THE APPLICATION OF A MOVEMENT STRATEGY IN DECREASING BIOMECHANICAL RISK FACTORS FOR ANTERIOR CRUCIATE LIGAMENT INJURY

by

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Abstract

Introduction

Anterior Cruciate Ligament (ACL) injury remains one of the most common and debilitating knee injuries in sport. Neuromuscular training programs show promise in improving biomechanical risk factors but we do not know which aspects of these programs are effective. There is a need to investigate the effect of specific movement strategies in reducing biomechanical risk factors for ACL injury.

Purpose

1) To evaluate the reproducibility of biomechanical variables at the knee during three soccer-specific tasks (Chapter 2).
2) To determine the feasibility of implementing a novel movement strategy (Core-PAC) into a soccer team warm-up (Chapter 3).
3) To determine whether the Core-PAC would improve biomechanical variables during the three tasks after immediate instruction and after a four-week training program (Chapter 3).
4) To conduct a randomized controlled trial (RCT) to compare a Core-PAC trained group to a control group for biomechanical variables during the three tasks after a six-week training program (Chapter 4).

Methods

Design: A test-retest design was used for the reliability study (Chapter 2). A single group pretest-posttest design was used for the feasibility study (Chapter 3). An RCT was used in Chapter 4.

Subjects: A cohort of female soccer players (n = 10) participated in the reliability study (Chapter 2) and the feasibility study (Chapter 3). A different cohort of female soccer players participated in the RCT (n = 20) (Chapter 4).
Results:

Chapter 2: Adequate reproducibility (flexion angles (ICC=0.88-0.95; SEM=1.0-1.9°); abduction moments (ICC=0.62-0.84; SEM=0.1-0.5 Nm/kg) were demonstrated during the three tasks.

Chapter 3: Feasibility of implementing the Core-PAC into a soccer warm-up was demonstrated. After immediate instruction, there were significant increases in peak flexion angles (3.5-6.4°) and decreases in abduction moments (0.17-0.27 Nm/kg) during the three tasks. After the training program, some individuals showed improvement.

Chapter 4: The Core-PAC group improved ($P < 0.05$) flexion angles during the side-hop task (6.2°) after training and during the side-cut (8.5°) and side-hop (10°) tasks after reminding them to use the Core-PAC.

Conclusions: The results of this study suggest that the Core-PAC may be one method of modifying high-risk movements to reduce the risk of ACL injury.
Preface

In consultation with my original committee members (Dr. Janice Eng, Dr. Donna MacIntyre, Dr. William Miller, Dr. Ian Franks), I conceptualized and developed this research program. With ongoing feedback from my current committee members (Dr. Janice Eng, Dr. Donna MacIntyre, and Dr. William Miller), I collected and analyzed data, and prepared manuscripts.

Submitted Papers:

A version of Chapter 2 has been submitted for publication. Celebrini RG, Eng JJ, Miller WC, Ekegren CL, Johnston JD, MacIntyre DL. Reproducibility of Biomechanics during Soccer Specific Tasks in Young Female Players. Submitted March, 2011.

Contribution: 80% - I provided study concept and design, study coordination, data analysis and manuscript preparation. Dr. Eng participated in the interpretation of results and was the key editor on this paper. Dr. MacIntyre, Dr. Eng, and Dr. Miller provided feedback during study design. Ms. Ekegren assisted with data collection, analysis, and study coordination. Dr. Johnston assisted with computer coding and set-up of the data collection and analysis program. All authors reviewed and edited the manuscript.

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Contribution: 80% - I provided study concept and design, study coordination, data analysis and manuscript preparation. Dr. Eng participated in the interpretation of results and was the key editor on this paper. Dr. MacIntyre, Dr. Eng, and Dr. Miller provided feedback during study design. Ms. Ekegren assisted with data collection, analysis, and study coordination. Dr. Johnston assisted with computer coding and set-up of the data collection and analysis program. All authors reviewed and edited the manuscript.

This study involved human subjects, and thus received approval from The Clinical Research Ethics Board of The University of British Columbia (certificate number: H05-70352).
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List of Abbreviations

ACL: Anterior Cruciate Ligament
BMI: Body Mass Index
BOS: Base of Support
COM: Center of Mass
COP: Center of Pressure
GRF: Ground Reaction Force
ICC: Intraclass Correlation Coefficient
IRED: Infrared Emitting Diode
OA: Osteoarthritis
SEM: Standard Error of Measure
3D: Three-Dimensional
SC: Side-Cut Task
USC: Unanticipated Side-cut Task
SH: Side-Hop Task
FIFA: Fédération Internationale de Football Association
FIFA 11+: Injury Prevention Program from F-MARC
F-MARC: FIFA’s Medical Assessment and Research Centre
PEP: Prevent Injury and Enhance Performance (injury prevention program)
Glossary

Closed skill - Skills that are performed in stable or predictable environmental settings (Schmidt and Lee, 2005).

Core - includes the active and passive structures of the thoracolumbar-pelvic-hip complex. The “inner unit” of the core is considered to be transversus abdominus, the pelvic floor muscles (PF), multifidus (MF), and the thoraco-abdominal diaphragm in an interrelated and interdependent myofascial cylinder (Hodges and Richardson, 1997a,b; Richardson et al., 1999).

Core-PAC - an acronym for “Core Position and Control”, a term used for knowledge translation that describes a movement strategy that places the center of mass close to the base of support during lower extremity movements. Includes a proximal to distal movement strategy (described below).

Dynamic stability - ability to maintain position and / or intended trajectory after internal or external disturbance (Zazulak et al., 2007a).

Dynamic valgus / abduction - the angle formed between the tibia and femur in the frontal plane as a result of hip adduction and internal rotation and knee flexion (Figure 1.6).

Distal to proximal movement strategy - observed as a “reaching” type movement of the lower extremity, in which the front or lead leg moves away from the COM with less displacement of the COM in the intended direction of movement as compared to a Core-PAC movement (see Core-PAC).

Ecologically valid movements - refers to whether or not one can generalize from observed behavior in the laboratory to natural behavior in the world.

High-risk movement patterns - those movements such as cutting, decelerating, and landing from a jump that have most frequently been associated with ACL injuries.

In vitro - Investigation performed in the lab (i.e. cadaver).
In vivo - Investigation performed with a living organism.

Joint moment - force causing rotation of a joint; may be internal (e.g. internal resistance provided by muscle) or external (e.g. external moment of gravity) (Norkin and White, 1985).

Kinematics - study of the motion of a body (e.g. joint angles) (Norkin and White, 1985).

Kinetics - study of the effects of forces on a body (e.g. joint moments) (Norkin and White, 1985).

Motor learning - a set of internal processes associated with practice or experience leading to relatively permanent changes in the capability for motor skill (Schmidt and Lee, 2005).

Movement strategy - extends beyond a simple description of the movement pattern and includes with it: how the learner organizes motor, sensory, and perceptual information necessary to perform the task in different environments (Shumway-Cook and Woollacott, 2007).

Multimodal programs - Neuromuscular training programs that use multiple training components such as plyometrics, balance, strength, and technique modification.

Muscle synergy - functional coupling of groups of muscles so that they are constrained to act together as a unit (Shumway-Cook and Woollacott, 2007).

Neuromuscular control - interplay between the neural and muscular systems (as in providing dynamic stability to a joint).

Non-contact ACL injury - an anterior cruciate ligament injury not caused by a direct blow to the involved lower extremity (Hewett et al., 2004).

Open skill - Skills that are performed in unpredictable, changing environmental settings (Schmidt and Lee, 2005).
**Proximal control** - the ability to control the position and motion of the trunk over the pelvis to allow optimum production, transfer, and control of force and motion to the terminal segment in integrated athletic activities (Kibler et al., 2006).

**Proximal to distal movement strategy** - a sequence of neuromuscular recruitment and segmental movement that begins proximally, or at the trunk / pelvis, and which is followed by muscle recruitment and movement in the periphery (Kibler et al., 2006; Putnam, 1993; Richardson and Jull, 1995; Richardson et al., 1999).

**Retention test** - a performance test administered after a time interval from the end of original learning of a task for the purpose of assessing learning (Schmidt and Lee, 2005).

**Setting** - is the muscle activation component of the proximal to distal strategy. It consists of a deep breath in and then out with a voluntary, sub-maximal contraction of the pelvic floor muscles (PF) and transversus abdominus (TrA) (Hodges, 1997a; Richardson and Jull, 1995; Richardson et al., 1999). The TrA is preferentially recruited by a “hollowing” of the lower abdominal wall without activation of the other abdominal muscles and without any movement of the lumbar spine or pelvis (Hodges and Richardson, 1997a,b; Richardson et al., 1999). The subject is instructed to recruit the PF at the end of the breath out by imagining a “stopping of mid-stream urination”. The inclusion of the PF is supported by the findings of a muscle synergy between the PF and the TrA (Sapsford and Hodges, 2001; Sapsford et al., 2001) as well as clinical experience of its effectiveness in contributing to the stability of the lumbo-pelvic region.

**Stability limits** - boundaries within which the body can maintain stability without changing the base of support (Shumway-Cook and Woollacott, 2007).

**Strain (in ACL)** - the change in length of the ACL from its original length.

**Strain gauge (in ACL)** - a device used to measure strain in the ACL.

**Technique modification** - modification of body positions and forces during movement tasks.
**Transfer test** - a performance test administered at the end of original learning of a task(s) using a novel, unpracticed task for the purpose of assessing learning (Schmidt and Lee, 2005).

**Valgus / abduction** - terms used interchangeably throughout the document as movement of a segment away from the midline of the body.
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Dedication

This thesis is dedicated to my wife, Robyn, and to my children - Aiden, Macklin, and Charlie. You have sacrificed so much. Robyn, we started this difficult journey together the year before Aiden, our oldest, was born. Together we have endured the sleepless nights and challenges that all new parents face while navigating through this academic process and the unexpectedness of the Olympic and Paralympic preparations and the death of my father. Throughout all of this, you have been our rock and my inspiration. Words cannot describe what you have meant to our children and to me. You are the reason that any of this was possible. I love you.

This thesis is also dedicated to my parents and my brother. Bro, our chats, when I needed them, were always inspirational, insightful, and invaluable - just like when we were kids. Thank you. Mom and Dad, you have given me everything. Your love and support, your integrity and your work ethic, your belief in the value of education and higher learning have impacted me more than you will ever know. I know completing this thesis meant a lot to you, Dad. I miss you.
1 Introduction

1.1 Scope of the problem

Anterior Cruciate Ligament (ACL) injury is one the most common serious orthopaedic sports injuries sustained during adolescence (Flynn et al., 2005). Most of these injuries are debilitating, requiring surgical reconstruction and 6-12 months of rehabilitation. The prevalence of osteoarthritis (OA) is as high as 48% in those individuals incurring the common combination of an ACL injury with meniscal involvement compared to 5% in those not injured (Oiestad et al., 2009; Roos, 2005). Unfortunately, surgical intervention does not slow this progression (Lohmander et al., 2007; Meunier et al., 2007). Multidirectional sports, including soccer and basketball, are among those most likely to result in ACL injury (Boden et al., 2000; Krosshaug et al., 2007a) and young women participating in these sports are 4-6 times more likely to sustain an ACL injury as compared to young men (Arendt and Dick, 1995; Griffin et al., 2000). The rapid increase of female participation in youth soccer, and other sports, has contributed to a magnification of this problem (Hewett et al., 2004).

A model for sports injury prevention originally introduced by van Mechelen et al. (1992) suggests that after establishing the extent of the injury problem, we must understand the aetiology and mechanisms of the injury before initiating prevention programs. Understanding the causes or risk factors of the injury allows us to better identify those at greatest risk and to develop targeted prevention programs. ACL injury is most likely the result of multiple factors, which can be divided into intrinsic (internal to the individual) and extrinsic (external to the individual) factors (Table 1.1). Most injury prevention programs have focused on the biomechanical and neuromuscular risk factors for ACL injury because most of the scientific evidence has been assembled in this area and because these risk factors are potentially modifiable.
Table 1.1 Evidence-based intrinsic and extrinsic risk factors for ACL injury

<table>
<thead>
<tr>
<th>Extrinsic</th>
<th>Intrinsic</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Competition</strong> - game vs. practice</td>
<td><strong>Gender</strong> – female</td>
</tr>
<tr>
<td><strong>Footwear: surface interaction</strong> - wearing cleats, artificial floor with higher torsional resistance</td>
<td><strong>Hormonal</strong> – pre-ovulatory phase of menstrual cycle, oral contraceptive use, joint laxity</td>
</tr>
<tr>
<td><strong>Weather</strong> - low rainfall and high evaporation</td>
<td><strong>Anatomical</strong> - smaller intercondylar notch and ACL size, ACL tissue properties, greater slope of lateral tibial plateau and lower slope of the medial tibial plateau, Q-angle, leg length, BMI, familial tendency, joint laxity, foot pronation, navicular drop</td>
</tr>
<tr>
<td><strong>Protective equipment</strong> – not using functional bracing (e.g. for ACL deficient knees in skiing)</td>
<td><strong>History</strong> - previous ACL or other lower extremity injury</td>
</tr>
<tr>
<td></td>
<td><strong>Biomechanical</strong> - landing with increased knee extension, higher quadriceps activation, increased knee abduction moment, reduced ankle plantar flexion, inadequate absorption of ground reaction forces of the lower leg, lateral trunk lean</td>
</tr>
<tr>
<td></td>
<td><strong>Neuromuscular</strong> - insufficient neuromuscular stabilization of the knee joint, fatigue, muscle; strength, stiffness, reaction time, time to peak force, quadriceps dominance, lower extremity asymmetry</td>
</tr>
</tbody>
</table>

1.2 Mechanism of injury

1.2.1 Biomechanical and neuromuscular effects

The ACL is ruptured when the strain produced within the ligament exceeds its tensile strength. Cadaveric (Markolf et al., 1995) and in vivo (Fleming et al., 2001) studies have demonstrated that the ACL is primarily loaded by anterior translation of the proximal tibia relative to the femur. The ACL is under increased tension as the knee approaches extension and is further stressed by patellar tendon induced anterior translation in knee flexion angles less than 45 degrees (Beynnon et al., 1997; Renstrom et al., 1986). Anterior translation increases as the force produced by the quadriceps increases and the angle between the patellar tendon and the longitudinal axis of the tibia increases with decreased flexion angles of the knee (Figure 1.1). Isolated anterior shear force is potentially sufficient to injure the ACL.
(DeMorat et al., 2004), and stress on the ACL is further compounded by the inability of the hamstring muscles to exert an effective posteriorly directed counterforce in these extended knee positions (Li et al., 1999; Markolf et al., 2004; Pandy and Shelburne, 1997). In vivo investigation of ACL strain behaviour using a surgically implanted strain gauge demonstrated peak ACL strain shortly after foot contact during a jump-landing task (Cerulli et al., 2003). This period corresponded to peak ground reaction forces (GRFs) when the knee was in a relatively extended position.

**Figure 1.1 Patellar tendon induced anterior tibial translation**
McLean et al. (2004a) used a modeling technique to simulate ACL injury during a side-cut movement and concluded that sagittal plane mechanics alone could not injure the ACL (Figure 1.2). In vitro experiments have demonstrated that, especially when combined with valgus and internal rotation moments, anterior translation produces much greater strain on the ACL than anterior translation alone (Figure 1.3) (Berns et al., 1992; Markolf et al., 1995). Combined valgus and external rotation may also increase ACL strain by a different method. This position may result in impingement of the ACL against the lateral wall of the femoral intercondylar notch putting additional strain on the ACL (Figure 1.4) (Fung and Zhang, 2003). An external abduction (or valgus) moment is thought to be the most dangerous out-of-sagittal-plane load on the knee and has been predictive of future ACL injury in female athletes (Hewett et al., 2004, 2005a). However, both anterior translation and frontal and transverse plane moments are reduced with increasing knee flexion angles (Hame et al., 2002; Markolf et al., 1995). Although there is ongoing debate as to whether sagittal or frontal plane loading poses the greater risk (Quatman et al., 2010; Yu and Garrett, 2007), there is consensus in the literature that combined forces are most likely to injure the ACL (Hame et al., 2002; Markolf et al., 1995; Withrow et al., 2006).

Figure 1.2 Anatomical planes: sagittal, frontal, transverse
Figure 1.3 ACL injury resulting from anterior translation, valgus, and internal rotation
Figure 1.4 ACL injury resulting from anterior translation, valgus, and external rotation
1.2.2 Summary - mechanism of injury (biomechanical and neuromuscular effects)

The ACL is under strain and at increased risk of injury when the knee is in decreasing degrees of knee flexion, especially with a valgus or abduction force. Internal and external rotation are potential contributors to this risk. In this dissertation, we have chosen to investigate knee flexion angles and external abduction moments based on the evidence for these variables as important risk factors and based on reliability testing of these variables (Chapter 1).

1.2.3 Mechanism of non-contact injury during sport

Most ACL injuries (70-80%) occur without any contact from an opponent and often occur while side-cutting or landing on one leg to change direction, decelerating quickly, or landing from a jump (Boden et al., 2000; Krosshaug et al., 2007a; McNair et al., 1990; Olsen et al., 2004). While side-cutting and single-leg landing are frequently performed during multidirectional sports, a typical strategy observed at the time of injury includes: a knee close to extension with a valgus angle; an abducted hip with the foot planted in front and lateral to the center of mass (COM); and a trunk that is side-flexed and rotated towards the plant leg (Figure 1.5) (Boden et al., 2000; Cochrane et al., 2007; Hewett et al., 2009; Ireland et al., 2003; McNair et al., 1990; Olsen et al., 2004; Teitz et al., 2001). A novel model-based image matching technique that allows for more accurate estimation of 3D kinematics during ACL injuries captured on video has confirmed that ACL injuries often occur shortly (within 30-40ms) after landing with an extended knee and a valgus load (Koga et al., 2010; Krosshaug et al., 2007b). A rapid increase in dynamic valgus is often observed during or immediately after the injury (Figure 1.6) (Krosshaug et al., 2007a). There is often a perturbation or an unexpected reaction to a game situation during the time of injury (Boden et al., 2000; Cochrane et al., 2007; Krosshaug et al., 2007a; Olsen et al., 2004). The athlete is often observed to be off-balance, landing awkwardly with high GRFs that are not effectively dissipated through hip, knee, and ankle flexion (Ford et al., 2005; Olsen et al., 2004; Renstrom et al., 2008). Hip position has been observed as the main difference between two common injury mechanisms:
hip abduction occurring during side-cutting movements (Figure 1.5) and hip adduction when landing on one or two legs (Figure 1.6) (Boden et al., 2000; Krosshaug et al., 2007a).

**Figure 1.5** Typical body position and movement strategy observed at the time of injury during side-cutting with hip abduction (“reach”)
1.2.4 Summary - mechanism of non-contact injury during sport

Effective strategies to prevent non-contact injury during sport should influence how an athlete moves during high-risk demands. Specifically, an athlete should avoid a knee close to extension with a valgus angle; an abducted hip with the foot planted in front and lateral to the center of mass (COM); and a trunk that is side-flexed and rotated towards the plant leg during side-cutting movements and single-leg landing. Prevention strategies should also improve an athlete’s ability to respond to unexpected forces and perturbations incurred within sporting
environments by optimizing their physical and physiological capabilities and positioning. Therefore, we will investigate the effects of a specific movement strategy that may modify movement characteristics observed at the time of ACL injury.

1.3 Laboratory analyses of high-risk tasks

Controlled laboratory-based biomechanical analysis of many of the high-risk movements described above has afforded better understanding of the characteristics and potential risk factors with which those movements are associated. The main tasks investigated to date have included drop vertical jump (DVJ), stop jump (SJ), and side-cutting (SC) tasks. Other tasks investigated have included cross-cutting maneuvers (Besier et al., 2001b; Myer et al., 2006), and a forward hop followed by a lateral hop (Sell et al., 2006). Recently, sport-specific and more ecologically valid demands have been added to these tasks (Chaudhari et al., 2005; Fedie et al., 2010).

