However, the other postures did reflect those previously associated with ACL injury.

In the final of the series of landing studies (Chapter 8) it was identified that a technique modification program was successful in increasing maximal knee flexion angle but did not elicit any other kinematic change. However, there was an increase in peak internal rotation moments recorded at the knee and no change on peak valgus or peak flexion moments. While there was an increase in peak internal rotation moment this may not have increased the risk of injury due to the peak moment occurring at knee angles where there is reduced transference to the ACL and increased muscular support. Despite this the technique modification program was not successful in its stated aim of reducing the potential risk of non-contact ACL injury.

Overall this thesis identified that whole body kinematics are related to knee moments in both sidestep cutting and landing tasks. Further it identified that that it is possible to modify both sidestep cutting and landing technique with six weeks of technique modification training. While this technique modification reduced valgus knee moments in sidestep cutting, there was an increase in knee internal rotation moments during the landing phase in the landing tasks.

9.2 Implications

This thesis is the first to investigate the relationship between full body kinematics and knee joint moments in both sidestep cutting and landing. Previous laboratory investigations relating technique to knee loading or risk of injury have focused on the lower body.[91, 150, 210] Only one study has looked at the relationship between upper body posture and knee loads in sidestep cutting, and that was primarily focused on the impact of ball carrying on arm position.[36] On the whole, joint postures associated with higher valgus and internal rotation moments at the knee reflected those previously identified in the literature as being related directly to injury[24, 38, 56, 117, 168] and with high knee moments.[91, 150, 210] This logically indicates that there are a number of body postures, which, if modified, can result in reduced knee moment magnitudes that have the potential to reduce the risk of non-contact ACL injury.

However, there were conflicting results for changing knee flexion posture when compared with the literature. Cadaveric and *in vivo* studies have identified that the ACL is highly loaded at more extended knee postures.[17-19, 64-66, 69, 70, 72, 74, 140] Investigations of actual injury has also identified that the knee is in an extended posture at the time of injury.[24, 25, 38, 116, 168] These results support the recommendation in the literature that athletes should increase knee flexion angles to reduce the risk of non-contact ACL injury.[90, 104, 137, 159, 170] However, results presented in this thesis suggest that increasing knee flexion has no affect on knee moments in sidestep cutting, and increased knee flexion is associated with both increased knee internal rotation and valgus moments in landing. This would suggest that, at best, increasing knee flexion angle will have no impact on the risk of non-contact ACL injury and may potentially increase an athlete's risk of injury. However, the impact of knee angle on other neuromuscular joint factors may have greater role here in regard to ACL injury risk.

The impact of knee flexion on non-contact ACL injury risk depends on the transmission of applied knee loads to the ACL and the muscular support of the applied knee loads. Markolf el al.[140] simultaneously applied knee loads in two different directions and identified that below 10° of knee flexion a combination of anterior drawer and internal rotation moments results in high loads at the ACL (Figure 2-1). Further, the resulting ACL load from the combination of a valgus moment and anterior drawer load is high from 10° and 50° of knee flexion and peaks around 20°-30° of knee flexion (Figure 2-1). In the current studies, peak valgus moment occurred within this peak loading range, irrespective of the technique training based change in maximal knee flexion angle in the landing phase. There was an increase in knee angle at peak internal rotation moment, although this increase may not be important as the pre-training knee angle was already well outside the high loading range. However, the change in knee angle from training almost doubles the potential for support of the internal rotation moment by the biceps femoris.[28] Therefore the increase in peak internal rotation moment observed in Chapter 8 may not have resulted in increased load on the ACL and therefore increased risk of non-contact ACL injury.

While potential muscular support is increased for internal rotation moments it decreases for valgus moments with increased knee flexion angles.[130] Even though there was no observed significant change in knee angle at peak valgus moment the there was a trend for increases. This would suggest that increasing knee flexion may increase the risk of injury arising from valgus loadings. Further investigations need to be undertaken into this relationship utilising tools such as electromyographic driven neuromuscular modelling[49, 132] to better understand the range of joint angle, loading and muscle activation in landing and sidestep cutting and stochastic modelling[127, 147] to understand how these ranges affect ACL loading.