DVJ consists of a drop down from a box of varying heights followed by a two-leg landing and a subsequent maximal vertical jump (Hewett et al., 2002). Increased loading of the knee and increased strain estimated on the ACL during this task occurs when there is less hip, knee and ankle joint flexion and a transfer of the moments from the sagittal to the frontal and transverse planes. This results in a more “ligament-dominant” strategy (Hewett et al., 2002) wherein more of the kinetic energy and GRFs are absorbed by the passive inert structures (i.e. ligaments) of the lower extremity as compared to the muscles (i.e. powerful hip extensors). The described movement strategy is often referred to as “dynamic valgus” (Figure 1.6).

SJ requires that the subject run and land on one leg prior to jumping vertically and describes many of the same biomechanical characteristics and risk factors as the drop jump. Chappell et al. (2007) found female athletes generally landed with decreased knee flexion, hip flexion, abduction, and external rotation, and increased knee internal rotation and quadriceps activation compared with male athletes. Female soccer players demonstrate decreased hip
and knee flexion angles during a stop jump task compared to male soccer players after 13 years old (Yu et al., 2005). Observations such as these may help explain the underlying reasons for the gender difference seen in the incidence of ACL injuries during adolescence.

Dynamic valgus is a typical high-risk movement strategy demonstrated during both DVJ and SJ. DVJ and SJ tasks differ from SC tasks mainly in the amount of hip adduction (DVJ and SJ) as compared to hip abduction (SC) observed during laboratory investigations that demonstrate high knee loads (Figures 1.5 and 1.6). As mentioned earlier, this is consistent with hip positions observed during injuries (Krosshaug et al., 2007a). Other biomechanical variables thought to contribute to ACL injury, such as abduction moments and high GRFs, are similar between tasks.

The DVJ and SJ tasks incorporate two key elements of high-risk movements, namely sharp decelerations and landing from a jump. However, the risk of injury may increase with a direction change after a landing or a quick deceleration. Of the ACL injuries occurring in handball that were captured on video, Olsen et al. (2004) found that all resulted from one of two mechanisms: a plant-and-cut or a single-leg jump shot landing (seldom in the sagittal plane). Sell et al. (2006) demonstrated that lateral jumps (to the medial side of the planted leg) were the most dangerous of the three stop jump directions they investigated. The authors found that lateral jumps produced higher GRFs, proximal anterior tibia shear forces, greater valgus and flexion moments, and lower flexion angles than vertical or horizontal jumps in the opposite direction. Increased valgus moments and angles have been demonstrated in side-cut compared to drop-jump landing movements (Cowley et al., 2006) and cutting movements or single-leg landing may be more likely to cause ACL injury (Besier et al., 2001b; Boden et al., 2000; Olsen et al., 2004). Interestingly, through surveying athletes that had recently injured their ACL, Fauno and Jakobsen (2006) found that the majority of ACL injuries in soccer occurred with the intention to turn towards the injured knee rather than towards the uninjured knee as described in other studies (Boden et al., 2000; Krosshaug et al., 2007a; Olsen et al., 2004).
1.3.1 Side-cutting biomechanical characteristics

Due to the aforementioned, many biomechanical studies have investigated the knee position and loads during side-cutting and single-leg landing movements (Besier et al., 2001a,b; Houck et al., 2006; Malinzak et al., 2001; McLean et al., 1999, 2005a,b; Pollard et al., 2004; Sigward and Powers, 2006) and, recently, the effects of potential interventions aimed at modifying them (Cochrane et al., 2010; Dempsey et al. 2007, 2009). These biomechanical studies are summarized in the next section.

1.3.1.1 Kinetic profile of female athletes during side-cutting

Besier et al. (2001a,b) demonstrated increased valgus and internal rotation moments at the knee in male athletes during side-cutting compared to straight ahead running or cross-over cutting movements. They also found that these moments were greatest during the weight acceptance or early deceleration phase of a side-cutting movement, indicating an increased risk for ACL injury during this period (Besier et al., 2001b). Despite inconsistent reports, female athletes have been shown to produce greater abduction moments at the knee compared to male athletes during side-cut movements (Chappell et al., 2002; McLean et al., 2005a,b; Pollard et al., 2007; Sigward and Powers, 2006).

1.3.1.2 Kinematic profile of female athletes during side-cutting

Several studies have demonstrated that female athletes perform side-cutting tasks with decreased knee flexion angles compared to male athletes (Fedie et al., 2010; Malinzak et al., 2001; McLean et al., 2004b, 2005b). Malinzak et al. (2001) observed increased quadriceps and decreased hamstrings activation with decreased flexion and increased valgus knee angles in female compared to male athletes during preplanned side-cut maneuvers. McLean et al. (2005b) found decreased hip and knee flexion angles and increased valgus moments in female college basketball players compared to experienced and age-matched males while performing sidestep, side-jump, and shuttle-run tasks. Other studies have not demonstrated a gender difference in knee flexion angles during side-cutting (Ford et al., 2005; McLean et al.,...
A recent systematic review concluded there was insufficient evidence in the literature to support a gender difference in biomechanical and neuromuscular risk factors during plant- and-cut maneuvers (Benjaminse et al., 2011). However, these authors cautioned against making inferences due to subject and study heterogeneity and low statistical power.

### 1.3.1.3 Sport-specific tasks

In an attempt to produce demands on the knee that more closely resemble those incurred at the time of injury, investigators have tried to create more ecologically valid or “game-like” conditions in the laboratory (Besier et al., 2001a; Chaudhari et al., 2005; Fedie et al., 2010; McLean et al., 2004b; Sell et al., 2006). Compared to preplanned side-cutting, unanticipated side-cutting has demonstrated increased adduction and abduction as well as internal and external rotation moments at the knee (Besier et al., 2001a). Sell et al. (2006) found that subjects performed reactive stop jumps with greater posterior GRFs, less knee flexion at peak posterior GRF, and greater flexion and valgus moments as compared to planned stop jumps. McLean et al. (2004b) observed increases in hip and knee flexion and abduction angles, as well as force increases, in both male and female subjects in response to a simulated defensive opponent that they had to sidestep to evade. In this study, female subjects demonstrated less hip and knee flexion and greater knee valgus compared to males. Increases in extensor moments and jump height have been observed during vertical jumps when the goal was to reach a ball overhead (Ford et al., 2005) and delays in hamstring activation have been observed when throwing (Miyatsu et al., 1988) or catching a ball (Cowling and Steele, 2001). Increases in frontal plane moments during side-cutting movements have been observed when holding a lacrosse stick or football (Chaudhari et al., 2005) or attending to a pass in basketball (Fedie et al., 2010).
1.3.1.4 Summary - laboratory analyses of high-risk tasks

The literature supports side-cutting and single-leg landing as high-risk movements that have demonstrated knee positions and forces consistent with those observed during actual injury scenarios on the field. Unanticipated tasks and tasks that involve sport-specific components often result in increased knee loading that more closely resembles ACL injuries in the sporting environment. Therefore, we chose to investigate three high-risk tasks: 1) a side-cut prior to kicking a soccer ball; 2) an unanticipated side-cut prior to kicking a soccer ball; and 3) a lateral single-leg landing task.

1.4 Body position, control, and movement – potential contributors to ACL loading

Loading of the ACL during sporting activities is a result of the forces generated and controlled above and below the knee. Therefore, the posture and control of the lumbo-pelvic-hip complex (core) may have a direct influence on the stresses to the knee (Ireland et al., 2003; Leetun et al., 2004; Lephart et al., 2002; Nadler et al., 2000) and, consequently, the ACL. Powers (2010) effectively explains how the position and control of the body’s COM relative to the center of pressure (COP) (located within the stance foot) influences the direction and magnitude of the resultant GRF vector. The direction and magnitude of the resultant GRF vector relative to the knee joint centre ultimately dictates the moments experienced at the knee (Figure 1.7a) (Powers, 2010). This will also be explained in section 1.4.1, page 16 and section 1.4.3.1, pages 20-21.
Figure 1.7 Side-cutting movement demonstrating ground reaction forces (GRF). Figure 1.7a- Shifting the COM over the stance leg with lateral trunk flexion increases the perpendicular distance from the resultant GRF to the knee joint centre, increasing the abduction moments at the knee. Figure 1.7b- Contribution of increased lateral GRF and increased hip abduction moving the COP lateral to the COM of the tibia and increasing the VGRF moment arm – both of which result in an increase in abduction moment at the knee.
There is increasing evidence of an association between core function and lower extremity injury (Beynnon et al., 2006; Bullock-Saxton et al., 1994; Devlin, 2000; Ireland et al., 2003). For example, delays in gluteus maximus onset have been associated with lateral ankle sprains (Bullock-Saxton et al., 1994) and abdominal muscle fatigue has been associated with hamstring injuries (Devlin, 2000). In a prospective study, female athletes that demonstrated increased body sway were more likely to sprain their ankle (Beynnon et al., 2006). Leetun et al. (2007) prospectively identified hip external rotation weakness as the only true predictor of lower extremity injury status (OR 0.86, 95% CI = 0.77 - 0.97) of the variables they investigated. They also found that male athletes had greater hip abductor and external rotation strength compared to female athletes. They suggested this weakness may contribute to decreased frontal and transverse plane control in female athletes, and increased risk of injury.

1.4.1 Trunk – potential contribution to ACL loading

The position and control of the trunk may influence the biomechanics of the lower extremity and potentially contribute to injury. Hewett et al. (2009) found that lateral trunk and knee abduction angles were greater ($P \leq 0.05$) in female compared to male athletes during ACL injuries captured on video. Female athletes sustaining an ACL injury also showed less forward lean ($1.6 (9.3)^\circ$ vs. $14.0 (7.3)^\circ$, $P \leq 0.01$) and a trend toward greater lateral trunk and knee abduction angles compared to female controls. These authors suggested that deficits in trunk control that result in lateral trunk flexion can increase abduction forces on the knee via mechanical and / or neuromuscular mechanisms. Mechanically, the GRF is more lateral to the knee joint centre, which creates a greater lever arm for abduction forces at the knee (Figure 1.7a). The GRF is also lateral to the hip joint, increasing the neuromuscular demand as the external hip abduction moment must be countered by an increase in hip adductor muscle torque. Increased hip adductor torque has been associated with increased abduction moments at the knee that may increase loading of the ACL (Granata et al., 2001; Hewett et al., 2009). However, lateral trunk flexion may not be a result of inadequate neuromuscular
control at the trunk but may instead be a strategy to compensate for weak hip abductors. By laterally flexing the trunk towards the stance leg (in a common “trendelenburg” type compensation), the COM is shifted closer to the stance leg and the resultant GRF vector is directed closer to the hip joint centre, thus decreasing the control required by the hip abductors (Hewett et al., 2009; Mackinnon et al., 2003; Powers, 2010). Therefore, lateral trunk flexion may be a learned response to effectively compensate for weak abductors.

Laboratory-based biomechanical and neuromuscular studies provide additional support for the influence that trunk position and control has on ACL loading and injury risk (Blackburn and Padua, 2009; Dempsey et al., 2007; Zazulak et al., 2007a,b). An extended (i.e. more vertical) trunk position during a drop jump was shown to increase quadriceps activity and anterior shear forces at the knee when compared to a flexed trunk position (Blackburn and Padua, 2009). Flexion of the trunk places the resultant GRF vector more anterior which increases the eccentric demand on the hip extensors rather than the knee extensors to decelerate the COM (Figure 1.8) (Powers, 2010). Dempsey et al. (2007) demonstrated that increased lateral flexion of the trunk towards the plant leg of a side-cut movement increased valgus moments at the knee and trunk rotation towards the plant leg increased knee internal rotation moments. Because their findings were consistent with mechanisms of ACL injury reported in the literature, they recommended avoiding side-cut techniques that employ these postures to reduce the risk of ACL injury. Deficits in trunk proprioception have predicted knee injury in female but not male athletes with high specificity (56%) and sensitivity (90%) (Zazulak et al., 2007a). Lateral trunk displacement in response to a sudden force release was the strongest predictor of ligament injury \( (P = 0.009) \) in female athletes that went on to ACL injury as compared to those that did not (Zazulak et al., 2007b).
Figure 1.8 Relationship of COM to forefoot loading
1.4.2 Summary - trunk (potential contribution to ACL loading)

Improved control and positioning of the trunk may decrease the biomechanical risk factors for ACL injury at the knee. Therefore, we included a focus on neuromuscular recruitment of the thoraco-lumbar and pelvic stabilizing muscles within our intervention strategy to potentially improve control and positioning of the trunk.

1.4.3 Hip – potential contribution to ACL loading

As compared to their male counterparts, some female athletes may not use their hips as effectively to absorb GRFs when landing and, therefore, may increase the demand on their knees and ankles (Decker et al., 2002). Increased hip internal rotation and adductor moments and decreased hip flexion angles and extensor moments have been observed in female compared to male subjects during side-cut movements (Pollard et al., 2006). Pollard et al. (2010) demonstrated over two times greater internal adductor moments at the knee \( P = 0.03 \) and decreased energy absorption at the hip and knee \( P = 0.02 \) in young female soccer players that landed from a drop jump with decreased hip and knee flexion angles compared to those with increased flexion angles. They proposed a strategy wherein deceleration of the COM was not effectively controlled in the sagittal plane, and so was transferred to the passive structures (i.e. ligaments and joint capsules) of the lower extremity in the frontal plane.

Similarly, Hewett et al. (2002) described a strategy of ligament rather than muscle dominance in controlling GRFs during sporting activities. The ligaments of the knee were proposed to be under increased load because valgus and internal rotation of the knee did not allow the muscles to effectively dissipate GRFs. This was explained earlier as dynamic valgus; females are thought to have a predisposition for this pattern of movement as compared to their male counterparts (Ford et al., 2005; Hewett et al., 2005a; Sigward and Powers, 2006).

Boden et al. (2009) proposed an axial force theory to explain ACL injury based on their video analysis comparing hip and foot position of athletes injuring their ACL to those that did not. They observed increased hip flexion and a flatter foot on landing in those athletes
sustaining an ACL injury compared to non-injured controls, and suggested that this pattern of movement did not allow the hip and ankle joints to dissipate enough energy from the GRFs, leaving the knee exposed to potentially injurious loads. Although others have described decreased rather than increased hip flexion angles contributing to increased GRFs and knee loading (McLean et al., 2005b; Pollard et al., 2010), both descriptions of hip movement are of a hip that is not effectively absorbing forces and therefore increasing the demand on the knee. This may help explain observations by Krosshaug et al. (2007a) that a constant hip flexion position (i.e. flexion angle at the hip did not change) during side-cutting movements was often present when ACL injuries occurred.

Hip strength may not be critical in protecting the knee from excessive loads (Powers, 2010). While there exist a number of studies relating decreased hip strength to biomechanical risk factors at the knee (Jacobs et al., 2007; Lawrence et al., 2008; Wilson et al., 2006), Sigward et al. (2008) found no association between hip strength and landing biomechanics. Moreover, Mizner et al. (2008) were able to improve the landing mechanics of female collegiate athletes during a drop vertical jump with a brief instruction on technique irrespective of hip strength. They concluded that factors other than muscle strength may be responsible for short term corrections in landing mechanics after instruction. It appears that technique has a potentially important role in decreasing loads on the knee.

1.4.3.1 Hip abduction or “reaching” – potential contribution to ACL loading

Dempsey et al. (2007) found that widening the normal stance position (i.e. abducting the hip) resulted in increased flexion, valgus and internal rotation moments at the knee during a side-cut movement. Sigward and Powers (2007) evaluated the differences in lower extremity kinematics between a group of 14-18 year old female soccer players that demonstrated excessive knee valgus moments compared to those that had normal valgus moments during a cutting maneuver. Excessive valgus moments were defined from another study (Sigward and Powers, 2006) as moments two standard deviations above the average for male athletes.
They found that those with excessive valgus moments demonstrated greater laterally directed GRFs ($P < 0.001$, effect size 1.51), increased hip abduction ($P = 0.002$, effect size 0.79), increased hip internal rotation ($P = 0.008$, effect size 0.71), and increased foot internal rotation ($P = 0.04$, effect size 0.55). They concluded that those athletes demonstrating greater valgus moments used a different strategy to perform the side-cut movement. Specifically, the athlete would reach out further with their plant leg as a preplanned strategy to cut in a known direction of travel (away from the plant leg). A result of this movement strategy was a COP that was at a greater distance from the COM of the body (Figure 1.7b). Those with normal valgus moments had a COP closer to the body’s COM (Sigward and Powers, 2007). This reaching position or strategy is also observed during ACL injuries (Teitz et al., 2001).

1.4.4 Summary - hip control and movement (potential contribution to ACL loading)

The position and control of the hip may have a direct influence on the forces at the knee. The hip must be in a position that allows the movement and muscle actions of the hip to effectively absorb the forces that are otherwise transferred to the knee. Technique may be more important than strength. Therefore, we have included within our intervention movement strategy a focus on positioning the COM and hip over the planted foot to encourage increased hip flexion, decreased frontal or transverse plane forces, and forefoot loading.

1.5 Injury prevention training programs

Positions observed at the time of injury: a knee close to extension with a valgus angle; an abducted hip with the foot planted in front and lateral to the COM; and a trunk that is side-flexed and rotated towards the plant leg, have each been associated with increases in biomechanical risk factors for ACL injury during laboratory-based experiments. Modifying one or more of these movement characteristics may be effective in disrupting the chain of events that are commonly associated with ACL injury in young female athletes.
1.5.1 Current injury prevention training programs – design considerations

ACL injury prevention programs have been successful in reducing ACL injuries by up to 89% in soccer, basketball, handball, and skiing (Silvers and Mandelbaum, 2007). Most ACL injury prevention programs effective at decreasing the incidence of ACL injury are designed to modify biomechanical and neuromuscular risk factors during high-risk athletic movements through neuromuscular training (Table 1.2). Important components of successful prevention programs are thought to be strengthening, awareness of high-risk positions, technique modification, core and trunk control, aerobic conditioning, agility, balance, and plyometrics (Alentorn-Geli et al., 2009; Renstrom et al., 2008). However, we do not know which components of the programs are most effective at modifying movement patterns that are thought to contribute to ACL injury. Only recently have studies started to investigate whether these programs can modify movement (Hewett et al., 1996; Pollard et al., 2006) and to discern the separate effects that individual training components may have on the biomechanics of the knee during high-risk tasks (Dempsey et al., 2009; Herman et al., 2008; Myer et al., 2006).

Of the intervention programs aimed at decreasing ACL injury incidence included in Table 1.2, only the programs by Hewett et al. (1999) and Mandelbaum et al. (2005) have been evaluated for their effects on kinematic and kinetic variables. The program by Hewett et al. (1999) resulted in decreases in peak impact forces of 80% and peak knee valgus moments of 50% after six weeks of training (Hewett et al., 1996). The PEP program (Mandelbaum et al., 2005) was evaluated after a season long implementation of the program within soccer practices (Pollard et al., 2006). The authors found no differences in knee flexion or valgus angles but found significantly less hip rotation (7.1° vs. 1.9°; \( P = 0.01 \)) and greater hip abduction angles (4.9° vs. 7.7°; \( P = 0.02 \)) on a drop jump task.

Compliance rates as low as 26% have been reported in programs aimed at decreasing ACL injuries in female athletes (Mykelbust et al., 2003). However, compliance may be
improved in a number of ways. Training programs that focus on performance enhancement rather than injury prevention have compliance rates of up to 80-90% (Myer et al., 2004). Therefore, content and design of programs that have the dual purpose of preventing injuries and improving performance may have improved uptake from this demographic of athletes. Myer et al. (2005b) were effective at improving both injury prevention and performance parameters with the same comprehensive training program.

Programs that are time-efficient and cost-effective may improve compliance (Finch, 2006; Soligard, et al., 2010). Programs shown to be effective at reducing ACL injury but that require dedicated sessions of over an hour, three times per week for 60 minutes or more (Heidt et al., 2000; Hewett et al., 1999) are less likely to be completed. A team warm-up is a dedicated, consistent opportunity for focused movement that is often supervised by a coach or trainer. It is a regular component of team practice with the main purpose of getting the players ready to play or train. Therefore, it is an ideal time to correct or reinforce proper movement patterns just prior to playing as long as it does not contribute to fatigue. The use of equipment such as balance boards and resistance equipment makes it more difficult to implement such programs. Successful injury prevention programs have been implemented using a 15-30 minute team warm-up with very little or no equipment required (Gilchrist et al., 2008; Mandelbaum et al., 2005; Mykelbust et al., 2003; Olsen et al., 2005).

A common element included in most successful ACL prevention programs is an emphasis on technique modification. Ultimately components such as strength, balance, and agility are included within injury prevention training programs with the intention that they will contribute to a change in movement but most successful programs also include specific instructions to modify high-risk movement (Gilchrist et al., 2008; Hewett et al., 1999; Mandelbaum et al., 2005; Mykelbust et al., 2003; Olsen et al., 2005). In a study that investigated the effects of modifying technique only, Henning (Griffis et al., 1989; Henning and Griffis, 1990) was able to decrease the incidence of ACL injury in female basketball players.
Players were taught to bend their knees more, avoid side-cutting by using a rounded turn, and use multiple steps rather than a sudden stop to decelerate. His work is often cited as one of the first attempts at technique modification to prevent ACL injury and has provided the basis from which many prevention programs have been designed (Mandelbaum et al., 2005; Mykelbust et al., 2003; Olsen et al., 2005; Renstrom et al., 2008). Unfortunately, his death in 1991 has precluded the publication of his work. Despite the effectiveness of Henning’s strategy, it may not be practical, as the unpredictable and competitive environment of multidirectional sports often necessitates the need to land on one leg or side-cut quickly to avoid another player.

1.5.2 Summary - current injury prevention training programs (design considerations)

Although comprehensive training programs are effective in decreasing the incidence of ACL injury, we do not know which components are most effective to allow for more efficient and effective program development and implementation in the future. Technique modification is likely an important component of prevention programs. To ensure compliance, programs should be: implemented within the team warm-up; completed in 15-20 minutes; and require little or no equipment. Therefore, we chose to investigate whether a movement strategy was effective at modifying technique when trained during a 20-minute team warm-up with minimal or no equipment required.
<table>
<thead>
<tr>
<th>Study (author, year)</th>
<th>Study design</th>
<th>Sport (type, level)</th>
<th>Subject (sample size (N), age, sex)</th>
<th>Overall length of intervention, frequency and duration of each session</th>
<th>Training components</th>
<th>Technique addressed</th>
<th>Compliance/ adherence</th>
<th>Effectiveness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gilchrist et al., 2008</td>
<td>Randomized</td>
<td>Soccer, Division I NCAA</td>
<td>N = 1435, U-18 to U-22, females</td>
<td>12-week intervention, 2-3 per week, 20 minute duration</td>
<td>Strength, flexibility, agility, plyometrics, balance/ proprioception, video</td>
<td>Hip and knee position, landing technique</td>
<td>N/A - 8 teams excluded from analysis for performing program less than 12 times</td>
<td>72% reduction in ACL injury overall.</td>
</tr>
<tr>
<td>Soligard et al., 2008</td>
<td>Randomized controlled cluster trial</td>
<td>Soccer, club league</td>
<td>N = 1892, 15-16, female</td>
<td>8-month intervention, 57 sessions, 15 minute duration</td>
<td>Strength, flexibility, agility, plyometrics, proprioception</td>
<td>Hip control and proper knee alignment</td>
<td>77%</td>
<td>Significantly lower risk of overall injuries, overuse injuries and severe injuries, but not knee injuries ($P = 0.079$) in the intervention group vs. control.</td>
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<tr>
<td>Pfeiffer et al., 2006</td>
<td>Prospective non-randomized</td>
<td>Soccer, volleyball, basketball, high school</td>
<td>N = 1439 (112 teams), high school age, female</td>
<td>2-season intervention, 2 per week, 15 minute duration</td>
<td>Flexibility, agility, plyometrics, video</td>
<td>Proper landing technique and directional changes</td>
<td>Average total sessions per player by sport: basketball: 18, soccer: 23, volleyball: 22.</td>
<td>Equal injury rates between intervention and control groups.</td>
</tr>
<tr>
<td>Study (author, year)</td>
<td>Study design</td>
<td>Sport (type, level)</td>
<td>Subject (sample size (N), age, sex)</td>
<td>Overall length of intervention, frequency and duration of each session</td>
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<td>Olsen et al., 2005</td>
<td>Randomized controlled cluster trial</td>
<td>European team handball</td>
<td>N = 1837, 15-17, male and female</td>
<td>8-month intervention, 15 consecutive sessions and once per week thereafter, 15-20 minute duration</td>
<td>Strength, flexibility, agility, plyometrics, balance/ proprioception</td>
<td>Proper landing technique (knee over toe)</td>
<td>73%</td>
<td>Significantly less acute knee injuries in intervention vs. control groups $P = 0.007$).</td>
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<tr>
<td>Mandelbaum et al., 2005</td>
<td>Prospective non-randomized</td>
<td>Soccer, U14-U18 league</td>
<td>N = 5703, 14-18, female</td>
<td>2-year intervention, 2-3 per week, 20 minute duration</td>
<td>Strength, flexibility, agility, plyometrics, proprioception, video</td>
<td>Hip and knee position, landing technique</td>
<td>98%</td>
<td>82% reduction in ACL tears in intervention groups ($P &lt; 0.001$).</td>
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<tr>
<td>Petersen et al., 2005</td>
<td>Controlled prospective case control</td>
<td>Team handball, semi-professional and amateur</td>
<td>N = 276 (20 teams), adult, female</td>
<td>One-season intervention, 3 per week during preseason, 1 per week during season, 10 minute duration</td>
<td>Plyometrics, balance/ proprioception</td>
<td>Bent knee/ knee over toe landing, three step stop with knees bent and accelerated rounded turn</td>
<td>83%</td>
<td>No significant difference between groups, although risk was 83% lower in intervention group.</td>
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<tr>
<td>Study (author, year)</td>
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<td>Sport (type, level)</td>
<td>Subject (sample size (N), age, sex)</td>
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<tr>
<td>Myklebust et al., 2003</td>
<td>Prospective non-randomized</td>
<td>European team handball, Division I-III</td>
<td>N = 2647, 16-35, female</td>
<td>One-season intervention, 3 per week during preseason, 1 per week during season, 15 minute duration</td>
<td>Flexibility, agility, balance/proprioception, plyometrics</td>
<td>Knee over toe position</td>
<td>26% in first year of data collection, 29% in second year</td>
<td>Risk of injury was reduced for elite division players who complied to program (OR: 0.06, P = 0.01) compared to control.</td>
</tr>
<tr>
<td>Wedderkopp et al., 2003</td>
<td>Randomized controlled cluster trial</td>
<td>European team handball, recreational, intermediate and elite</td>
<td>N = 236 (20 teams), 17-18, female</td>
<td>10-month intervention, every practice, 10-15 minute duration</td>
<td>Strength, plyometrics, balance/proprioception</td>
<td>N/A</td>
<td>N/A</td>
<td>&quot;Knee injuries&quot; were not less in trained (6.9) group vs. control (0.6).</td>
</tr>
<tr>
<td>Heidt et al., 2000</td>
<td>Prospective non-randomized</td>
<td>Soccer, U14-U18 league</td>
<td>N = 300, 14-18, female</td>
<td>7-week intervention, 3 days/week, 60 minute duration</td>
<td>Strength, flexibility, agility, plyometrics, proprioception/balance</td>
<td>Acceleration training technique to avoid injury situations</td>
<td>100%</td>
<td>Reduced knee/ankle injury rate in intervention (2.4%) vs. control (3.1%).</td>
</tr>
<tr>
<td>Söderman et al., 2000</td>
<td>Prospective randomized</td>
<td>Soccer, semi-professional and professional</td>
<td>N = 221, 20 ± 5, female,</td>
<td>7-month (1 season) intervention, 30 sessions in first month, then 3 per week, 10-15 minute duration</td>
<td>Balance/proprioception</td>
<td>Single-leg balance instruction of slightly flexed knee</td>
<td>70%</td>
<td>Significantly more total injuries in control vs. intervention group, but no reduced risk of primary traumatic injuries to lower extremity.</td>
</tr>
<tr>
<td>Study (author, year)</td>
<td>Study design</td>
<td>Sport (type, level)</td>
<td>Subject (sample size (N), age, sex)</td>
<td>Overall length of intervention, frequency and duration of each session</td>
<td>Training components</td>
<td>Technique addressed</td>
<td>Compliance/ adherence</td>
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<tr>
<td>Hewett et al., 1999</td>
<td>Prospective non-randomized</td>
<td>Basketball, volleyball and soccer, trained and untrained</td>
<td>N = 1263, 14-18, male and female</td>
<td>6-week preseason intervention, 3 per week, 60-90 minute duration</td>
<td>Strength, flexibility, plyometrics, balance/proprioception, video</td>
<td>2-week jump and land technique training</td>
<td>70%</td>
<td>Higher ACL injury rate in untrained females (0.43) vs. trained females (0.12) and male controls (0.09).</td>
</tr>
<tr>
<td>Caraffa et al., 1996</td>
<td>Prospective non-randomized</td>
<td>Soccer, semi-professional and amateur</td>
<td>N = 600 (40 teams), male</td>
<td>3 season intervention, every day during preseason (minimum of 30 days), 20 minute duration</td>
<td>PNF facilitation, balance/proprioception</td>
<td>No</td>
<td>Not monitored</td>
<td>87% decrease in noncontact ACL injury between intervention (0.15 per team) &amp; control groups (1.15 per team) (P &lt; 0.001).</td>
</tr>
<tr>
<td>Ettlinger et al., 1995</td>
<td>Prospective non-randomized</td>
<td>Alpine skiing, ski personnel (patrollers and instructors)</td>
<td>N = 4000, age N/A, male and female</td>
<td>1-year intervention, 1 per week, 60 minute duration</td>
<td>Video of skiers falling with differences between those who did and did not sustain an ACL injury highlighted for injury prevention education.</td>
<td>Fall technique addressed</td>
<td>N/A – 29% returned response card</td>
<td>“Severe knee sprains” were reduced by 62% vs. historic control.</td>
</tr>
<tr>
<td>Study (author, year)</td>
<td>Study design</td>
<td>Sport (type, level)</td>
<td>Subject (sample size (N), age, sex)</td>
<td>Overall length of intervention, frequency and duration of each session</td>
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<tr>
<td>Griffis et al., 1989</td>
<td>Prospective non-randomized</td>
<td>Basketball, Division I college</td>
<td>Females 8-year intervention Plyometrics, proprioception</td>
<td>Knee flexion when landing, accelerated rounded turns and deceleration with a multistep stop</td>
<td>N/A</td>
<td>89% reduction in noncontact ACL injury.</td>
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</tbody>
</table>
1.6 Effects of injury prevention training on biomechanical risk factors

Training programs have been effective at modifying a variety of potential risk factors for ACL injury (Table 1.3). Outcome measures have included electromyographic (EMG) timing and activation levels of muscle (Chimera et al., 2004; Lephart et al., 2005; Zebis et al., 2008); isolated and functional strength (Herman et al., 2008; Holcomb et al., 2007; Lephart et al., 2005; Myer et al., 2005a); single-leg stability (Paterno et al., 2004); and kinematic and kinetic variables at the knee during various functional tasks (Chappell and Limpisvasti, 2008; Herman et al., 2008; Lephart et al., 2005; Myer et al., 2005b; Pollard et al., 2006). We have chosen to review studies that have investigated training program effects on kinematic and / or kinetic variables during high-risk athletic movements because they potentially provide the most direct evidence for the ability to modify these movements (Table 1.3).

Multimodal training programs have improved kinematic and / or kinetic variables during high-risk athletic movements (Chappell and Limpisvasti, 2008; Hewett et al., 1996; Lephart et al., 2005; Lim et al., 2009; Myer et al., 2005b). Chappell and Limpisvasti (2008) demonstrated decreased knee valgus moments ($P = 0.04$) during a stop jump task and increased initial ($P = 0.003$) and maximum ($P = 0.006$) knee flexion angles during a drop jump task after a neuromuscular training program that included core and lower extremity strength, balance, plyometrics, jumping, and agility drills. Lim et al. (2009) investigated biomechanical variables during a basketball rebounding task that involved jumping for an over-head ball and landing, tested before and after an 8-week training program. They compared an experimental group that underwent a modified PEP training program (Mandelbaum et al., 2005) that consisted of running, stretching, strengthening, plyometric and agility drills to a control group that continued their regular training. The experimental group demonstrated increased knee flexion angles ($P = 0.023$) but also increased abduction moments ($P = 0.043$) compared to the control group. Because we don’t know which training components are responsible for the positive or, in the case of the increased abduction moments found by Lim et al. (2009), negative influences on biomechanical risk factors, we must further study the effects of isolated components.
An example of isolating one training program component for further investigation is strength training. Strength training has been included in several successful injury prevention programs (Gilchrist et al., 2008; Hewett et al., 1999; Mandelbaum et al., 2005; Olsen et al., 2005) and has been included in multimodal training programs that have demonstrated improvements in kinematic and kinetic variables (Chappell and Limpisvasti, 2008; Hewett et al., 1996; Lephart et al., 2005; Myer et al., 2006). However, strength training alone may not modify biomechanical risk factors at the knee. Herman et al. (2008) found no differences in hip and knee kinematics in recreational female athletes during a stop jump task after a 9-week strength-training program. Cochrane et al. (2010) found that balance training reduced peak knee valgus and internal rotation moments while strength training increased internal rotation moments and decreased flexion angles at the knee during various cutting maneuvers. Although strength may not directly modify movement patterns, it may still be an important component of training programs. For example, fatigue has been demonstrated to adversely affect kinematic and kinetic variables during functional tasks (Chappell et al., 2005; McLean et al., 2007); strength training may increase the threshold to fatigue, thus lessening the negative effects of fatigue (Herman et al., 2008). More investigation is needed to determine the role that strength training plays within time-efficient and cost-effective training programs.

Few studies have investigated the separate effects of technique modification on biomechanical variables during high-risk athletic tasks (Cowling et al., 2003; Dempsey et al., 2009; Mizner et al., 2008; Onate et al., 2005) and only one study evaluated the effects on side-cutting movements (Dempsey et al., 2009). Dempsey et al. (2009) investigated the effects of a six-week training program aimed at modifying whole body side-cutting technique. They trained twelve male team sport athletes two times per week for 15 minutes per session, gradually progressing from a predictable “closed skill” environment to a more unpredictable “open skill” environment. Weekly drills and goals were successfully completed before moving onto the next set of drills and goals. Technique modifications included; bringing the foot closer to the midline of the body (i.e. less hip abduction), ensuring the foot was not internally or
externally rotated, and maintaining the trunk in an upright, forward facing position. Verbal and visual feedback was provided. After completing the training program, subjects demonstrated a narrower stance and a more upright trunk on initial foot contact. Importantly, both of these positional modifications were associated with a 36% decrease in valgus moments during the weight acceptance phase of stance. They were not, however, able to change trunk rotation, which may have been why they did not change internal rotation moments. Although this study only included male subjects, who commonly show different movement patterns than female subjects, it demonstrates the effectiveness of technique modification on biomechanical risk factors.

Although biomechanical analyses have been valuable in improving our understanding of how different interventions may modify high-risk movements, caution should be exercised in drawing definitive conclusions. Kinematic and kinetic variables studied in the laboratory are surrogate measures to ACL injury risk but improving even the most relevant biomechanical variables to ACL injury risk in the laboratory may not transfer to the field. For example, researchers have used a preplanned, drop vertical jump as a functional test of their training programs after including similar jumps in their training program (Hewett et al., 1996; Myer et al., 2005b, 2007). Although this may be effective in demonstrating improvements in a controlled laboratory environment, these same effects may not transfer effectively to untrained tasks in a competitive, unpredictable sporting environment (Lee et al., 1991).

1.6.1 Summary - effects of injury prevention training on biomechanical risk factors

Multimodal training programs have demonstrated effectiveness at decreasing ACL injuries and improving biomechanical risk factors. Studies have started to isolate specific components of these training programs to better understand their individual effects on biomechanical risk factors. However, there have been very few studies that have looked at technique modification and only one study that has looked at technique modification during a
side-cut task. Therefore, we investigated the isolated effects that technique modification, using a novel movement strategy, may have on biomechanical risk factors during side-cutting and single-leg landing tasks.
Table 1.3 Effects of training programs on kinematic and kinetic risk factors for ACL injury