The results from the two technique training investigations presented in this study (Chapter 5 and Chapter 8) indicate that it is possible to modify both sidestep cutting and landing techniques within the laboratory settings with six weeks of training. However, they also reveal that undertaking technique modification programs to achieve theoretically safer joint positions does not necessarily result in improved joint loading patterns, with reference to non-contact ACL injury. The results presented in Chapter 5 show that modifying sidestep cutting was successful in both changing technique and reducing peak valgus moments. As it has been identified that intervention programs aimed at reducing non-contact ACL injury are most successful when they contain multiple components,[93] this technique modification program should be integrated with balance and plyometric programs known to reduce the incidence of knee injuries in team sports.[31, 86, 90, 137, 159, 214] The impact of such hybrid interventions should be tested in both the laboratory setting and the field. Should this prove successful the program should be widely promoted to both community level and elite coaches of team sports in an attempt to reduce the incidence of injury.

As presented in Chapter 8 the increase in internal rotation moment associated with the increase in knee flexion during landing indicates a more cautionary approach to implementing technique modification programs. Any technique modification protocol should be tested within the laboratory setting to identify that it does achieve the required change, and that it does not result in increased risk of non-contact ACL injury. While the increase in internal rotation moment may not have resulted in increased ACL loading and therefore risk of injury, the appropriateness of inducing changes in athletes’ technique patterns for no reduction in risk is questionable. The requirements of the athletic task should also be considered prior to planning technique modification. In Chapter 8 the task required athletes to reach outside their body to take possession of a ball. This requirement may have resulted in the lack of change observed in torso rotation and lateral flexion. While a technique modification may reduce knee loads if it results in athletes being unable to perform the requirements of the tasks within their sports, it will either have no effect or not be adopted by coaches.

Despite the increase in internal rotation moments identified with increase knee flexion, there is currently still insufficient data to suggest that the recommendation for aiming to increase knee flexion be removed from plyometric training programs for ACL injury reduction.[90, 137, 187] It may be that when the two components are combined the observed benefits of increasing knee flexion angle, moving away from areas of high transmission and increase muscular support, may be retained without the associated increase in join moments. Rather, as previously recommended further investigation into the impact of knee flexion angle on joint moments, muscular support and transmission of any loads to the ACL needs to be undertaken.

9.3 Limitations

While the results from this thesis will allow for the further development of training programs aimed at reducing the risk of non-contact ACL injuries there are a number of limitations.

- Only male team sport athletes were tested during the course of study. The results may therefore not be directly relatable to female athletes.

- All testing was undertaken in the laboratory due to limits in technology able to calculate kinematics and kinetics. It is expected that the techniques participants used to perform the task within the laboratory reflected those used in game. As the assessment was only undertaken in the laboratory it cannot be concluded that the athletes were utilising the modified techniques during games.

- While sidestep cutting is similar across sports the requirements of landing tasks is vastly different. The landing task utilised in this thesis replicated an overhead mark in Australian football. The results from the investigations in landing (Chapter 6 Chapter 7 and Chapter 8 may not be applicable to sports where the requirements of landing tasks are different.

9.4 Directions for Future Research

Directions for future research into technique and knee loading can be broadly grouped into two categories:

1. Further development of our understanding of the relationship between technique and risk for non-contact ACL injury; and

2. Further development and testing of technique modification for reducing the risk of non-contact ACL injury.

Potential future research will be briefly discussed for both categories.

9.4.1 Relationship between Technique and Non-Contact ACL Injury Risk

This thesis solely investigated the relationship between kinematics and joint moments in both sidestep cutting and landing and did not investigate the activation of the knee musculature. The muscles crossing the knee have been show to absorb loads at the knee, thereby protecting the ACL.[131] However the ability of these muscles to support the loads is affected by joint angle.[28, 130] Therefore the following research is suggested:

- Investigation of relationship between muscle activation, ankle, knee and hip kinematics and knee moments during laboratory testing of sporting tasks.

- As this is a complex interaction, tools such as neuromuscular modelling should be utilised. This will allow for investigation of the impact of varying full body kinematics or muscle activation properties on knee moments.

- Results from variations from neuromuscular modelling should then be used to drive stochastic biomechanical models capable of estimating ACL load, such as that described by McLean et al.[147] and Lin et al.[127]

Results from neuromuscular biomechanical investigations and stochastic biomechanical model investigations will also allow for a better understanding of the complex relationship between knee flexion angle, knee moments and ACL loading. These investigations should also investigate the impact of variation in upper body position on knee moments and ACL loading.

As previously discussed this study did not investigate the relationship between technique and knee moments in females. This was due to the known effect of the menstrual cycle on injury risk.[95] The following research is suggested to address this:

- Investigation of relationship between muscle activation, ankle, knee and hip kinematics and knee moments during laboratory testing of sporting tasks, within phases of the menstrual cycle associated with both higher risk and lower risk of non-contact ACL injury.