<table>
<thead>
<tr>
<th>Study (author, year)</th>
<th>Study design</th>
<th>Sport (type, level)</th>
<th>Subject (sample size (N), age, sex)</th>
<th>Overall length of intervention, frequency and duration of each session</th>
<th>Training components</th>
<th>Technique addressed</th>
<th>Compliance /adherence</th>
<th>Results</th>
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</thead>
<tbody>
<tr>
<td>Cochrane et al., 2010</td>
<td>Prospective randomized controlled trial</td>
<td>Australian Rules Football, assumed professional</td>
<td>N = 50, 23 ± 5.5, male</td>
<td>12-week intervention, 3 sessions per week, 30 minute durations</td>
<td>Strengthening, balance</td>
<td>None</td>
<td>Not reported</td>
<td>Balance training reduced peak valgus moments and internal rotation for crossover, sidestepping at 30 and 60 degrees as well as straight line running. Free weight training increased peak internal rotation moment and decreased knee flexion angles. Machine weight training increased knee flexion moments and reduced peak valgus moments. Balance and machine weight training no effect.</td>
</tr>
<tr>
<td>Ortiz et al., 2010</td>
<td>Prospective cluster randomized controlled trial</td>
<td>Soccer, competitive</td>
<td>N = 30, 14-17, female</td>
<td>6-week intervention, 2 sessions per week, 20-25 minute duration</td>
<td>Strengthening, flexibility, plyometrics</td>
<td>Control of hip and knee position during execution and landing of jumps</td>
<td>83%</td>
<td>Groups were not equal at baseline. When baseline measurements used as covariate, no significant differences were seen between groups for knee flexion, valgus or internal rotation joint angles for drop jump task. No differences between groups for peak knee valgus and extension moments for the drop jump, but both significantly increased from pre to post.</td>
</tr>
<tr>
<td>Study (author, year)</td>
<td>Study design</td>
<td>Sport (type, level)</td>
<td>Subject (sample size (N), age, sex)</td>
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<tr>
<td>Dempsey et al., 2009</td>
<td>Prospective non-controlled</td>
<td>Australian football, rugby union and soccer, club and university</td>
<td>N = 9, male</td>
<td>6-week intervention, 2 sessions per week, 15 minute duration</td>
<td>Technique modification training using verbal and visual feedback for performance of side-cutting technique</td>
<td>Side-cutting with plant leg closer to torso midline, no rotation of foot, torso upright and in-line with direction of motion</td>
<td>Not reported</td>
<td>No change in peak flexion moment or internal rotation moment, 36% reduction in peak valgus moment ($P = 0.034$), no changes in knee flexion angles. Decreased lateral trunk flexion ($P = 0.005$) and distance of plant foot to torso ($P = 0.039$).</td>
</tr>
<tr>
<td>Lim et al., 2009</td>
<td>Prospective randomized controlled trial</td>
<td>Basketball, high school</td>
<td>N = 22, 15-17, female</td>
<td>8-week intervention, every practice, 20 minute duration</td>
<td>Strengthening, flexibility, plyometrics, agility</td>
<td>2x1.5 hour training sessions implemented by athletic trainer focusing on proper exercise technique</td>
<td>Not reported</td>
<td>The intervention group increased knee flexion angle relative to both pre-intervention measures ($P = 0.024$) and the control group ($P = 0.023$).</td>
</tr>
<tr>
<td>Chappell and Limpisvasti, 2008</td>
<td>Prospective non-randomized</td>
<td>Basketball and soccer, NCAA division 1</td>
<td>N = 30, 19±1.2, female</td>
<td>6-weeks intervention, 6 per week, 10-15 minute duration</td>
<td>Strengthening, plyometrics</td>
<td>Modified from F-MARC</td>
<td>100%</td>
<td>Decreased knee abduction moment for the stop jump, increased knee flexion angle for the drop jump.</td>
</tr>
<tr>
<td>Herman et al., 2008</td>
<td>Prospective randomized controlled trial</td>
<td>Soccer, basketball, volleyball, recreational</td>
<td>N=66, 18-30, female</td>
<td>9-week intervention, 3 sessions per week</td>
<td>Strengthening</td>
<td>None</td>
<td>85%</td>
<td>No changes in knee kinetic or kinematic values for stop jump task.</td>
</tr>
<tr>
<td>Study (author, year)</td>
<td>Study design</td>
<td>Sport (type, level)</td>
<td>Subject (sample size (N), age, sex)</td>
<td>Overall length of intervention, frequency and duration of each session</td>
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<tr>
<td>Myer et al., 2007</td>
<td>Prospective controlled trial</td>
<td>Basketball and soccer, high school</td>
<td>N=18, 16±1, female</td>
<td>7-week intervention, 3 sessions per week</td>
<td>Strengthening, flexibility, plyometric, balance</td>
<td>Unspecified</td>
<td>Minimum 67%</td>
<td>“High-risk” intervention group decreased peak knee abduction torque by 13%.</td>
</tr>
<tr>
<td>Myer et al., 2006</td>
<td>Prospective randomized uncontrolled</td>
<td>Volleyball, high school</td>
<td>N=18, 16, females</td>
<td>7-week intervention, 2-3 sessions per week, 90 minute duration</td>
<td>Plyometric, agility, balance</td>
<td>No knee valgus during landing, and cutting, increased knee flexion during landing</td>
<td>Minimum 67%</td>
<td>Both plyometrics and balance interventions reduced hip abduction, ankle eversion angles for the drop vertical jump and knee abduction angle for the medial drop landing. Plyometrics group increased knee flexion angle with the drop vertical jump, balance group increased knee flexion angle with the medial drop landing.</td>
</tr>
<tr>
<td>Pollard et al., 2006</td>
<td>Prospective non-randomized</td>
<td>Soccer, club and high school</td>
<td>N = 18, 14-17, female</td>
<td>One-season intervention, 2-3 sessions per week, 20 minute duration</td>
<td>Strength, flexibility, agility, plyometric, proprioception, instruction and video</td>
<td>Soft landing with deep hip and knee flexion</td>
<td>Minimum 80%</td>
<td>No changes in knee kinematics, decreased hip internal rotation angle, increase in hip abduction angle.</td>
</tr>
<tr>
<td>Study (author, year)</td>
<td>Study design</td>
<td>Sport (type, level)</td>
<td>Subject (sample size (N), age, sex)</td>
<td>Overall length of intervention, frequency and duration of each session</td>
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<tr>
<td>Lephart et al., 2005</td>
<td>Prospective randomized non-controlled</td>
<td>Soccer and basketball, club league</td>
<td>N = 27, 14, female</td>
<td>8-week intervention, 3 sessions per week, 30 minute duration</td>
<td>Strengthening, flexibility, balance for first 4 weeks. Then plyometric group added plyometrics and agility. Basic training group continued as before.</td>
<td>None</td>
<td>Not reported</td>
<td>For jump landing, both groups increased hip flexion at initial contact ($P = 0.016$) and peak hip and knee flexion ($P = 0.17$, $P = 0.009$), time to peak knee flexion ($P = 0.006$), peak knee and hip flexion moments ($P = 0.013$, $P = 0.008$). No differences for initial knee flexion, varus or valgus, hip adduction or abduction or peak hip adduction angles. No difference in peak knee valgus or hip adduction moments or in vertical ground reaction forces. No differences between groups.</td>
</tr>
<tr>
<td>Hewett et al., 1996</td>
<td>Prospective non-randomized</td>
<td>Volleyball, high school</td>
<td>N = 11, 15, females</td>
<td>6 weeks, 3 sessions per week, 2 hour duration</td>
<td>Jumping, plyometrics, strength, flexibility</td>
<td>Proper jumping technique</td>
<td>Not reported</td>
<td>22% reduction in landing forces ($P = 0.006$). No difference in knee flexion angles at takeoff and landing.</td>
</tr>
</tbody>
</table>
1.7 A novel movement strategy

The results of Dempsey et al. (2009) are important and provide a basis and a rationale to explore other means of technique modification. A movement strategy extends beyond a simple description of the movement pattern and includes with it: how the learner organizes motor, sensory, and perceptual information necessary to perform the tasks in different environments (Shumway-Cook and Woollacott, 2007). We propose a novel movement strategy to reduce biomechanical risk with a method that requires the athlete to move their COM closer to the plant foot with increased trunk control rather than requiring the athlete to attend to and change multiple joint and body segment positions. This movement strategy is referred to as Core Position and Control (Core-PAC) and was originally developed by our group as a clinical technique to treat recalcitrant groin and abdominal injuries but shows promise for athletic movement technique modification. It includes a proximal to distal movement sequence, which has been described by several authors relative to enhancing force and speed production (Kibler et al., 2006; Putnam, 1993) and precision and control (Kibler et al., 2006) of the distal segments of the extremities. The Core-PAC is introduced here as a sequence of neuromuscular recruitment and segmental movements that begin proximally, or at the trunk / pelvis, followed by muscle recruitment and movement in the periphery (Kibler et al., 2006; Putnam, 1993; Richardson and Jull, 1995). The practical application involves the athlete first increasing proximal muscle recruitment (Richardson and Jull, 1995) and then moving their pelvic centre (focus is often on the navel) in the intended direction of movement such that the COM is positioned as close to the planted foot as possible (Figure 1.9b). The Core-PAC results in a similar whole body orientation as described by Dempsey et al. (2009), but with a single focus of attention for the athlete that avoids individual coordination of the upper and lower extremity joints and segments (Figure 1.9c). The following explains the key elements of the movement strategy and how these elements may address some of the biomechanical considerations mentioned above.
1.7.1 Increased proximal muscle recruitment

A “kegel-type” recruitment pattern of the pelvic floor and transversus abdominus is performed and maintained before and throughout the movement (Richardson and Jull, 1995; Sapsford and Hodges, 2001; Sapsford et al., 2001; Urquhart et al., 2005). We refer to this neuromuscular recruitment pattern as “setting” (see detailed description in “Glossary”, page xii). This technique of isolating the transversus abdominus muscle was first described by Richardson and Jull (1995). Transversus abdominus activation has since been shown to control spinal motion by increasing intervertebral stiffness (Barker et al., 2006; Hodges et al., 2003b). The goal with this pattern of muscle activation is to optimize dynamic stability of the thoracolumbar-pelvic-hip complex, thereby providing the lower limbs with a stable base for motion and allowing optimal force production (Kibler et al., 2006). Proximal muscle activation has also been described as enhancing anticipatory postural adjustments that position the body in more stable positions to resist forces and perturbations (Kibler et al., 2006, Zattara and Bouisset, 1988).

1.7.1.1 How might increased proximal muscle recruitment / activation address risk factors?

Proximal muscle activation may have a positive effect on decreased lateral and rotational control of the trunk, which have been observed during ACL injury (Hewett et al., 2009) and have been associated with potential biomechanical risk factors such as increased knee abduction moments (Dempsey et al., 2007). More importantly, it may have a positive influence on neuromuscular risk factors that have been predictive of future knee injury such as deficits in core proprioception (Zazulak et al., 2007b) and increased lateral trunk displacement in response to a sudden force release (Zazulak et al., 2007a).

1.7.2 Proximal to distal movement sequence

After setting, the Core-PAC involves a push into the ground off the back leg such that the athlete’s focus is on moving the centre of the pelvis in the intended direction. The instruction is to “move from the center” or “lead with the center of the body”. The goal is to position the navel or pelvic centre
over, or as close to, the plant foot as possible by displacing the COM in the intended direction of movement (Figure 1.9b). This movement strategy is in contrast to a distal to proximal strategy in which the lead leg reaches forward or laterally (abducts) first and the foot plants at a distance from the COM (Figure 1.9a).

1.7.2.1 How might a proximal to distal movement sequence address risk factors?

ACL injury is thought to occur early (30-40ms) in the deceleration phase of athletic movements (Krosshaug et al., 2007a). This does not allow enough time for muscles to respond at the spinal cord level (>70ms) or at the cortical level (intermediate > 130ms; voluntary > 220ms) (Huston and Wojtys, 1996). Therefore, the outcome of the movement, injury or no injury, may be predetermined prior to heel contact (Griffin, 2000). Athletes can develop neuromuscular control and movement strategies that allow them to better respond to unexpected perturbations and demands (Cowling et al., 2003; Hewett et al., 2009). A Core-PAC potentially positions the body’s COM closer to the planted foot and increases neuromuscular control of the trunk in this position.

Observations made by Boden et al. (2009) suggest that athletes who injured their ACL tended to land on their whole foot or heel with an increase in hip flexion compared to athletes that were not injured and landed on the ball of their foot with less hip flexion. Compared to landing with the forefoot, landing with the rear foot results in decreased hip and knee flexion at peak GRF and decreased maximal knee flexion angle (Cortes et al., 2007). Burkhart et al. (2008) prospectively predicted an increased risk of non-contact ACL injury in athletes that landed on their rear foot compared to their forefoot. A Core-PAC may encourage forefoot loading by getting the COM forward as a result of “leading from the centre” (Figure 1.8).

1.7.3 Compliance

1.7.3.1 Simpler and (potentially) more effective instruction

Hodges and Franks suggest that “too often we teach based on how a skill is to be performed rather than how people learn” (Hodges and Franks 2004, p.145). Existing intervention programs use commands such as “keep your knees over your toes” and “bend your hips and knees on landing” or
“land with less hip internal rotation and less knee abduction”. Instructions such as these - that focus the attention of the athlete on their limbs - have been shown to be less effective in learning a skill than a focus on an end point, outside of the body (Wulf et al., 2010). A styrofoam ball is a tool that can be used initially during teaching and then removed (Figure 1.9b). Directing an athlete’s attention away from their lower extremity and trunk to the movement of a styrofoam ball located just above their pelvis results in a focus on an end point external to the resultant lower extremity coordination. Although most of the motor control literature describes the effectiveness of this external focus relative to an object such as a golf club or baseball bat (Wulf et al., 1999; Wulf et al., 2010), a focus on the styrofoam ball serves a similar function.

Dempsey et al. (2009) have demonstrated that lower extremity kinematics and kinetics can be influenced by changes in trunk and hip position. However, once again this involves multiple areas of the body to focus on. The author’s instructions to (1) bring the foot in and (2) straighten the torso essentially result in the same body posture as does displacing the COM laterally over the planted foot (Figure 1.9b,c). Considering that these potential strategies and cues will be transferred to coaches on the playing field, the simpler and the less instruction, the better.
Figure 1.9 Core-PAC (proximal to distal) vs. reach (distal to proximal) movement strategy

Figure 1.9a. A distal to proximal or “reaching” movement resulting in hip abduction and ipsilateral trunk side-flexion with the COM at a distance from the planted foot. Figure 1.9b. Correction of the reaching movement by a Core-PAC strategy focused on getting the COM (styrofoam ball=white circle), over the planted foot. Figure 1.9c. An alternative correction of the reaching movement by bringing the foot under the midline of the body and straightening the trunk.

1.7.3.2 Performance

One of the greatest challenges in successfully implementing injury prevention training programs is compliance (Finch, 2006; Myer et al., 2004; Soligard et al., 2010). Coaches and athletes are more likely to comply with a program if there are potential performance benefits (Finch, 2006). Putnam (1991, 1993) has described how proximal muscle activation may create interactive moments through the peripheral joints resulting in optimal force transfer and positioning of the distal joints in throwing, kicking and striking movements. Kibler et al. (2006) explained that because preprogrammed activation patterns
of the core muscles and interactive moments largely control joint force production, smaller peripheral muscles are able to contribute more to precision and control rather than force production. These are both desirable performance outcomes for an athlete, especially a soccer player.

1.7.4 Summary - Core-PAC movement strategy

The underlying rationale for the Core-PAC is a simple method of getting the COM closer to the plant foot with an increase in neuromuscular activity of key proximal stabilizing muscles. Based on the literature, getting the COM closer to the BOS may bias joint loading to the sagittal rather than the frontal and transverse planes, which often occurs in female athletes and poses a risk for ACL injury (Hewett et al., 2002; Pollard et al., 2010). This improved sagittal plane alignment (ankle, knee, and hip in line) may allow the muscles rather than the ligaments to absorb kinetic energy throughout the lower extremity (Hewett et al., 2002; Pollard et al., 2010) and may result in increased hip, knee and ankle flexion angles. The increased proximal muscle activity and the positioning of the COM well within stability limits may allow for an increased capacity of the athlete to respond to unexpected perturbations and a decreased risk of injury.

1.8 Purpose, objectives and hypotheses

The purpose of this research is to determine whether a novel movement strategy (Core-PAC) can improve biomechanical risk factors for ACL injury in athletic movements (Figure 1.10).

1.8.1 Objectives

1) In order to detect change in biomechanical variables, outcome measures must demonstrate adequate reliability. Therefore, our first objective was to evaluate the between day test-retest reliability of biomechanical variables at the knee during soccer-specific tasks.

2) To use a single group pretest-posttest design to a) determine the feasibility of implementing a Core-PAC into a team warm-up prior to regular soccer training based on subject compliance and integration of the Core-PAC into the warm-up and 2) to determine whether the Core-PAC would improve peak knee flexion angles and peak abduction moments at the knee during three dynamic tasks after immediate instruction and after a four-week training program. The three
tasks were a side-cut (SC) and an unanticipated side-cut (USC) prior to kicking a soccer ball, and a side-hop (SH) task.

3) Conduct a randomized controlled trial to compare a Core-PAC trained group to a control group for peak flexion angles and peak abduction moments at the knee during a side-cut, an unanticipated side-cut, and a side-hop task after a six-week training program.

1.8.2 Hypotheses

1) Flexion angles, abduction angles, and abduction moments at the knee will demonstrate acceptable reliability (ICC ≥ 0.75, significant at the 0.05 level) during a side-cut, an unanticipated side-cut, and a side-hop task.

2) A randomized controlled trial will be feasible based on a) adequate recruitment, b) adequate compliance from subjects, and c) effective implementation of training into a pre-practice soccer warm-up during the pilot study.

3) A Core-PAC will be efficacious in decreasing peak abduction moments and increasing peak flexion angles at the knee during a side-cut, an unanticipated side-cut, and a side-hop task after immediate instruction and a four-week training program.

4) A randomized controlled trial will demonstrate that a Core-PAC group will have greater peak flexion angles and lower peak abduction moments at the knee as compared to a control group during a side-cut, an unanticipated side-cut, and a side-hop task after a 6-week training program.
**Overall Purpose:** to investigate the effect of a novel movement strategy (Core-PAC) in reducing biomechanical risk factors for ACL injury during three soccer-specific tasks (side-cut, unanticipated side-cut, side-hop).

**Study 1**  
*(Chapter 2)*  
Reliability  
Between-day test-retest reliability of biomechanical variables  
*n=10; one group pretest-posttest design*

**Study 2**  
*(Chapter 3)*  
Feasibility  
Feasibility of incorporating Core-PAC movement strategy into soccer team warm up  
Core-PAC effect on biomechanical variables after immediate instruction and after 4-week training program  
*n=10; one group pretest-posttest design*

**Study 3**  
*(Chapter 4)*  
RCT  
Compare Core-PAC trained group to control for biomechanical variables after 6-week training program  
*n=19; randomized control trial design*
2 Reproducibility of Biomechanical Data during Sport Specific Tasks in Young Female Soccer Players

2.1 Introduction

Anterior Cruciate Ligament (ACL) injury is one of the most common and debilitating knee injuries in sport and can lead to significant long-term impairment (Gillquist and Messner, 1999; Hartwick et al., 2003), reduced function (Feagin and Lambert, 1985; Maletius and Messner, 1999) and diminished quality of life (Hartwick et al., 2003). It is typically managed by surgical reconstruction and extensive postoperative rehabilitation and is associated with the highest costs of any sporting knee injury (Gottlob et al., 1999; Gottlob and Baker, 2000). An estimated 250,000 ACL injuries occur every year in the United States at a cost of nearly two billion dollars (Silvers and Mandelbaum, 2007). The financial cost of a single ACL reconstruction and rehabilitation has been conservatively estimated at $17,000 (US) (Hewett et al., 1999). As a result, there have been many studies attempting to identify and decrease risk factors for ACL injuries (Besier et al., 2001a,b; Hewett et al., 1999; Myklebust et al., 2003).

ACL injuries typically occur during high-risk movements such as cutting to change direction, decelerating quickly, or landing from a jump during multidirectional sports such as soccer and basketball (Boden et al., 2000; Krosshaug et al., 2007b). Approximately 70% of ACL injuries occurring in these sports are “non-contact” (i.e. do not involve direct contact with another player) (Boden et al., 2000; McNair et al., 1990; Olsen et al., 2004). Young women participating in multidirectional sports are 4-6 times more likely to sustain an ACL injury compared with young men (Arendt and Dick, 1995; Griffin et al., 2000). There is increasing evidence that a major reason for this gender difference in ACL injury incidence is the movement strategy that young female athletes use to perform these high-risk movements (Griffin et al., 2000; Hewett, 2000; McLean et al., 2004b). In addition, movement strategies represent one of the few modifiable risk factors for ACL injury.
Young female athletes, more commonly than their male counterparts, perform these high-risk movements with a knee that is within 30° of full extension, a greater abduction angle, and a greater external abduction moment (Chappell et al., 2002; Ferber et al., 2003; McLean et al., 2005a,b). These are also the positions and forces that are similar to actual non-contact ACL injuries occurring in sport (Boden et al., 2000; Krosshaug et al., 2007a). Various modeling techniques (Fung and Zhang, 2003; Krosshaug et al., 2007b; McLean et al., 2003; Shin et al., 2007), in vivo studies (Cerulli et al., 2003), and in vitro studies of ACL loading (Markolf et al., 1995) have confirmed that these positions and forces can potentially increase strain in the ACL. In a prospective study, Hewett et al. (2005a) demonstrated that those female athletes that went on to an ACL injury in the upcoming season had, among other characteristics, 10.5° less flexion angle, 7.6° greater abduction angle, and 2.5 times greater abduction moment at the knee on a drop vertical jump. Decreased knee flexion and increased abduction angles have also been identified as biomechanical characteristics within a female strategy of movement that differs from their male counterparts in numerous studies (Hewett, 2008; Malinzak et al., 2001; McLean et al., 2004a, 2005b). Therefore, modifying knee joint angles and moments in female athletes performing high-risk athletic movements may help to decrease injury to the ACL. Effective modification of biomechanical risk factors for ACL injury during high-risk athletic movements is necessary in designing injury prevention training programs and ultimately in decreasing the incidence of ACL injury (Hewett et al., 1999, 2005b; Lephart et al., 2002).

Quantitative biomechanical analyses are commonly performed during high-risk movements to better understand how different intervention programs may or may not modify biomechanical risk factors for ACL injury. However, any outcome measure analyzed must have adequate validity and reliability (Streiner and Norman, 2003). Reproducibility is the degree to which a measurement demonstrates consistent results during repeated measures (de Vet et al., 2006). Test-retest reliability (e.g. intraclass correlation coefficient (ICC)) and agreement (e.g. standard errors of measurement (SEM)) are two distinct but related concepts that can be
considered within the umbrella term “reproducibility” (de Vet et al., 2006). Both are essential to the inferences and conclusions one can make from data collected during movements at high-risk for ACL injury (Portney and Watkins, 2000).

Although there have been many studies in the ACL literature which examine the effect of gender or intervention programs on knee kinematics and kinetics during cutting tasks, only a few have reported test-retest reliability for these performance measures (Besier et al., 2001b; Ford et al., 2005; Sigward and Powers, 2006) and none have reported measures of agreement.

Previous studies have demonstrated moderate to high test-retest reliability of 3D motion analysis variables at the knee during gait and running trials (Ferber et al., 2002; Kadaba et al., 1989). Kadaba et al. (1989) were among the first to investigate the reliability of kinematic and kinetic data and found good test-retest reliability ($R_{\text{kinematics}} = 0.61-0.98$; $R_{\text{kinetics}} = 0.94-0.95$) of 3D motion analysis variables at the knee during gait. The reliability of these variables has also been demonstrated in running trials (Ferber et al., 2002). More recently, reliability studies have been extended to more complex tasks. Acceptable test-retest reliability ($R = 0.61-0.98$) has been previously reported for 3D kinematic and kinetic variables of soccer players for a running side-cut task (Besier et al., 2001a; Sigward and Powers, 2006). Ford et al. (2007) found good to excellent test-retest reliability ($R = 0.65-0.98$; $ICC_{3,1} = 0.62-0.87$) of three-dimensional (3D) lower extremity variables for a drop jump task. Webster et al. (2010) demonstrated that tibial rotation could be reliably measured between sessions ($ICC_{3,1} = 0.68-0.76$) during a step down from a two-step height with a 90° pivot turn.

No previous studies have evaluated the reliability of 3D motion analysis variables for more complex, sport-specific tasks such as side-cutting to kick a soccer ball, despite the recent emphasis on including “ecologically valid” tasks (laboratory-based tasks that approximate real life conditions). Kicking a soccer ball during a side-cut task often requires an athlete to transfer their center of mass (COM) from their plant leg to their kicking leg. Teitz and colleagues (2001)
demonstrated that many non-contact ACL injuries occur when the COM is behind and away from the base of support (i.e. planted foot) during reaching type movements.

The purpose of this study was to evaluate the test-retest reliability and agreement for knee flexion and abduction angles, and knee abduction moments during a side-cut (SC) and an unanticipated side-cut (USC) prior to kicking a soccer ball, and a side-hop (SH) task. We chose the SC task because it is often performed in soccer and other sports at high-risk for ACL injury and has been included in many biomechanical studies investigating ACL risk factors (Besier et al., 2001b; Cochrane et al., 2010; Cowley et al., 2006; Dowling et al., 2010; Malinzak et al. 2001; Sigward and Powers, 2006). We have added the unanticipated component because this has been shown to increase the risk of biomechanical risk factors for ACL injury (Besier et al., 2001a; Ford et al., 2005). However, we have built on the complexity and sport specificity of these tasks from previous studies by adding the kicking of a soccer ball to the SC and USC tasks. Finally, we have included the side-hop task because it is an ecologically valid movement for high-risk sports that mimics single-leg landing with hip abduction, a position that has been associated with ACL injury (Olsen et al., 2004) but has rarely been investigated in other studies (McLean et al., 2005b; Sell et al., 2006).

2.2 Methods

2.2.1 Subjects

Ten female youth soccer players were recruited in January, 2007 using a convenience sampling approach from Under 15, 16, and 17 gold level soccer teams in Port Moody, British Columbia, Canada (Table 2.1). Gold level teams consist of players that are one level lower than the top players for that age group. These ages were chosen because, although preadolescent female and male athletes have similar rates of ligament injuries, female athletes are especially vulnerable to ACL injury after the onset of puberty (Ford et al., 2005; Shea et al., 2004; Tursz and Crost, 1986).
Table 2.1 Subject characteristics for study 1 (n = 10)

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Mean</th>
<th>SD</th>
<th>Range</th>
</tr>
</thead>
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<td>1.3</td>
<td>14-17</td>
</tr>
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<td>Height (m)</td>
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<td>0.05</td>
<td>1.58-1.71</td>
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<td>Weight (kg)</td>
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<td>43.8-76.1</td>
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<td>BMI (kg/m²)</td>
<td>21.5</td>
<td>3.3</td>
<td>17.3-26.1</td>
</tr>
</tbody>
</table>

2.2.1.1 Inclusion / exclusion criteria

Subjects were included if they were: (1) 14-17 years of age; (2) had no injuries for six weeks prior to testing; (3) had no medical problems preventing them from participating in the study. They were excluded from the study if they reported any of the following: (1) a previous ACL injury or repair; (2) a back or lower limb injury that kept them from playing or training for greater than 30 days in the past year; (3) presently using a supplemental exercise based program; or (4) any medical or neurologic condition that would impair their ability to perform the tasks. Informed consent was provided for all subjects prior to testing (Appendix one). Ethical approval was granted by the University of British Columbia’s Clinical Research Ethics Board.

2.2.2 Experimental design

After obtaining written and informed consent, subjects were scheduled for a data collection session (Appendix two and three). All data collection occurred at the GF Strong Rehabilitation Research Laboratory, located in Vancouver, Canada. Upon arrival at the laboratory, subjects were asked to fill out an information sheet with their demographic details, injury history and limb dominance (Appendix four). Limb dominance was determined by asking the subject with which leg they would prefer to kick a ball. There is conflicting evidence in the literature regarding the effect of limb dominance on the risk of ACL injury (Brophy et al., 2010; Hewett et al., 2005a; Matava et al., 2002; Negrete et al., 2007). For consistency, the dominant leg was chosen as the test leg across subjects. Subjects wore tight-fitting Lycra shorts and their own running shoes.
For the purposes of the biomechanical analysis, height, weight, limb segment length and limb circumference were measured (Appendix four). Height was measured in centimeters (cm) and weight was measured in kilograms (kg) using a height rod and calibrated mechanical balance scale (Health-O-Meter, Continental Scale Corporation, Bridgeview, Ill., USA). The length and circumference of the leg and foot were measured in centimeters (cm) at points defined by Yeadon and Morlock (1989).

2.2.3 Testing protocol

Upon completion of set-up and measurement of anthropometric data, subjects were allowed three to five practice trials prior to performing nine consecutive test trials of each of the three performance tasks – SC, USC, and SH. The practice trials allowed an adaptation period to minimize variability due to learning effects. The number of practice and performance trials has been shown to be sufficient to capture true landing performance with minimal fatigue and variability influencing performance (Decker et al., 2004). To prevent fatigue, subjects adhered to a work / rest time ratio of at least 1:5. With each trial taking a maximum of two seconds to complete, subjects were given rest periods of ten seconds (minimum) between each trial. On average, the testing procedures took two hours to complete. Subjects were tested on two occasions, one week apart.

2.2.3.1 Performance tasks

Side-cut (SC)

To perform the SC, the subject started with her feet in a staggered stance position with the right foot 50cm in front of the left (Figure 2.1a). The toes of the left (take-off) foot were positioned 50 cm to the left and 83, 93 or 103 cm behind the centre of the landing force plate, depending on whether the subject’s height fell between 150-160 cm, 160-170 cm or 170-180 cm, respectively. These distances were selected to allow subjects of different heights to perform similar movements and to challenge them to get their COM initially over their right foot as it contacted the force plate and then to move their COM to their left foot as it kicked the ball.
A soccer ball was positioned at a distance 80% of the subject’s height away from the centre of the force plate and at an angle 55° counterclockwise to the plane of progression. This angle has been shown to be within the range of cutting angles occurring most frequently during game situations (McLean et al., 1999).

Standardized instructions were given to each subject as follows:

“On the command ‘go’, and as quickly as you can, you will step backwards with your right foot then stride forward so that your entire right foot lands on the force plate. You will then use your left foot to kick the ball into the net.” (Figure 2.1b)

As the subject stepped back with her right foot a laser beam was broken. The laser beam initiated the start of data collection for the trial.

Unanticipated Side-cut (USC)

For the USC task, the subject assumed the same starting position as during the SC trials (Figure 2.1a).

This time there were two soccer balls. The left-sided ball was positioned in the same position as during the SC trials. A second, right-sided ball was positioned 80 cm from the centre of the force plate and at an angle of 15° counterclockwise to the plane of progression.

Standardized instructions were given to each subject as follows:

“On the command ‘go’, and as quickly as you can, you will step backwards with your right foot then stride forward so that your entire right foot lands on the force plate. You will then use your left foot to kick the ball into the net. The arrow will tell you whether to kick the ball on the right or the left.” (Figure 2.1b)

When the subject stepped back with her right foot a laser beam was broken, triggering a direction arrow informing her whether to kick left or right. If the subject received a left arrow she had to perform a SC to kick the ball on the left, just as in the preceding SC trials. If she received
a right arrow she had to perform a cross-over cut (across her body) to kick the ball on the right (not shown in Figure 2.1a-c). Test trials were randomized to either direction, ensuring an unanticipated component to the task. The appearance of the arrow was timed to force the subject to react quickly. The arrow appeared on a monitor positioned at approximately chest height, 275 cm forwards of the centre of the force plate. Only the side-cutting (left arrow) and not the cross-over cutting (right arrow) kicks were used for analysis as the former are more commonly involved in ACL injury mechanisms (Boden et al., 2000).

**Side-hop (SH)**

To perform the SH, the subject started with her left foot on the outer edge of a line marked at a distance of 70% of the subject's height directly to the left of the centre of the force plate. The right foot was positioned slightly closer than hip-width apart from the left foot (Figure 2.1a). Standardized instructions were given to each subject as follows:

“On the command ‘go’ and as quickly as you can, you will hop onto your right foot, landing in the centre of the force plate. You will then hop back onto your left foot, landing in the starting position.” (Figure 2.1c)
**Figure 2.1 Diagram of experimental set-up and movement tasks tested:** The laser beam was broken as the subject stepped back with her right foot, triggering the start of timing for SC and USC and the direction arrow for USC. The subject then stepped forward with her right foot onto the force plate followed by a side-cut to kick the soccer ball (L) into a net on the left for SC and USC or used a cross cut to kick the soccer ball (R) into a net on the right for the USC (not analyzed or shown here). **SH Task:** Starting with both feet on the ground, the subject hopped onto the force plate, landing on the right foot, and then hopped back to the starting position, landing on the left foot.

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### a) Starting positions

![Diagram of Starting Positions](image)

### b) Side-cut

![Images of Side-cut](image)

### c) Side-hop

![Images of Side-hop](image)
2.2.4 Data collection

2.2.4.1 Kinematic data

An Optotrak® 3-D motion analysis system (Optotrak 3020, NDI, Waterloo, Canada) was used to track 12 markers (infrared emitting diodes - IREDs) attached to the subject’s lower extremity and pelvis as described by Jian et al. (1993) and Eng and Winter (1995) to generate a 3-D model of the lower body. Marker attachment sites were located over boney landmarks as much as possible to minimize the effects of marker movement and wands were used at the greater trochanter, distal quadriceps and dorsum of the foot (Appendix five). The other foot markers were placed directly on the shoes. All marker positions were measured and recorded and the same investigator positioned the markers for all subjects. Standardized joint coordinate systems for each segment were defined using digitized landmarks and three non-collinear markers were used to track each body segment during movement. Kinematic data were collected for four seconds with the subject standing with feet hip width apart in a static neutral position to define the zero position. Having the subject stand along standardized markings taped to the force plate optimized the subjects’ static neutral position relative to the lab. Alignment of the lower extremity was also visually inspected and, if required, adjustments were made as necessary to ensure a neutral position. Kinematic data were sampled at 120Hz.

2.2.4.2 Kinetic data

Ground reaction forces were collected using a force platform (Bertec, Columbus, Ohio) embedded in the ground along the plane of progression. Force plate data were sampled at 600 Hz. The force plate was synchronized with the Optotrak system.

2.2.5 Data analysis

2.2.5.1 Kinematic data

Three-dimensional motion data were processed and filtered using custom algorithms (Matlab, Version 14, The Mathworks, Inc., Natick MA). Missing markers were recovered using a B-spline fitting method (semi-automatic generalized cross-variance 5th order spline, 10Hz low
pass filter) (Woltring, 1986). Data were filtered using a Butterworth filter (4th-order, zero-lag, low pass cut-off at 10Hz). Knee angles were defined using the Cardan sequence (extension / adduction / internal rotation) and describe the motion of the distal segment relative to the proximal segment (Grood and Suntay, 1983). Knee extension, adduction, and internal rotation angles were defined as positive values and were equal to zero in each subject when the long axes of the femur and tibia were aligned during the neutral position.

Trials were excluded during testing if the subject’s whole foot did not land on the force plate or if she did not perform the task correctly (e.g. hesitating to receive the directional cue before kicking). Additional trials were excluded during Matlab processing if markers were missing at the start or end of the stance phase. Trials were also excluded if there was more than 10mm of motion between the markers on each limb segment because this marker motion can significantly increase error. The kinematics of all remaining trials were time normalized to 100% of the stance phase. Through visual inspection, trials were excluded if they did not follow the same pattern of kinematic motion as the majority. If there were more than seven acceptable trials for a subject during analysis, the first seven were chosen.

Four different kinematic variables at the knee were analyzed during stance phase – peak flexion angle, change in flexion angle, peak abduction angle, and change in abduction angle. The peak flexion and abduction angles were taken as the maximum absolute degree of angle reached during stance phase. Change in knee flexion and abduction angles were determined by the absolute difference between the angle at initial contact and the maximum angle during stance. These kinematic variables were chosen because they represent a relative (change angle) and an absolute (peak angle) measure of the two most relevant kinematic risk factors contributing to the gender difference in ACL injury incidence.

### 2.2.5.2 Kinetic data

A 3-D inverse dynamics solution was used to estimate the forces and moments at the joints starting at the most distal joint (Bresler and Frankel, 1950; Winter, 2004; Yeadon and
Morlock, 1989). Force plate data enabled delineation of kinematic analysis to the stance phase. The stance phase, defined as the period from foot contact to toe-off, was manually selected (via Matlab) from a graph of the vertical ground reaction force (VGRF) plotted against time. The start of the stance phase was demarcated as the first data point rising above baseline and the end of stance as the last data point before the VGRF returned to baseline.

Knee abduction moments were included in our kinetic analysis and were defined as external moments at the knee (i.e. forces producing an abduction or resisting an adduction angle at the knee). Peak abduction moment was analyzed during the first 20% of stance phase because most non-contact ACL injuries occur during this phase (Boden et al., 2000). Although some studies have suggested that transverse motions may be related to ACL injuries (Boden et al., 2000; Markolf et al., 1995), we did not include variables in this plane because we could not identify a consistent pattern or peak to extract and analyze across subjects in this plane.

2.2.6 Statistical analysis

Statistical analyses were done using PASW Statistics 18 (SPSS Inc., Chicago IL). Descriptive statistics for sample characteristics were expressed using mean ± standard deviation as well as the range of values.

Test-retest reliability and agreement were evaluated for mean values of five variables at the knee – peak flexion angle, change in flexion angle, peak abduction angle, change in abduction angle (all over the entire stance phase), and peak abduction moment during the first 20% of stance phase. Consensus in the literature suggests that no single reliability measure provides a complete picture of reliability or reproducibility and that a combination of measures is a more accurate approach (Atkinson and Nevill, 1998; Rankin and Stokes, 1998). Therefore, Intraclass correlation coefficients (ICC) (model 3,k), standard errors of measurement (SEM), and Bland and Altman methods of agreement were calculated for each variable in this study.
The ICC provided an indication of relative reliability of the measures as it represents the ratio of the true variance to the total variance and is a unit less value (Streiner and Norman, 2003). The ICC$_{3,k}$ was calculated using a repeated measures analysis of variance (ANOVA) design. The first integer in this model (3) indicates that a two-way mixed model is used. The second integer (k) indicates that reliability analysis was performed using mean (rather than individual trial) values from motion analysis (Shrout and Fleiss, 1979). ICC values were interpreted as; excellent (0.75-1.0), modest (0.4-0.74), or poor (0-0.39) (Shrout and Fleiss, 1979). The 95% confidence intervals (CI) for ICC values were also calculated.

The ICC does not tell us how much agreement exists between measurements so the SEM and the Bland and Altman methods of agreement were also calculated. The SEM is an estimate of measurement error that, unlike the ICC, is expressed in the same units as the measurements of interest and is not influenced by the between-subjects variability (Domholdt, 1993; Stratford and Goldsmith, 1997). SEM is equal to the square root of the error variance (i.e. mean square error term from an ANOVA) and lower numbers indicate less error (de Vet et al., 2006; Stratford and Goldsmith, 1997). SEMs were also calculated and expressed as percentages of the mean angles and moments (SEM / mean angle x 100%) to allow comparisons across variables.

Bland and Altman methods of agreement estimate the agreement between values and are particularly useful for clinical measures (Bland and Altman, 1986; Rankin and Stokes, 1998). The scatterplots of the data allow for visual inspection and easy identification of outliers, patterns of bias, and spread or range of the difference scores. The differences between each subject’s time one and time two means were plotted against the average of the two means. The mean of the differences and the 95% limits of agreement (2 x standard deviation of differences) were also calculated (Bland and Altman, 1986). ICC, SEM, and Bland and Altman formulae appear in Appendix six.
2.3 Results

2.3.1 Subject characteristics

All ten subjects completed both test sessions. Patient characteristics are summarized in Table 2.1. The time between sessions was 6.6 ± 3.9 days (mean ± SD). All ten subjects selected the right leg as their dominant leg. Therefore, biomechanical and statistical analyses were performed on the right lower limb only. Knee joint angles and moments (mean ± SD) for the SC, USC, and SH tasks are presented in Table 2.2. A comparison of test 1 and test 2 measures of each variable across the three tasks for two sample subjects are shown in Figure 2.2. The average speeds for the group in completing the three tasks were not significantly different between testing sessions (Table 2.2). After removing outliers, trials with missing or excessively moving markers, or bad trials (e.g. missed force plate), we used an average of 7.0 SC trials, 6.8 USC trials, and 7.5 SH trials from the original nine trials captured for each subject. This represented 79% of all collected data.

2.3.2 Kinematics

ICCs and SEMs for the four motion analysis variables of interest are shown in Table 2.3. Bland and Altman plots are shown in Figure 2.3a-o.

2.3.2.1 Peak knee flexion angle

Peak knee flexion angle demonstrated excellent reliability across all three tasks (ICC range = 0.88-0.95). This variable also demonstrated agreement across all three tasks with low SEMs (SEM range = 1.0°-1.9°, SEM ratio = 1.6-3.2%). There was good agreement and no systematic bias evident from observing the Bland and Altman plots; data points were equally distributed above and below the mean difference line (Figure 2.3a,f,k). All the data points fell within the limits of agreement with no outliers and a slight bias for the USC task (+1.4°). The limits of agreement were narrower for the SH as compared to the SC and USC tasks.
2.3.2.2 Change in knee flexion angle

Excellent reliability was found for the change in knee flexion angles for the SC (ICC = 0.89) and USC (ICC = 0.84), with modest ICC values for the SH task (ICC = 0.69). Agreement was also demonstrated with low SEMs across all three tasks (SEM range = 1.9°-2.5°, SEM ratio = 4.2-6.1%). Again there was good agreement with no bias observed during the SC and SH tasks and a negative bias (-1.8°) for the USC data point distribution (Figures 2.3b-l). One data point fell outside the limits of agreement during the USC task but all others were distributed around zero.