Finally a better understanding of the kinematics of actual injury is required. This should be undertaken in two areas:

- Utilisation of new video analysis tools, such as that described by Krosshaug and collegues,[114, 115, 117] should be used to provide more accurate discrete and time series data of actual injury situations for all lower limb joint posture and upper body postures

- There is a need to understand of the normal kinematics of sidestep cutting and landing tasks as usually performed by athletes during normal game scenarios. This will allow for the identification of normal ranges and then the comparison to injury scenarios. While undertaken briefly by Boden et al.[25] and Hewett et al.[96] it needs to be performed on a large number of sidestep cutting and landing tasks.

9.4.2 Technique Modification to Reduce Non-Contact ACL Injury Risk

The technique modification program trialled for landing tasks within this thesis was unsuccessful in reducing knee loads. A better understanding of the relationship between technique and risk of non-contact ACL injury will allow for the development of a more targeted technique modification program for landing. Research should be undertaken to:

- Identify the efficacy of any new technique modification program in reducing joint loading and therefore non-contact ACL injury risk in a variety of ecologically valid landing tasks.

While both technique modification programs describe in this thesis were successful in changing an individual athlete's technique the following should be investigated:

- If technique changes are utilised in game scenarios.

- If technique changes are maintained in both the short term, i.e. remainder of the current sporting season, and long term, i.e. future sporting seasons.

- If the use of new technologies, such as biofeedback, are capable of improving both the rate and magnitude of any required change.

- If the technique modification program can be implemented in a team setting.

- If technique modification is better suited and more successful in reducing loads in athletes identified as having poor techniques.

While the technique modification program in sidestep cutting was successful in reducing joint loading it cannot be conclusively stated that the program reduces non-contact ACL injury risk. As such:

- The technique modification program should be assessed for effectiveness in reducing non-contact ACL injury rates within the team sport setting though a prospective epidemiology study.

There have previously been a number of interventions aimed at reducing ACL injury rates using balance and plyometric training, which have been successful both in the laboratory and in reducing injury rates in the field. Therefore:

- The technique modification program should be assessed in comparison to programs previously shown to reduce non-contact ACL injury risk.

- The technique modification programs should be combined with previously successful programs and assessed both in the laboratory and field for effectives in reducing non-contact ACL injury risk.

9.5 Summary

The continual problem of non-contact ACL injuries in team sports indicates that further refinement and improvement of interventions to reduce the risk of injury is required. While previously suggested as a component of prevention programs for non-contact ACL injuries this is the first study to investigate how technique modification in sidestep cutting and landing tasks impact on knee moments, and therefore risk of non-contact ACL injury. Results from this thesis suggest that technique modification can reduce knee moments, and should be considered part of intervention programs aimed at reducing non-contact ACL injury rates. However they also indicate that the relationship between technique and knee loads is complex and that inverse dynamic modelling techniques on their own may be insufficient to fully understand this relationship. Therefore including neuromuscular skeletal modelling to analyse laboratory based tests of sporting tasks will permit further understanding of mechanisms of injury and injury prevention. Adding stochastic biomechanical models will permit evaluation of possible training interventions *in silico*. Then it is possible to test these training interventions in restricted laboratory trials, as performed in this thesis. These laboratory and simulation studies can be done prior to implementing the refined training interventions in the community and carrying out expensive and difficult epidemiological studies to see if these new programs can indeed reduce injury rates.

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APPENDIX A ETHICS DOCUMENTS

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Can we reduce anterior cruciate ligament loading by changing technique in landing and cutting manoeuvres?

— Subject Information Sheet: Study 1—

Background and Purpose

In this study, which is supported by a research grant from the AFL Research and Development Board, we are investigating which landing and cutting techniques will reduce the number of serious knee ligament injuries which occur during Australian Rules Football matches and other high risk sports.

The anterior cruciate ligament (ACL) injury in the knee is common in sport, but ways to prevent these injuries still remain largely unknown. It is important to discover ways to reduce risk of injury due to the high incidence, the serious nature of the injury, and the long-term detrimental effects it may have. The purpose of this study is to establish the landing and cutting techniques that that reduce knee ligament loading during sporting manoeuvres. Identifying the techniques that increase or decrease joint stability and ligament loading will enable us to develop the best type of techniques for training to prevent knee ligament injury.

In this study we will ask you to adopt different types of trunk, hip and knee postures while you carry out side stepping and landing tasks. We hope to identify the postures that decrease knee ligament loading.