2.3.2.3 Peak knee abduction angle

Peak knee abduction angle showed the worst reliability and agreement across all three tasks. ICC values were poor for SC (ICC = 0.30) and SH (ICC = 0.09) and modest for USC tasks (ICC = 0.65). SEM values ranged from 3.3° to 5.0° and percentages ranged from 32-68% as a result of the high variability of this measure. There were wide limits of agreement for all three tasks and a positive bias (+1.5°) for the SH task (Figures 2.3c-m). The data point for subject 3 was an outlier in all three tasks.

2.3.2.4 Change in knee abduction angle

Excellent reliability was found for the change in knee abduction angles during the USC (ICC = 0.90) and SH tasks (ICC = 0.77) and modest reliability for the SC task (ICC = 0.72). SEM values were similar between tasks (SEM range = 1.0°-1.6°). This corresponded to SEM percentages (9.9% to 18.4%) that were higher than the two knee flexion variables but lower than those for peak knee abduction angle. The Bland and Altman plots (Figures 2.3d-n) showed a slight positive bias for SC (+1.1°) and a slight negative bias for SH (-0.9°). One data point fell outside the limits of agreement during the SC and the USC tasks.
2.3.3 Kinetics

2.3.3.1 Peak knee abduction moment

Reliability was excellent for peak knee abduction moment during the first 20% of stance phase for SC (ICC = 0.84) and SH (ICC = 0.84) and modest for USC (ICC = 0.62). SEM values were higher for USC (0.23 N·m/kg), and SH (0.17 N·m/kg) as compared to SC (0.10 N·m/kg/kg). SEM as a ratio was similar across trials (USC (13.2%), SH (10.9%), and SC (10.3%). Peak abduction moments showed good agreement between measures with no outliers but a negative bias for SC (-0.19 N·m/kg) and USC (-0.16 N·m/kg) and a positive bias for SH tasks (+0.12 N·m/kg) (Figures 2.3e-o). The limits of agreement were wider for the SH as compared to the SC and the USC tasks.
### Table 2.2 Knee joint angles and moments for side-cut, unanticipated side-cut, and side-hop tasks (mean ± standard deviation)

<table>
<thead>
<tr>
<th>Speed (m/s)</th>
<th>Peak Flexion Angle (°)</th>
<th>Change in Flexion Angle (°)</th>
<th>Peak Abduction Angle (°)</th>
<th>Change in Abduction Angle (°)</th>
<th>Peak Abduction Moment (N·m/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Side-cut</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Test</td>
<td>2.69 ± 0.15</td>
<td>59.0 ± 6.4</td>
<td>39.1 ± 5.8</td>
<td>12.8 ± 5.5</td>
<td>10.3 ± 3.5</td>
</tr>
<tr>
<td>Retest</td>
<td>2.77 ± 0.21</td>
<td>59.5 ± 4.8</td>
<td>39.2 ± 5.9</td>
<td>13.2 ± 6.4</td>
<td>9.2 ± 2.5</td>
</tr>
<tr>
<td>Unanticipated side-cut</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Test</td>
<td>2.33 ± 0.32</td>
<td>60.9 ± 5.8</td>
<td>40.2 ± 6.1</td>
<td>13.8 ± 5.4</td>
<td>9.9 ± 3.7</td>
</tr>
<tr>
<td>Retest</td>
<td>2.66 ± 0.26</td>
<td>62.3 ± 5.2</td>
<td>42.0 ± 6.4</td>
<td>14.2 ± 5.7</td>
<td>9.8 ± 2.6</td>
</tr>
<tr>
<td>Side-hop</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Test</td>
<td>2.51 ± 0.32</td>
<td>62.3 ± 4.2</td>
<td>47.8 ± 3.2</td>
<td>10.7 ± 4.8</td>
<td>7.2 ± 3.1</td>
</tr>
<tr>
<td>Retest</td>
<td>2.65 ± 0.21</td>
<td>63.0 ± 4.8</td>
<td>47.7 ± 3.9</td>
<td>12.2 ± 5.4</td>
<td>8.1 ± 2.8</td>
</tr>
</tbody>
</table>
Table 2.3 Reliability and agreement of mean knee flexion and abduction angles and mean knee abduction moment for the side-cut, unanticipated side-cut, and side-hop tasks (mean (CI))

<table>
<thead>
<tr>
<th>Task</th>
<th>Peak Flexion Angle (°)</th>
<th>Change in Flexion Angle (°)</th>
<th>Peak Abduction Angle (°)</th>
<th>Change in Abduction Angle (°)</th>
<th>Peak Abduction Moment (N·m/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Side-cut</strong></td>
<td>0.88 (.52-.97)</td>
<td>0.89 (.53-.97)</td>
<td>0.30 (2.67-.84)</td>
<td>0.72 (.31-.93)</td>
<td>0.84 (.35-.96)</td>
</tr>
<tr>
<td><strong>Unanticipated side-cut</strong></td>
<td>0.89 (.59-.97)</td>
<td>.84 (.40-.96)</td>
<td>0.65 (.56-.92)</td>
<td>0.9 (.58-.98)</td>
<td>0.62 (.52-.91)</td>
</tr>
<tr>
<td><strong>Side-hop</strong></td>
<td>0.95 (.79-.99)</td>
<td>0.69 (.37-.93)</td>
<td>0.09 (-3.30-.78)</td>
<td>0.77 (.16-.94)</td>
<td>0.84 (.35-.96)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Task</th>
<th>SEM</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Side-cut</strong></td>
<td>1.9 (-1.9-5.7)</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>1.9 (-1.9-5.7)</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>5.0 (-4.8-14.7)</td>
<td>38</td>
</tr>
<tr>
<td></td>
<td>1.6 (-1.5-4.7)</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>0.1 (-0.1-.3)</td>
<td>10</td>
</tr>
<tr>
<td><strong>Unanticipated side-cut</strong></td>
<td>1.8 (-1.8-5.4)</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>2.50 (-2.4-7.4)</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>3.28 (-3.2-9.7)</td>
<td>23</td>
</tr>
<tr>
<td></td>
<td>0.98 (-0.9-2.9)</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>0.23 (-0.1-0.4)</td>
<td>13</td>
</tr>
<tr>
<td><strong>Side-hop</strong></td>
<td>1.0 (-1.0-3.0)</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>2.0 (-1.9-5.9)</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>4.9 (-4.7-14.4)</td>
<td>42</td>
</tr>
<tr>
<td></td>
<td>1.4 (-1.4-4.2)</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>0.17 (-0.2-0.5)</td>
<td>11</td>
</tr>
</tbody>
</table>

**Percentage**: SEM expressed as a percentage of mean value attained for that variable and task (see Table 2.2)

**ICC**: intraclass coefficient

**CI**: 95% confidence intervals

**SEM**: standard error of measurement
Figure 2.2 Comparison of flexion and abduction angles and abduction moments of initial test and retest for a representative subject during the side-cut, unanticipated side-cut, and side-hop tasks. Solid line (—) denotes initial test, dotted line (—) denotes retest. Flexion and abduction angles are greater in the negative direction and abduction moments are greater in the positive direction.
Figure 2.3 Bland and Altman plots of agreement for flexion and abduction angles and abduction moments for the side-cut (a-e), unanticipated side-cut (f-j), and side-hop (k-o) tasks. Plots represent the difference between each subject’s (n = 10) time one and time two means vs. the average of the two means. The mean of the differences ( —— ) and the 95% limits of agreement (———) are also shown.
2.4 Discussion

The purpose of this study was to evaluate the test-retest reliability and agreement of ten female youth soccer players for knee flexion and abduction angles, and knee abduction moments during a SC and an USC before kicking a soccer ball and a SH task. These measures were chosen because they are of interest as potential risk factors for ACL injury. Intraclass correlation coefficients (ICC) (model 3,k) were calculated to estimate reliability and standard errors of measurement (SEM) and Bland and Altman methods of agreement were used to calculate agreement between two sessions, one week apart. To our knowledge, this is the first study to establish that key biomechanical variables that are of interest as potential ACL risk factors demonstrate reliability and agreement between testing sessions for complex, soccer-specific tasks.

Subject characteristics were similar for age, height and weight to other studies reporting reliability findings of ACL risk factors (Ford et al., 2003, 2007; Hewett et al., 2004; Sigward and Powers, 2006). Knee joint flexion and abduction angles for the SC and USC tasks were similar in our study to those reported in previous studies looking at side-cut tasks (Ford et al., 2005; McLean et al., 2004b; Sigward and Powers, 2006). The peak abduction moments observed in our study for SC and USC tasks (range = 0.86-1.17 N·m/kg) were higher than those reported by Sigward and Powers (2006) (range = 0.4-0.9 N·m/kg), McLean et al. (2005a) (0.63 N·m/kg·m) and Besier et al. (2001b) (0.53 N·m/kg) in trials with a running approach to a side-cutting task.

The ICC is considered an appropriate index to discriminate or differentiate between subjects (de Vet et al., 2006). The modest to excellent ICC values for all but the peak abduction angle variable during the SC and SH tasks in this study indicate that these biomechanical variables are valuable in discriminating between subjects performing these tasks. The SEM is only concerned with the amount of measurement error and does not take into account the variance between subjects. SEM values were low across the three tasks for all variables but the peak abduction angle, indicating that adequate agreement was attained. This result is important.
when we consider these variables in studies investigating the efficacy or effectiveness of certain interventions aimed at improving ACL risk factors. The lower the measurement error, the easier it may be to detect improvements (or deteriorations) in performance on different tasks because the change will be detected beyond that of measurement error (de Vet et al., 2006).

Our study demonstrated better reproducibility of sagittal plane movements compared to coronal and transverse planes. These findings are consistent with previous reliability studies investigating kinematic and kinetic variables during running and gait (Besier et al., 2003; Ferber et al., 2002; Kadaba et al., 1989) and side-cutting tasks (Ford et al. 2007; Sigward and Powers, 2006). Our ICC values were higher for peak knee flexion angles across all three tasks (range = 0.88-0.95) and lower for peak abduction angles (range = 0.09-0.65). The large intersubject variability of transverse plane data in our study precluded the extraction of variables in this plane. Others have chosen to exclude rotational measures because of concerns regarding measurement error (Landry et al., 2007; McLean et al., 2004b). This variability in frontal and transverse plane measurements has been attributed to various factors, including marker reapplication and skin motion errors, and kinematic cross talk (Piazza and Cavanagh 2000; Ramakrishnan and Kadaba, 1991; Reinschmidt et al., 1997).

The difficulty in consistently re-applying and aligning markers between testing sessions has been identified in previous studies (Ferber et al., 2002; Kadaba et al., 1989). We attempted to minimize this error by having a single investigator take careful measurements and notes during application and reapplication of the markers, as well as standardizing our static reference alignment. These strategies have been successful in minimizing measurement errors in previous studies (Besier et al., 2001b; Ford et al., 2007). Marker motion due to skin, muscle bulk, or wand movement can be accentuated in dynamic tasks such as the ones performed in our study. In a study of running kinematics by Reinschmidt et al. (1997), there were differences in knee abduction angles of up to 11.1°, depending on whether intra-cortical or surface markers were used suggesting that the use of surface markers was potentially a significant source of
error. In an attempt to lessen the influence of marker motion in our study we excluded trials with excessive marker motion (>10mm). Kinematic cross talk is an error that affects frontal and transverse plane angle calculations as a result of an incorrectly defined flexion-extension axis (Piazza and Cavanagh, 2000; Ramakrishnan and Kadaba, 1991). Sagittal plane movements are relatively unaffected by this misplaced axis.

Previous studies have demonstrated that relative variables, such as changes in joint angles or joint angle excursions, are more reliable than absolute or peak angle measurements (Ferber et al., 2002; Kadaba et al., 1989). For the most part, reliability was similar between peak flexion and change in flexion angles in our study. However, the changes in abduction angles were more reproducible than our absolute measures of abduction angles across all three tasks. The relative measure for abduction angle seems to have minimized the limitations of the absolute peak abduction angle as a reliable measure in the frontal plane, suggesting that it may be a better measure to include in future studies. Webster et al. (2010) also identified a constant offset that resulted in joint excursion values for tibial rotation (ICC = 0.76) being more reliable than peak tibial rotation angles (ICC = 0.68) during a pivoting task.

A novel aspect to our study was kicking a soccer ball as part of the SC and USC tasks. We anticipated the SC and USC tasks would be less reliable than the SH task because the reliability of a test can decrease as the complexity of the task increases (Young et al., 1997). In fact, the USC, which was our most complex task, had the highest ICCs and narrowest limits of agreement across most of our measures. Yu et al. (1997) attributed the majority of biomechanical variance within their study to variations in motor performance during a stair-climbing task. Webster et al. (2010) explained that the greater variance in tibial rotation for their pivot and turn task as compared to the drop jump task described by Ford et al. (2007) was because the drop jump is performed primarily in one plane of movement. We attempted to control for this intra-subject variability in motor performance with detailed instructions, standardized foot and ball placements, and adequate practice trials. The SC, USC, and SH
tasks could all be considered for future investigations measuring the same kinematic and kinetic variables that we included in our study, except for the peak abduction angle.

The relationship between ACL strain and 3D biomechanics at the knee remains unclear. The many in vitro, in vivo, modeling and computer simulation studies have provided us with a clearer understanding of the types of positions and forces that place the ACL at risk for injury. These biomechanical variables have been included in our study. However, we do not know how much or what combination of these joint angles and forces in non-injurious tasks, such as ours, should be of concern. Consensus within the literature is that interventions aimed at reducing valgus angles and moments (or abduction angles and moments, as in our study) potentially hold the most promise in reducing loads on the ACL (Besier et al., 2001b; Hewett et al., 2005a; McLean et al., 2003). Hewett et al. (2005a) prospectively predicted female athletes that went on to an ACL injury as compared to those that did not by their increased valgus angles (+7.6°) and valgus moments (+26.6 N·m) during a drop jump task. Unfortunately, there have not been any similar prospective studies investigating side-cut or side-hop tasks, such as those included in our study, to assist us in estimating clinically important values for these variables. Given our measurement error in peak abduction moments during the SC task (SEM = 0.1 N·m/kg), we would be able to detect changes in this important variable arising from training programs reported recently by Cochrane et al. (2010) (0.15 N·m/kg) and Dempsey et al. (2009) (0.14 N·m/kg). We did not find peak knee abduction angles to be reliable across tasks. McLean et al. (2004b) demonstrated that a 2° change in peak knee abduction angle resulted in a 40 N·m change in valgus moment at the knee. With SEMs between 3° and 5°, we would not be able to pick up such small but potentially important changes in knee abduction as described by McLean and colleagues (2004a).
2.4.1 Limitations

A limitation of our study was the small sample size. However, it was a homogeneous sample that was representative of the age and characteristics of the population at risk for non-contact ACL injuries. Future studies should include athletes performing multidirectional, sport-specific tasks from other high-risk sports such as basketball and handball.

2.5 Conclusion

The results of our study demonstrate that despite the many sources of error inherent in this type of biomechanical study, key variables relevant to ACL injury risk can be measured reliably and demonstrate agreement across days during complex, sport-specific tasks. The degree of reliability and agreement depends on the task and the outcome measure analyzed. Specifically, reliability estimates demonstrate that peak flexion angle, change in flexion angle, and change in abduction angle across stance and peak abduction moment during the first 20% of stance are all appropriate measures for distinguishing among subjects, for example, in studies of various interventions intended to decrease ACL risk factors. Of clinical importance, estimates of agreement suggest that these same four variables are suitable measures to distinguish between true changes that are a result of an intervention program and those that are a result of measurement error.
Bridging Statement I

To detect change in biomechanical variables, outcome measures must demonstrate adequate reliability and agreement. Reliability estimates from the previous study indicate that biomechanical risk factors for ACL injury - peak flexion angle, change in flexion angle, and change in abduction angle across stance and peak abduction moment during the first 20% of stance - are appropriate measures for differentiating between subjects in future intervention studies. Estimates of agreement suggest that these measures are acceptable for distinguishing between true changes that are a result of an intervention program and those that are a result of measurement error. These results are consistent with other studies that have reported test-retest reliability of 3D biomechanical variables during side-cutting tasks (Besier et al., 2001a; Sigward and Powers, 2006). However, it was important to establish reproducibility of these biomechanical variables during the SC and USC tasks prior to kicking a soccer ball and the SH task because these tasks had not been included in previous studies. In selecting outcome measures for our subsequent intervention studies we considered the reproducibility and clinical relevancy of the variables measured. Peak flexion angles provided the most reproducible kinematic variable across tasks and peak abduction moments provided a reproducible kinetic variable in the frontal plane. These two variables have consistently been recognized in the literature as important risk factors for ACL injury (Hewett et al., 2005a; Markolf et al., 1995). Therefore, we have chosen to investigate the effects of a novel movement strategy on peak flexion angles and peak abduction moments at the knee during SC, USC, and SH tasks.
3 The Effect of a Novel Movement Strategy in Decreasing ACL Risk Factors in Female Adolescent Soccer Players

3.1 Introduction

Anterior Cruciate Ligament (ACL) injury remains a common and costly challenge for the sports medicine and science community. Every year approximately 250,000 ACL injuries occur at a cost of over 2 billion dollars in the United States (Silvers and Mandelbaum, 2007). More importantly, ACL injuries often result in short and long term disability (Hartwick et al., 2003; Lohmander et al., 2007), decreased quality of life (Hartwick et al., 2003), and an increased risk of osteoarthritis (Lohmander et al., 2007; Meunier et al., 2007; Roos, 2005). Female athletes are 4-6 times more likely to suffer an ACL injury while playing multidirectional sports such as soccer and basketball as compared to male athletes (Arendt and Dick, 1995; Griffin et al., 2000).

ACL injuries often occur without any direct contact from an opponent during quick decelerations, side-cutting to change direction, or landing from a jump (Boden et al., 2000; Krosshaug et al., 2007a; McNair et al., 1990; Olsen et al., 2004). In vitro (Markolf et al., 1995; Renstrom et al., 1986) and in vivo (Beynnon et al., 1997; Cerulli, et al., 2003; Fleming et al., 2001) experiments have demonstrated that the ACL is under increased load and is at greatest risk of injury when the knee is in less than 30-45 degrees of flexion and experiences a valgus or external abduction force with either internal or external rotation (Berns et al., 1992; Fung and Zhang, 2003). ACL injuries often occur during a side-cutting movement on the field of play; the pattern typically includes the knee of the stance leg close to extension with a valgus angle, an abducted hip with the foot planted in front and lateral to the center of mass (COM), and a trunk that is side-flexed and rotated towards the plant leg (Boden et al., 2000; Cochrane et al., 2007; Hewett et al., 2009; Ireland et al., 2003; Olsen et al., 2004; Teitz et al., 2001). Video analyses of ACL injuries have confirmed that these injuries often occur shortly after planting the foot (within approximately 30-40 milliseconds (ms) of the foot contacting the
ground) with an extended knee and a valgus load (Koga et al., 2010; Krosshaug et al.,
2007a). There is often a perturbation or an unexpected reaction to a game situation at the
time of injury (Boden et al., 2000; Cochrane et al., 2007; Krosshaug et al., 2007a; Olsen et al.,
2004). The athlete is often observed to be off-balance and to have landed awkwardly with high
ground reaction forces that are not dissipated effectively through hip, knee, and ankle flexion
(Ford et al., 2005; Olsen et al., 2004; Renstrom et al., 2008).

Laboratory-based investigations have simulated dynamic athletic movements in an
attempt to replicate the biomechanical conditions observed at the time of ACL injuries on the
field of play. Increased valgus and internal rotation moments occur at the knee during side-
cutting compared to straight-ahead running or cross-over cutting movements (Besier et al.,
2001b). Besier et al. (2001b) found that these moments were greatest during the weight
acceptance or early deceleration phase of a side-cutting movement, which may indicate an
increased risk for ACL injury during this period of movement. Female athletes often demonstrate
increased abduction moments (Chappell et al., 2002; McLean et al., 2005a,b; Pollard et al.,
2007; Sigward and Powers, 2006) and decreased flexion angles (Fedie et al., 2010; Malinzak et
al., 2001; McLean et al., 2004b, 2005b) at the knee compared to male athletes during side-
cutting movements. The addition of more “game-like” conditions to side-cutting tasks such as
reacting to a direction cue (Besier et al., 2001a; Sell et al., 2006) or a defensive opponent
(McLean et al., 2004b), holding a lacrosse stick or football (Chaudhari et al., 2005), and
attending to a pass in basketball (Fedie et al., 2010) may increase biomechanical risk factors in
the laboratory setting.

The association of certain biomechanical characteristics with ACL injury risk, both on
the field and in the laboratory, provides a strong rationale for modifying these risk factors
within ACL injury prevention programs. Important components of successful ACL injury
prevention programs are thought to include strength, awareness of high-risk positions,
technique, core and trunk control, aerobic endurance, agility, balance, and plyometrics
(Alentorn-Geli et al., 2009; Renstrom et al., 2008). However, we do not know which of these components are most effective at modifying movement patterns that are thought to contribute to ACL injury. In order to develop and implement more efficient and effective injury prevention programs, the identification of the components or exercises that are most effective at reducing biomechanical and neuromuscular risk factors is necessary.

Multimodal training programs have demonstrated improvements in kinematic and kinetic variables during high-risk athletic movements in several laboratory-based experiments (Chappell and Limpisvasti, 2008; Hewett et al., 1996; Lephart et al., 2005; Lim et al., 2009; Myer et al., 2006). Investigations have started to isolate strength (Cochrane et al., 2010; Herman et al., 2008; Lephart et al., 2005), balance (Cochrane et al., 2010; Myer et al., 2006), fatigue (Chappell et al., 2005; McLean et al., 2007), and plyometrics (Lephart et al., 2005; Myer et al., 2006) to better understand the independent effects on kinematic and kinetic variables. However, four studies have looked at the specific effects that technique modification (i.e. modification of high-risk movement patterns) may have on kinematic and kinetic variables during high-risk athletic tasks (Cowling et al., 2003; Dempsey et al., 2009; Mizner et al., 2008; Onate et al., 2005) and only one study has looked at the effects of technique modification on side-cutting movements (Dempsey et al., 2009).

Dempsey et al. (2009) investigated the effects of a six-week training program aimed at modifying whole body side-cutting technique in twelve male team sport athletes. Technique modifications included: bringing the foot closer to the midline of the body (i.e. less hip abduction), ensuring the foot was not internally or externally rotated, and maintaining the trunk in an upright, forward facing position. After completing the training program, subjects demonstrated a narrower stance and a more upright trunk (in the coronal plane) on initial foot contact. Importantly, both of these positional modifications were associated with a 36% decrease in valgus moments during the weight acceptance phase of stance. This study
demonstrated the potential effectiveness of technique modification on biomechanical risk factors.

The results of Dempsey et al. (2009) are important and provide a basis and a rationale to explore other means of technique modification. We propose a novel movement strategy to reduce biomechanical risk with a method that requires the athlete to move their COM closer to the plant foot with increased trunk control rather than requiring the athlete to attend to and change multiple joint and body segment positions. This movement strategy is referred to as Core Position and Control (Core-PAC) and was originally developed as a clinical technique to treat recalcitrant groin and abdominal injuries but shows promise for athletic movement technique modification. It includes a proximal to distal movement sequence, which has been described by several authors relative to enhancing force and speed production (Kibler et al., 2006; Putnam, 1993) and precision and control (Hirashima et al., 2002; Kibler et al., 2006) of the distal segments of the extremities. The Core-PAC is introduced here as a sequence of neuromuscular recruitment and segmental movements that begin proximally, or at the trunk / pelvis, followed by muscle recruitment and movement in the periphery (Hodges and Richardson, 1997a; Kibler et al., 2006; Putnam, 1993). The practical application involves the athlete moving their pelvic centre (focus is often on the navel) in the intended direction of movement such that the COM is positioned as close to the planted foot as possible with increased trunk control. The Core-PAC results in a similar whole body orientation as described by Dempsey et al. (2009), but with a single focus of attention for the athlete that does not involve individual coordination of the upper and lower extremity joints and segments (Figure 1.9a-c).

The underlying rationale for using the Core-PAC is that it is a simple method of getting the COM closer to the plant foot with improved trunk control. Based on the literature, getting the COM closer to the base of support may bias joint loading to the sagittal rather than the frontal and transverse planes (Hewett et al., 2002; Pollard et al., 2010). This improved sagittal
plane alignment (ankle, knee, and hip in line) may allow the muscles rather than the ligaments to absorb kinetic energy throughout the lower extremity and may result in increased hip, knee and ankle flexion angles (Hewett et al., 2002; Pollard et al., 2010). Improving an athlete’s ability to position their COM over their base of support with increased trunk control may allow them to better respond to unexpected perturbations and to decrease their risk of injury.

The purpose of this study was 1) to determine the feasibility of implementing the Core-PAC into a team warm-up prior to regular soccer training based on subject compliance and integration of the Core-PAC into the warm-up and 2) to determine whether the Core-PAC would improve peak knee flexion angles and peak abduction moments at the knee during three dynamic tasks after immediate instruction and after a four-week training program. The three tasks were a side-cut (SC) and an unanticipated side-cut (USC) prior to kicking a soccer ball, and a side-hop (SH) task. It was hypothesized that the feasibility of Core-PAC implementation would be demonstrated by adequate subject compliance and effective implementation of the Core-PAC within a regular soccer team warm-up. It was also hypothesized that the Core-PAC would result in decreased peak abduction moments and increased peak flexion angles at the knee after all three tasks following immediate instruction and after a four-week training program.

3.2 Methods
General methods were the same as Study 1 (Chapter 2, pages 49-57) and therefore, we will highlight the differences from Study 1 and provide a summary of methods used in this chapter.

3.2.1 Subjects
The same cohort of female youth soccer players described in Study 1 (Chapter 2, page 49-50) participated in the present study (Table 3.1). Subject inclusion and exclusion criteria were unchanged. Informed consent was provided for all subjects prior to testing (Appendix one).
Ethical approval was granted by the University of British Columbia's Clinical Research Ethics Board.

Table 3.1 Subject characteristics for study 2 (n = 10)

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Mean</th>
<th>SD</th>
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</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>15.1</td>
<td>1.3</td>
<td>14-17</td>
</tr>
<tr>
<td>Height (m)</td>
<td>1.64</td>
<td>0.05</td>
<td>1.58-1.71</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>58.3</td>
<td>11.4</td>
<td>43.8-76.1</td>
</tr>
<tr>
<td>BMI (kg/m(^2))</td>
<td>21.5</td>
<td>3.3</td>
<td>17.3-26.1</td>
</tr>
</tbody>
</table>

3.2.2 Experimental design

Upon completion of set-up and measurement of anthropometric data (Table 3.1), subjects were allowed three to five practice trials prior to performing nine consecutive test trials of each of the three performance tasks (SC, USC, and SH) using their own strategy. After completing the three tasks with their own strategy, subjects were then instructed on how to perform the same tasks using the Core-PAC and tested again. The subjects were retested a final time after the four-week training program.

3.2.2.1 Performance tasks

Side-cut (SC): Standardized instructions were given to each subject to step backwards with her right foot and then stride forward so that her entire right foot landed on the force plate before kicking the ball into the net with her left foot (Figure 2.1b). Refer to Chapter 2, page 51 for details on the side-cut task set-up and descriptions.

Unanticipated Side-cut (USC): Standardized instructions were given to each subject as per the SC trials except that now the direction arrows would indicate whether to kick the ball on the left or the right with the right foot (Figure 2.1b). Refer to Chapter 2, page 52 for details on the unanticipated side-cut task set-up and descriptions.
Side-hop (SH): Standardized instructions were given to each subject to hop onto the force plate, landing on the right foot, and then hop back to the starting position, landing on the left foot (Figure 2.1c). Refer to Chapter 2, page 53 for details on the side-hop task set-up and descriptions.

3.2.2.2 Core-PAC instruction

Instructions such as “keep your knees over your toes”, “bend your knees”, and “bring the stance foot toward the midline of the body” that focus the attention of the athlete on their limbs have been shown to be less effective in learning a complex skill than a focus on a single end point outside of the body (Wulf et al., 2010). A styrofoam ball was used as a training tool to provide this single end point. Directing an athlete’s attention away from her lower extremity and trunk to the movement of a styrofoam ball located just above her pelvis results in a focus to an end point external to the resultant lower extremity coordination. Although most of the motor control literature describes the effectiveness of this external focus relative to an object such as a golf club or baseball bat (Wulf et al., 2010), a focus on the styrofoam ball serves a similar function. After completing the three tasks with their own strategy, a styrofoam ball was placed just above the center of the subject’s pelvis (pubic symphysis) using an elastic belt.

The subject was first instructed to draw the ball in toward the lumbar spine using a "kegel-type" recruitment pattern of the pelvic floor and transversus abdominus muscles and to maintain this recruitment throughout the movement (Richardson and Jull, 1995; Sapsford et al., 2001; Urquhart et al., 2005). They were then instructed to push off the left leg and lead with the styrofoam ball so that the ball would end up over the force plate prior to moving the styrofoam ball in the direction of the kicking movement. This was in contrast to a reaching type movement wherein the right leg would lead the movement resulting in the right foot contacting the force plate in front and lateral to the COM. Visual and verbal cues were used to explain and demonstrate the Core-PAC and correct the subject’s movements until they consistently demonstrated the new technique. The subjects would then practice the technique for as many
times as they needed to feel comfortable and were observed to maintain the new pattern. The total time for instruction and practice varied between 6 to 10 minutes per subject. The three tasks were then repeated as above with the only difference being that the subjects attempted to complete the tasks using the Core-PAC. The subjects were reminded once every four trials to maintain the new strategy. To prevent fatigue, subjects adhered to a work / rest time ratio of at least 1:5 (Jacobs and Mattacola, 2005). On average, the testing procedures took two hours to complete.

3.2.2.3 Training

Subjects were led by a physiotherapist (RGC) through a 20-minute warm-up two times per week for four-weeks, replacing their regular warm-up prior to soccer practice (Table 3.2). They were instructed to repeat the same warm-up another two times per week as homework on their own and to keep a journal of their compliance and any comments or questions. The warm-up consisted of standard components that were part of the players’ regular warm-up and are recommended as part of effective injury prevention warm-up programs (Mandelbaum et al., 2005; Myklebust et al., 2003). These components included core stability, balance, multidirectional running, and changes of direction. The content and intensity of the warm-up allowed for integration of the Core-PAC into functional athletic movements without creating a training stimulus for strength or plyometric power. For example, the focus of the hops and the lunges was on the movement rather than maximal effort for power and strength gains. Subjects wore the styrofoam ball during the scheduled sessions but not for the homework sessions. The Core-PAC was consistently reinforced throughout the warm-up but no other instructions (i.e. “bend your knees”, “keep your knee over your toes”) regarding technique were provided. Subjects were aligned in pairs so that they could observe and correct each other on their Core-PAC technique. This method of partner observation and correction of each other’s technique has been used to good effect in previous studies (Myklebust et al., 2003). The three performance tasks that were tested in the laboratory were not included in the content of the
warm-up. The styrofoam ball was not used and no reminders or mention of the Core-PAC were given during the post-training testing sessions.

**Table 3.2 Warm-up program exercises**

<table>
<thead>
<tr>
<th>Activity</th>
<th>Sets, Repetitions and/or Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slow jog</td>
<td>x 1 lap (full field)</td>
</tr>
<tr>
<td>Core set</td>
<td>5 x 10 seconds</td>
</tr>
<tr>
<td>Jog with diagonal push offs</td>
<td>x 1 lap (ends = stop and go / lengths = cutting from a jog)</td>
</tr>
<tr>
<td>Lateral shuttle</td>
<td>4 slow / 4, 3, 2, 1 fast</td>
</tr>
<tr>
<td>Core cross bar</td>
<td>3 x 10 second hold – progress as tolerated</td>
</tr>
<tr>
<td>Balance with rotation</td>
<td>3 x 20 sec / each leg</td>
</tr>
<tr>
<td>Diagonal lunges</td>
<td>2 widths</td>
</tr>
<tr>
<td>Lateral hops</td>
<td>3 x 10 hops</td>
</tr>
<tr>
<td>Diagonal hops</td>
<td>3 x 10 hops</td>
</tr>
</tbody>
</table>

* Details of the exercises are provided in Appendix nine (the same program as study 3).

**3.2.2.4 Questionnaire**

After completing the training program, an 8-item questionnaire was given to each subject to ascertain whether they thought the program was effectively instructed and implemented and to provide feedback on the importance and practicality of the Core-PAC for them (Appendix seven). The questionnaire consisted of forced-answer responses, such as circling either “yes” or “no”, and an opportunity to explain. Some examples of questions included in the questionnaire were “Did you feel you had enough instruction for the technique?”, “Did you feel you had enough time to practice the technique?”, and “Do you feel this is an important skill to have as an athlete?"
3.2.3 Data collection

Data collection was the same as described in Study 1 (Chapter 2, page 55). In summary, an Optotrak® 3-D motion analysis system (Optotrak 3020, NDI, Waterloo, Canada) was used to track 12 markers (infrared emitting diodes - IREDs) attached to the subject’s lower extremity and pelvis as described by Jian et al. (1993) and Eng and Winter (1995) to generate a 3-D model of the lower body. Kinematic data were sampled at 120Hz. Ground reaction forces were collected using a force platform (Bertec, Columbus, Ohio) embedded in the ground along the plane of progression. Force plate data were sampled at 600 Hz and synchronized with the Optotrak® system.

3.2.4 Data analysis

Data analysis was the same as described in Study 1 (Chapter 2, page 55). In summary, 3D motion data were processed and filtered using custom algorithms (Matlab, Version 14, The Mathworks, Inc., Natick MA). Data were filtered using a Butterworth filter (4th-order, zero-lag, low pass cut-off at 10Hz).

A 3-D inverse dynamics solution was used to estimate the forces and moments at the joints starting at the most distal joint (Winter, 2004). Knee abduction moments were included in our kinetic analysis and were defined as external moments at the knee (i.e. forces producing an abduction or resisting an adduction angle at the knee).

Test-retest reliability and agreement have been demonstrated for peak knee flexion angle (ICC range = 0.88-0.95, SEM range = 1°-1.9°) and peak knee abduction moments (ICC range = 0.62-0.84, SEM range = 0.10-0.23 Nm/kg) across all three tasks for this cohort.

3.2.5 Statistical analyses

Statistical analyses were done using PASW Statistics 18 (SPSS Inc., Chicago IL). Means and standard deviations were calculated for peak flexion angles and peak abduction moments at the knee for the SC, USC, and SH tasks at baseline, after immediate instruction,
and after the four-week training program. A paired-samples t-test was conducted to determine the effects of immediate instruction on baseline peak flexion angles and abduction moments for nine subjects. Statistical significance was set at $P < 0.05$. Given the small sample size and exploratory nature of this study, we did not adjust for multiple comparisons. Statistical analysis was not done on change values after the training program due to a small sample size ($n = 7$). Therefore, data is presented in graph form to show changes of all seven individual subjects (Figure 3.2). Effect sizes are provided in Appendix eight.

3.3 Results

3.3.1 Subjects

Subject characteristics are summarized in Table 3.1. All ten subjects completed the baseline testing but data were not retrievable for one subject after immediate instruction (mechanical error, $n = 9$). Seven subjects were tested after the training program (two subjects were injured early in the training while participating in unrelated activities and one subject was not available for post-training testing). The average time between the end of the training program and the post-training test sessions was 6.7 ± 3.5 days (mean ± SD). All ten subjects again selected the right leg as their dominant leg. Therefore, biomechanical and statistical analyses were performed on the right lower limb only. The speeds for the group in completing the three tasks were similar between baseline, immediate instruction, and post-training (Table 3.3). After removing incomplete trials (e.g. missed force plate data), we used an average of 7.1 SC trials, 7.1 USC trials, and 7.3 SH trials from the original nine trials captured for each subject. This represented 80% of all collected data.

3.3.2 Feasibility and compliance

Of the seven subjects completing the four-week training program, 49 out of 56 (88%) of the physiotherapist-led training sessions were attended and 50 out of 56 (89%) homework sessions were completed. When asked through the confidential questionnaire at the end of the program (Appendix seven), “What did you find most difficult about the training?” all seven
subjects chose “time to do it” rather than “technique required” or “physically taxing” as their response.

### 3.3.3 Core-PAC integration into warm-up

The Core-PAC was effectively integrated into the content of a 20-minute warm-up before regular soccer practices. Review and demonstration of the Core-PAC at the soccer field took 10 minutes prior to the warm-up for the first two practice sessions. After this, the warm-up was not extended or stopped for additional instruction or clarification of the Core-PAC. Within the questionnaire, all seven subjects felt that overall there was adequate instruction and enough time to practice the Core-PAC and subjects perceived the warm-up demand as no greater than a regular soccer warm-up.
Table 3.3 Effects of immediate instruction and training on peak flexion angles and abduction moments for the side-cut, unanticipated side-cut, and side-hop tasks (mean ± standard deviation)

<table>
<thead>
<tr>
<th></th>
<th>Peak flexion angles(°)</th>
<th>Peak abduction moments(N·m/kg)</th>
<th>Average speed of movement(m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pretest (n=9)</td>
<td>59.1 ± 4.8</td>
<td>61.8 ± 4.9</td>
<td>62.7 ± 5.0</td>
</tr>
<tr>
<td>Immediate Instruction (n=9)</td>
<td>65.5 ± 5.8</td>
<td>65.3 ± 6.0</td>
<td>68.5 ± 5.3</td>
</tr>
<tr>
<td>Pretest-Immediate Instruction Difference</td>
<td>6.4</td>
<td>3.5</td>
<td>5.8</td>
</tr>
<tr>
<td>Confidence Interval</td>
<td>3.4 - 9.3</td>
<td>1.3 - 5.8</td>
<td>3.7 - 7.9</td>
</tr>
<tr>
<td>P-value</td>
<td>0.001</td>
<td>0.007</td>
<td>0.000</td>
</tr>
<tr>
<td>Post-test (n=7)</td>
<td>60.7 ± 4.7</td>
<td>64.1 ± 4.6</td>
<td>64.7 ± 4.9</td>
</tr>
<tr>
<td>Pretest-Postest Difference</td>
<td>4.3</td>
<td>2.7</td>
<td>0.8</td>
</tr>
<tr>
<td>Confidence Interval</td>
<td>-0.6 - 9.3</td>
<td>-1.5 - 7.0</td>
<td>-4.3 - 5.9</td>
</tr>
</tbody>
</table>
3.3.4 Immediate instruction (n = 9)

3.3.4.1 Kinematics

A typical kinematic profile across the three tasks showed subjects landing on the force plate in approximately 20-40° of knee flexion angle with the knee increasing to peaks of 55-70° flexion at mid-stance before decreasing to 10-30° flexion at the end of stance (Figure 3.1a-c). Peak knee flexion angles occurred at similar time points within mid stance for all three tasks during baseline, immediate instruction, and post-training sessions. There were significant increases in peak knee flexion angles of a mean 6.4° during the SC (t (8) = 4.94, P = 0.001), 3.5° during the USC (t (8) = 3.62, P = 0.007), and 5.8° during the SH (t (8) = 6.39, P < 0.001) tasks after the immediate instruction (Table 3.3). Changes in angles across tasks are demonstrated for a typical subject in Figure 3.1a-c.