Procedures

Externally applied loading to knee joint and muscle activation patterns will be collected while you perform sidestep and landing tasks. Your movements will be recorded by a three-dimensional motion analysis system. At the same time a force plate in walkway surface will measure the forces you exert on the ground. Your muscle activation patterns, or electromyographic (EMG) data, are also collected. You will be asked to perform the manoeuvres at a speed equivalent to a medium jog (12-15km/hr), which is asafe speed and should not cause any injury.

To enable us to measure your movement, lightweight retro-reflective markers are stuck on your skin with double-sided tape. The motion analysis system only records the movement of these markers direct to the computer, and no video images are taken in this procedure so it is not possible to identify you from these recordings.

To identify which postural changes have an immediate effect on ACL loading, you will be asked to vary your knee, leg and trunk postures while you perform each landing and cutting tasks described above. First, you will be asked to perform tasks with your normal body position. You will be then asked to perform tasks with increased knee flexion, left and right trunk lean, increased trunk rotation and different foot position on their own and in combination.

A qualified instructor will supervise all testing sessions and demonstrate the required tasks.

Risks

The markers placed on your body to measure movement are stuck to your skin with low allergenic tape. This may cause some minor skin irritation that should abate quickly

The testing manoeuvres performed in the study are commonly related to injury in sport. In addition, some of the joint postures are may increase loading of the knee and may feel uncomfortable while performing the landing and cutting tasks. However, the speed at which you will be performing these manoeuvres at is a medium jog (12-15km/hr), which should place you at very little risk at all to injury. We have used these similar protocols on over 80 people in past 4 years and no injuries have occurred.

Since you will be exercising in these tests, it is expected that you may feel some minor discomfort from the testing sessions (delayed onset muscle soreness) but stretching and warm up included before the testing will help to alleviate this. There is no long-term discomfort caused by participation in this study.

Benefits

You will not receive personal benefit from this study. However, from a broader perspective this research has the potential to identify new technique training programmes to prevent knee injuries in sport. It will be of great benefit to the medical community from a financial and social perspective if optimal training is established as it may lead to a decrease in the incidence of knee ligamentous injuries.

Subject Rights

Firstly, if you have any questions concerning the research please ask the researcher at any time.

Secondly, participation in this research is voluntary and you are free to withdraw from the study at any time and for any reason, without prejudice in any way. You do not have to give any justification for your decision and your records will be destroyed unless otherwise agreed by you, the subject. If you withdraw from the study and you are an employee or student at the University of Western Australia (UWA) this will not prejudice your status and rights as employee or student of UWA.

Thirdly, your participation in this study does not prejudice any right to compensation, which you may have under the statute of common law.

Further information regarding this study may be obtained Dr David Lloyd or Professor Bruce Elliott on 9380 2361.

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Can we reduce anterior cruciate ligament loading by changing technique in landing and cutting manoeuvres?

— Subject Information Sheet: Study 2—

Background and Purpose

In this study, which is supported by a research grant from the AFL Research and Development Board, we are investigating which landing and cutting techniques will reduce the number of serious knee ligament injuries which occur during Australian Football matches and other high risk sports.

The anterior cruciate ligament (ACL) injury in the knee is common in sport, but ways to prevent these injuries still remain largely unknown. It is important to discover ways to reduce risk of injury due to the high incidence, the serious nature of the injury, and the long-term detrimental effects it may have. The purpose of this study is to establish the landing and cutting techniques that that reduce ACL loading during sporting manoeuvres. Identifying the techniques that increase or decrease joint stability and ACL loading will enable us to develop the best type of techniques for training to prevent knee ligament injury.

In this study you will be asked to participate in a training programme or to be part of a control (non-training) group. The purpose of the study is to see if we can teach different techniques for landing and cutting tasks seen in sport. We hope to demonstrate that these postures can be maintained during these sporting tasks, even after training has ceased, and they decrease ACL loading and risk of injury.

Procedures

You will be randomly assigned to the training group or control (non-training) group. If you are to be entered into the training group you will be required to attend training sessions held in conjunction with your clubs regular training sessions. The training session will be over a period of 6 weeks, 2 sessions per week for approximately 10 minutes a session. In these sessions you will be given verbal instructions, demonstrations, visual feedback and repeated skill development activities. If you are assigned to the non-training group you will follow your normal football training programmes.

Both training and control groups will have their leg muscle strength, landing and cutting techniques biomechanically evaluated just before and just after the training period, and the 4-weeks after the training period, at the School of Human Movement and Exercise Science at The University of Western Australia. In this the externally applied loading to knee joint and muscle activation patterns will be collected while you perform different sporting manoeuvres. These tasks to be tested are landing, sidestepping, crossover cutting and running in preplanned and unanticipated conditions. A randomly selected group of players will also be asked to complete 4-6 extra side-stepping trials using ankle tape, which is a common injury-prevention modality used by many football clubs. This will take about an extra 10 minutes to complete. Your movements will be recorded by the three-dimensional motion analysis system. At the same time a force plate in walkway surface will measure the forces you exert on the ground. Your muscle activation patterns, or electromyographic (EMG) data, will be also collected. You will be asked to perform the manoeuvres at a speed equivalent to a fast jog (16-20km/hr), which is a safe speed and should not cause any injury. A qualified instructor supervises all testing sessions. Strength testing will be undertaken using a Biodex dynamometer and will consist of maximal flexion and extension tasks.

To enable us to measure your movement, lightweight retro-reflective markers are stuck on your skin with double-sided tape. The motion analysis system only records the movement of these markers direct to the computer. However, we also take digital videos of you performing the tasks to ensure that these are performed correctly. The measurement of your muscle activation patterns requires us to place disposal electrodes on the skin over your leg muscles.

Risks

For the EMG to work, the electrodes need to have a clean contact with the skin. This requires us to shave and clean the area onto which the electrode will be placed. This process, along with the electrode gel applied to gain greater conductivity, can cause some minor irritation that should abate quickly. In addition, the markers placed on your body to measure movement are stuck to your skin with low allergenic tape. This may also cause some minor skin irritation that should abate quickly

If you are in the training group, even though some of the skill activities in training are designed to lower risk of ACL injury, these activities may feel uncomfortable. However, these should not place you at any risk of injury.

The testing manoeuvres performed in the study are commonly related to injury in sport. If you are asked and are performing trials with ankle taping, there will a reduced risk of ankle injury and a slight increased risk of knee injury. However, the speed at which you will be performing these manoeuvres at is a fast jog (16-20km/hr), which should place you at very little risk at all to injury. We have used similar protocols on over 80 people in past 4 years and no injuries have occurred.

Since you will be exercising in the training sessions and test sessions, it is expected that you will also feel some minor discomfort from the testing sessions (delayed onset muscle soreness) but stretching and warm up included before the training and testing will help to alleviate this. There will be no long-term discomfort caused by participation in this study.

Data Security

All data and video collected will be stored on digital storage media, eg computer hard drives, CD-ROMs and DVDs. Data stored on computer drives will be password protected and will be stored in a locked cupboard. CD-ROMs and DVDs will be stored in a locked cupboard. All identifying video data will be destroyed when they are no longer required.

Benefits

If you are in the training group you may benefit from learning how to perform landing and side stepping in safer manner. If you are in the control group you will not receive any personal benefit from the study. From a broader perspective this research has the potential to identify new technique training programmes to prevent knee injuries in sport. It will be of great benefit to the medical community from a financial and social perspective if optimal training is established as it may lead to a decrease in the incidence of knee ligament injuries.

Subject Rights

Firstly, if you have any questions concerning the research please ask the researcher at any time.

Secondly, participation in this research is voluntary and you are free to withdraw from the study at any time and for any reason, without prejudice in any way. You do not have to give any justification for your decision and your records will be destroyed unless otherwise agreed by you, the subject. If you withdraw from the study and you are an employee or student at the University of Western Australia (UWA) this will not prejudice your status and rights as employee or student of UWA.

Thirdly, your participation in this study does not prejudice any right to compensation, which you may have under the statute of common law.

Further information regarding this study may be obtained Dr David Lloyd or Professor Bruce Elliott on 9380 2361.

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THE UNIVERSITY OF WESTERN AUSTRALIA

Can we reduce anterior cruciate ligament loading by changing technique in landing and cutting manoeuvres?

— Consent Form —

I ______________________________ understand the tasks and the risk as explained by the examiners and any questions I have asked have been answered to my satisfaction. I agree to participate in this activity, realising that I may withdraw at any time without reason and without prejudice.

I understand that all information provided is treated as strictly confidential and will not be released by the investigator unless required to so by law. I have been also advised as to what data is being collected, what the purpose is, and what will be done with the data.

I agree that research data gathered for the study may be published provided my name or other identifying information is not used.

____________________ ________________________

Participant Date

The Human Research Ethics Committee at the University of Western Australia requires that all participants are informed that, if they have any complaint regarding the manner, in which a research project is conducted, it may be given to the researcher or, alternatively to the Secretary, Human Research Ethics Committee, Registrar's Office, University of Western Australia, 35 Stirling Highway, Crawley, WA 6009 (telephone number 9380-3703). All study participants will be provided with a copy of the Information Sheet and Consent Form for their personal records.

APPENDIX B EXEMPLAR VIDEOS USED IN CHAPTER 4

Exemplar videos are on the attached CD-ROM. The names of the imposed sidestep cutting tasks were changed prior to publication. Please refer to the list below for the task name used in the videos. Tasks names are based on an individual performing the sidestep cuts with the right leg.

Published name	Video Name
F_{Close}	1. Leg Close
F_{Wide}	2. Leg Wide
F_{In}	3. Foot Turned In
F_{Out}	4. Foot Turned Out
K_{Flexed}	5. Knee Flexed
$K_{Straight}$	6. Knee Straight
$T_{Opposite}$	7. Leaning Right
T_{Same}	8. Leaning Left
$T_{Rotated}$	9. Rotating in the Opposite Direction

APPENDIX C EXEMPLAR VIDEOS USED IN TRAINING

The following exemplar videos are on the attached CD-ROM.

1. Sidestep Cut Technique
2. Sidestep Cut with Ball
3. Sidestep Cut Trainer Cued
4. Sidestep Cut Defender Cued
5. Landing from Bench
6. Landing from Jump
7. Landing Catching Ball

APPENDIX D VIDEO OF LANDING TASK

A video of the landing task is available on the attached CD-ROM. The video features a left footed participant. Therefore Left Early became Towards Early, Left Late – Towards Late, Right Late – Away Late, Right Early – Away Early.

APPENDIX E MATLAB AND BODYBUILDER CODE USED IN THE THESIS

The following code is available on attached CD-ROM in .pdf format:

BodyBuilder Code

DirectionofTravel	This code was used to calculate the knee-path rotation angle used in Chapter 6 and Chapter 7
UWADynamicLB	This code was used to calculate the lower body kinematics and knee kinetics for all studies.
UWADynamicUB	This code was used to calculate the upper body kinematics for all studies.
UWAStaticLB	This code is used to perform the subject calibrations required for the UWADynamicLB model
UWAStaticUB	This code is used to perform the subject calibrations required for the UWADynamicUB model

MATLAB Code

PECS_AddEventsForAFLSidestep_MSVersion

This code calculated the weight acceptance phase for sidestep cutting trials (Chapter 4 and Chapter 5

PECS_AddEventsForAFLLanding2

This code calculated the landing phase for the landing trials (Chapter 6 Chapter 7 Chapter 8

APPENDIX F COPIES OF PUBLICATIONS ARISING FROM THIS THESIS

The following publications are available on the attached CD-ROM:

1. Dempsey AR, Lloyd DG, Elliott BC, Steele JR, Munro BJ, Russo KA. The effect of technique change on knee loads during sidestep cutting. *Medicine and Science in Sports and Exercise.* 2007;39(10):1765 - 1773.

2. Dempsey AR, Lloyd DG, Elliott BC, Steele JR, Munro BJ. Changing sidestep cutting technique reduces knee valgus loading *Am J Sports Med.* 2009;37(11):2194-2200.

3. Dempsey AR, Lloyd DG, Elliott BC, Russo K. What affect does different sidestepping technique have on knee loads? Paper presented at: 2nd Australian Association for Exercise and Sports Science Conference and the 4th Sports Dieticians Australia Update: From Research to Practice 2, 2006; Sydney, Australia.

4. Dempsey AR, Lloyd DG, Elliott BC. Does peak vertical ground reaction force correlate with peak knee moments in functional landing tasks? *Journal of Biomechanics.* 2007;40(S2):S245.

5. Dempsey AR, Lloyd DG, Elliott BC. Can full body technique change modify knee loads in sidestepping? Paper presented at: 3rd Australian Association for Exercise and Sports Science Conference and the 5th Sports Dieticians Australia Update: From Research to Practice, 2008; Melbourne.

6. Dempsey AR, Elliott BC, Munro BJ, Steele JR, Lloyd DG. Increasing knee flexion in landing tasks may not reduce the risk of non-contact anterior cruciate ligament injury. Paper presented at: 7th Australasian Biomechanics Conference; 2009; Gold Coast, Australia. (This abstract is related to Chapter 8)