3.3.4.2 Kinetics

Across all three tasks, subjects demonstrated a bimodal peak in abduction moment; the first, sharper peak of 0.75-1.75 N·m/kg occurring between heel contact and 20% of stance phase and a second, lesser or equal, and more gradual peak at the end of stance during push-off phase with moments between the two peaks decreasing between 70% of peak moment to similar base-line levels as those occurring at initial contact (Figure 3.1d-f). Peak knee abduction moments always occurred within the first 20% of stance for all three tasks during baseline, immediate instruction, and post-training testing sessions. Peak knee abduction moments decreased by a mean of 0.25 N·m/kg during the SC (t (8) = 2.58, P < 0.03), 0.17 N·m/kg during the USC (t (8) = 2.36, P = 0.05), and 0.27 N·m/kg during the SH (t (8) = 2.50, P = 0.04) tasks (Table 3.3). Changes in abduction moments across tasks are demonstrated for a typical subject in Figure 3.1d-f.
Figure 3.1 Mean changes in peak flexion angle (a, b, c) and peak abduction moment (d, e, f) for a sample subject. Baseline (—), Immediate Instruction (---), Post Training (•••).
3.3.5 Training program (n = 7)

3.3.5.1 Kinematics

During the SC task, five of the seven subjects demonstrated increased peak knee flexion angles (range = 1 to 14°) with three subjects demonstrating increases of over 5°. In contrast, two subjects showed small decreases of 1° each after the four-week training period (Figure 4.2a-c). During the USC, four of seven subjects showed an increase (range = 4 to 11°) and three subjects showed a decrease (range = 1 to 4°) in peak flexion angles. Three subjects showed an increase (range = 4 to 12°) and four subjects showed a decrease (range = 1 to 7°) in peak flexion angles during the SH task.

3.3.5.2 Kinetics

After the four-week training period for the SC task, five of the seven subjects decreased peak abduction moments (range = 0.07 to 0.55 N·m/kg), with four of the seven decreasing by over 0.17 N·m/kg. In contrast, two subjects increased their peak abduction moment by 0.08 and 0.22 N·m/kg (Figure 3.2d-f). During the USC, five of the seven subjects decreased peak abduction moments (range = 0.13 to 0.43 N·m/kg), one subject did not change, and one subject increased by 0.12 Nm/kg. During the SH task, six of the seven subjects decreased peak abduction moments (0.04 to 0.79 N·m/kg), with four decreasing by more than 0.29 N·m/kg. In contrast, one subject increased by 0.28 N·m/kg.
Figure 3.2 Individual changes in peak flexion angles (a, b, c) and abduction moments (d, e, f) by task and subject number for baseline (Base) to immediate instruction (Imm), and from Base to post-training (Post) testing sessions.
3.4 Discussion

3.4.1 Feasibility

The findings of our study support our main hypothesis that implementation of a Core-PAC into a team warm-up prior to regular soccer training is feasible. Compliance of the training program was excellent with attendance close to 90% for the instructed and the self-directed training sessions, much higher than those reported in other studies (Engebretsen et al., 2008; Pfeiffer et al., 2006; Soligard et al., 2010). The Core-PAC appeared to be effectively implemented into the team warm-up without disrupting the flow or the physiological benefits of the warm-up. Subjects were able to quickly understand and incorporate the Core-PAC into the warm-up and were satisfied with the mode of instruction and amount of practice. These observations and feedback are important practical considerations when implementing an injury prevention program because compliance is one of the greatest challenges to the success of injury prevention programs (Finch, 2006; Myer et al., 2004; Soligard et al., 2010). Compliance may be improved with interventions that are easily and effectively integrated by athletes into their regular preparation routine without additional time or equipment requirements and without interfering with their performance (Soligard et al., 2010). With respect to feasibility, the findings of this pilot work are important to consider when designing future controlled trials investigating methods to change movement, such as the Core-PAC.

The Core-PAC is a novel movement strategy that may provide an important contribution to the content and delivery of ACL injury prevention training programs. Some recent studies using technique modification have demonstrated improvements in biomechanical risk factors during typical movements that increase risk of ACL injury (Cowling et al., 2003; Dempsey et al., 2009; Mizner et al., 2008; Onate et al., 2005). However, instructions are typically focused on modifying several joint and body positions (Dempsey et al., 2009; Hewett et al., 1996; Mizner et al., 2008; Onate et al., 2005) which may not be the most effective method of changing complex movements compared to a single end point focus
A single end point focus also may provide the coach and the athlete with a simpler means of instructing, learning, and monitoring changes in movement strategy.

3.4.2 Immediate instruction

Our second hypothesis was also supported by the results of this study. Significant increases in peak flexion angles and decreases in peak abduction moments were demonstrated across tasks after the immediate instruction of the Core-PAC.

The significant improvements in both peak flexion angles and peak abduction moments after immediate instruction across the SC, USC, and SH tasks are a novel finding. Dempsey et al. (2009) were able to decrease abduction moments but did not change flexion angles at the knee during a side-cut task after a six-week training program. Mizner et al. (2008) demonstrated an increase in peak flexion angles and a decrease in peak abduction moments at the knee on a drop jump landing technique after verbal instruction. Other studies that have shown increased flexion angles immediately after instruction also used a jump landing maneuver (Cowling et al., 2003; Onate et al., 2005) rather than side-cutting tasks. These drop jump and jump landing studies used specific instructions and feedback to increase bending of the knees upon landing (Cowling et al., 2003; Mizner et al., 2008; Onate et al., 2005). In the current study, instruction of the Core-PAC did not include any reference to the knees. An increase in peak knee flexion angle and decrease in peak abduction moment after the Core-PAC instruction was achieved by encouraging subjects to move their COM closer to their base of support (planted foot) which may have transferred more joint loading to the sagittal rather than the frontal and transverse planes (Hewett et al., 2002; Pollard et al., 2010).

3.4.3 Training program

After the four-week training program, subjects generally improved in both of our biomechanical variables across all three tasks. These results are encouraging considering our initial uncertainty of how effective the Core-PAC instruction would be in a practical, field-based setting as compared to the controlled laboratory environment and is an important exploratory
aspect of this study. We wanted to get an indication of whether a practical application of the Core-PAC might still be effective in improving biomechanical risk factors.

The post-training results should be considered in the context of several factors. First, there were no reminders or demonstrations for the subjects of the Core-PAC prior to the post-training testing sessions, which took place between two and eleven days after the end of the training program. These factors suggest that the post-training testing sessions may have been evaluating the amount of learning of a motor skill through retention rather than simply performance of a skill demonstrated after the immediate instruction (Schmidt and Lee, 2005). Instruction of the Core-PAC on the field during a team warm-up is practical but potentially less effective compared to individual instruction in the laboratory. Video demonstration and feedback individually or in small groups have been successful in improving biomechanical risk factors (Dempsey et al., 2009; Onate et al., 2005) but this may not always be accessible or feasible for youth sports teams. We chose to explore the effects of this instruction within a realistic and practical setting for a youth sports team. The training program did not include the SC, USC, or SH tasks because we wanted to evaluate the transfer of the training program effects to unpracticed tasks. Transfer of a movement strategy from one task to another, along with retention, are means of evaluating learning rather than the short-term performance of a skill (Schmidt and Lee, 2005). In light of the above considerations, the modest improvements demonstrated after the training period are encouraging.

Biomechanical improvements at the knee after immediate instruction and the training program were demonstrated during side-cutting tasks that preceded the kicking of a soccer ball. The addition of more sport-specific conditions to side-cutting tasks has been shown to increase biomechanical risk factors in the laboratory setting (Chaudhari et al., 2005; Fedie et al., 2010; McLean et al., 2004b). Overall improvements were also maintained during the unanticipated side-cut which has also been shown to increase kinematic and kinetic risk factors (Besier et al., 2001a; Sell et al., 2006).
3.4.4 Clinical relevance

The ACL is under increased tension as the knee approaches extension and is further stressed by patellar tendon induced anterior translation in knee flexion angles less than 45 degrees (Beynnon et al., 1997; Renstrom et al., 1986). Although the ACL is primarily loaded by anterior translation of the proximal tibia relative to the femur (Fleming and Beynnon, 2004; Markolf et al., 1995), external abduction moments are thought to be the most dangerous out-of-sagittal-plane load on the knee and have been predictive of future ACL injury in female athletes (Hewett et al., 2005a). There is consensus in the literature that a combination of forces are most likely to injure the ACL (Hame et al., 2002; Markolf et al., 1995; Withrow et al., 2006). Both anterior translation and abduction moments are reduced with increasing knee flexion angles (Hame et al., 2002; Markolf et al., 1995). However, we do not know what combinations or degrees of change in flexion angles and abduction moments are clinically relevant and how this interacts with other variables such as transverse plane biomechanics and the effects of neuromuscular control. For the majority of subjects, the Core-PAC led to improvements in both the peak flexion angle and peak abduction moment, particularly for the immediate instruction condition.

3.4.5 Limitations

The current study has several limitations. First, we initiated the study with a small sample size (n = 10) that was further compromised by three dropouts for the post-training testing. However, it was a homogeneous sample that was representative of the age and characteristics of the population most at risk for non-contact ACL injuries. There was no control group to compare the changes that may have resulted from implementation of the Core-PAC during either testing session. We also cannot discount the effects that other parts of the warm-up (core strength, balance, lower extremity strength, or agility) may have had on our results. However, these other components were performed at a volume and intensity that were similar to the subjects’ regular warm-up except for a focus on the movement technique. Subjects
confirmed that the demand was not greater than their regular soccer warm-up through the questionnaire provided at the end of the training program. Four weeks may not have been long enough to learn the Core-PAC and transfer it to unpracticed tasks after a retention interval. Finally, we do not know how well these effects would transfer to a competitive, “real-world” sport setting. Perhaps the Core-PAC should be taught and reinforced during practice and game situations. This may provide for the most practical and direct application of a movement strategy intervention as it offers more time to practice in a real world environment without taking additional time from the athletes or the coaches. These are all important considerations in increasing compliance of an intervention (Finch, 2006; Myer et al., 2004; Soligard et al., 2010).

3.4.6 Future directions

The Core-PAC shows promise in providing a means of modifying technique in high-risk movements for ACL injury. These preliminary results warrant further investigation to build on this work and ascertain the potential isolated effects of the Core-PAC in reducing biomechanical risk factors.

3.5 Conclusion

The results of this study suggest that the Core-PAC may be one method of modifying high-risk movements such as side-cutting and single-leg landing. The Core-PAC was feasible and successfully implemented into a team warm-up prior to regular soccer training. It appeared that the Core-PAC was easily understood and accepted by the subjects and incorporated into their warm-up activities and self-directed homework sessions with good compliance. The Core-PAC also demonstrated improvements in biomechanical risk factors after immediate instruction and showed improvement in some individuals after a four-week training program.
Bridging Statement II

The Core-PAC shows promise in providing one method of modifying technique in high-risk movements associated with ACL injury. However, studies without a control group, as in the preceding single group pretest-posttest design (Study 2), are prone to inflated effect sizes compared to controlled trials (Lipsey and Wilson, 1993). In our study, this may have been a result of learning or practice of the tasks or other extraneous variables such as the training effects from the other exercise components in the warm-up. Preliminary results from Study 2 warrant further investigation to build on this work and ascertain the potential isolated effects of the Core-PAC in reducing biomechanical risk factors in the form of a randomized controlled trial (RCT). A carefully designed RCT (Study 3) could provide additional laboratory-based support for the Core-PAC as an effective method of changing movement, allowing for comparison to other forms of practical, on-field methods of instruction. Important changes we made from Study 2 for Study 3, in addition to the control group and randomization, included a longer duration (six-week vs. 4-week program), increased frequency of supervised training sessions (four vs. two per week), and standardized instructions and feedback provided by physiotherapists and coaches assigned to the experimental and the control group in Study 3 vs. the principle investigator (RGC) implementing the training program in Study 2.
4 Effectiveness of a Novel Movement Strategy in Decreasing Biomechanical Risk Factors for ACL Injury in Female Adolescent Soccer Players – A Randomized Controlled Trial

4.1 Introduction

The rationale for Chapter 3 was provided in detail in Chapter 2. A brief summary will be provided here.

1) ACL injuries are a significant source of short and long term morbidities (Hartwick et al., 2003; Lohmander et al., 2007) and personal and institutional costs (Silvers and Mandelbaum, 2007) for the adolescent athlete. Multidirectional sports, such as soccer, are among those most likely to result in ACL injury (Boden et al., 2000; Krosshaug et al., 2007a) and young women participating in these sports are 4-6 times more likely to sustain an ACL injury as compared with young men (Arendt and Dick, 1995; Griffin et al., 2000).

2) The ACL is at greatest risk of injury when the knee is in a relatively extended position and experiences combined forces such as anterior translation and external abduction moments (Beynnon et al., 1997; Hewett et al., 2005a; Markolf et al., 1995; Renstrom et al., 1986). Conversely, anterior translation and coronal plane moments are reduced with increasing knee flexion angles (Hame et al., 2002; Markolf et al., 1995). Side-cutting and single-leg landing are frequently performed during multidirectional sports but a typical strategy observed at the time of injury includes: a knee close to extension with a valgus angle; an abducted hip with the foot planted in front and lateral to the center of mass (COM); and a trunk that is side-flexed and rotated towards the plant leg (Boden et al., 2000; Cochrane et al., 2007; Hewett et al., 2009; Ireland et al., 2003; McNair et al., 1990; Olsen et al., 2004; Teitz et al., 2001).

3) There is evidence that neuromuscular training using multimodal programs can change movement patterns that improve biomechanical risk factors and can decrease the incidence of ACL injuries in female athletes (Alentorn-Geli et al., 2009; Hewett et al., 2006; Renstrom et al., 2008). ACL injury prevention programs have been successful in reducing ACL injuries by up to 89% in soccer, basketball, handball, and skiing (Silvers and Mandelbaum, 2007). Most ACL
injury prevention programs that are effective at decreasing the incidence of ACL injury are designed to modify biomechanical and neuromuscular risk factors during high-risk athletic movements through neuromuscular training. Important components of successful prevention programs are thought to be strengthening, awareness of high-risk positions, technique modification, core and trunk control, aerobic conditioning, agility, balance, and plyometrics (Alentorn-Geli et al., 2009; Renstrom et al., 2008). However, we do not know which components of the programs are most effective at modifying movement patterns that are thought to contribute to ACL injury. Only recently have studies started to investigate whether these programs can, in fact, modify movement (Hewett et al., 1996; Pollard et al., 2006) and to discern the separate effects that individual training components may have on the biomechanics of the knee during high-risk tasks (Cochrane et al., 2010; Dempsey et al., 2009; Herman et al., 2008; Myer et al., 2006).

4) There is a need to differentiate between and ascertain the effectiveness of these multimodal program components so that the most effective components can be emphasized in time-efficient programs. Few studies have looked at the separate effects of technique modification on biomechanical variables during high-risk athletic tasks (Cowling et al., 2003; Dempsey et al., 2009; Mizner et al., 2008; Onate et al., 2005), and only one study has looked at the effects on side-cutting movements (Dempsey et al., 2009). Dempsey et al. (2009) demonstrated improvements in biomechanical risk factors for ACL injury after a six-week training program aimed at modifying whole body side-cutting technique.

5) A core position and control movement strategy (Core-PAC) may be one method of modifying high-risk movements such as side-cutting and single-leg landing. The Core-PAC was feasible and successfully implemented into a team warm-up prior to regular soccer training (Chapter 3). It appeared that the Core-PAC was easily understood and accepted by the subjects, who incorporated it into their warm-up activities and self-directed homework sessions with good compliance. The Core-PAC also demonstrated improvements in biomechanical risk
factors after immediate instruction and showed improvement in some individuals after a four-week training program.

This study builds on the results of the exploratory work in Chapter 3. Specifically, this study addresses the main threats to internal and, to a lesser extent, external validity that were inherent in the single-group pretest-posttest design of the previous study. The ability to control for the confounding effects of extraneous variables is best achieved using a randomized controlled trial (RCT) and is necessary if we are to have confidence in the outcomes of our studies (Portney and Watkins, 2000). Although the RCT provides the strongest evidence to support the effectiveness of an intervention in modifying biomechanical risk factors or reducing the incidence of ACL injury, there have been few RCTs in this area of research.

There is increasing evidence that multimodal neuromuscular training programs can decrease the incidence of ACL injuries, however, these studies vary in their methodological quality and design (Table 1.2). Studies without a control group, as in single group pretest-posttest designs, often demonstrate greatly inflated effect sizes compared to controlled trials (Lipsey and Wilson, 1993). Effect sizes may be exaggerated even in controlled trials without proper random allocation because random allocation controls for systematic differences and potential confounding events between treatment groups that may influence the outcome of the study (Sibbald and Roland, 1998). Of the fifteen studies investigating the effects of training programs in decreasing the incidence of ACL injuries listed in Table 1.2, only six studies were RCTs (Gilchrist et al., 2008; Olsen et al., 2005; Soderman et al., 2000; Soligard et al., 2008; Steffen et al., 2008; Wedderkopp et al., 2003). Of these six studies, only two (Gilchrist et al., 2008; Olsen et al., 2005) demonstrated a significant reduction in ACL injury. Despite positive results by some well-designed prospective cohort studies (Hewett et al, 1999; Mandelbaum et al., 2005; Myklebust et al., 2003), without randomization and a control group we cannot be confident that the noted improvements in injury incidence were a result of the intervention training program. Selection bias, for example to those that are motivated to participate in injury
prevention programs, is a potential risk in non-randomized trials. Other common limitations of these intervention studies in general include low statistical power (Heidt et al., 2000; Petersen et al., 2005; Soderman et al., 2000; Wedderkopp et al., 2003) and inconsistent accounts of compliance (Caraffa et al., 1996; Heidt et al., 2000; Hewett et al., 1999; Petersen et al., 2005; Wedderkopp et al., 2003). It is notable that four of the six RCTs have been conducted in the last six years and three in the last 3 years; there is an increased focus on the quality as well as the quantity of research in sports injury prevention and the RCT is becoming more common (Engebretsen, 2007).

Various training programs have been shown to improve kinematic and/or kinetic variables during high-risk athletic movements (Table 1.3), but few have been RCTs (Cochrane et al., 2010; Herman et al., 2008; Kato et al., 2008; Lim et al., 2009; Onate et al., 2005; Ortiz et al., 2010). Some RCTs have evaluated the effects of multimodal team warm-up sessions on biomechanical variables (Kato et al., 2008; Lim et al., 2009; Ortiz et al., 2010). Kato et al. (2008) and Lim et al. (2009) randomized players from two teams into either an intervention or a control group, whereas Ortiz et al. (2010) blocked the randomization to the two teams (i.e. one team was randomly assigned to the intervention and the other to the control). By randomizing to team rather than the individual, the potential confounding effect of team activities is not controlled. However, randomizing to team may improve external validity because this is likely how most intervention training programs are best implemented. By randomizing to individual there is an increased risk of contamination because of the potential for athletes from different groups exchanging information when they come back to their teams. However, despite the risk of contamination, randomizing to individual may provide greater internal validity when investigating the effects of training interventions.

In developing the most effective and time-efficient injury prevention training programs, the separate effects of components within multimodal programs must be discerned. RCTs that have isolated the effects of different components on knee joint angles and moments have been
limited to the effects of strength training on knee and hip kinematics and kinetics during a stop-jump task (Herman et al., 2008) and the comparison of different forms of strength training to balance training on knee angles and moments during running and cutting tasks (Cochrane et al., 2010). Despite the importance of technique modification within multimodal training programs (Hewett et al., 2006; Renstrom et al., 2008), few studies have looked at the separate effects of technique modification on biomechanical variables during high-risk athletic tasks (Cowling et al., 2003; Dempsey et al., 2009; Mizner et al., 2008; Onate et al., 2005) and only one study looked at the effects on side-cutting movements (Dempsey et al., 2009). All but one of these studies (Onate et al., 2005) were single-group pretest-posttest designs and were, therefore, prone to inflated effect sizes (Lipsey and Wilson, 1993). Again, without randomization and a control group we cannot be confident that the improvements in biomechanical variables were a result of the intervention training programs. Onate et al. (2005) randomized subjects to one of three videotape feedback groups and a control group to assess the effects of different types of feedback on jump-landing technique. This study did not fulfill some criteria required of level I RCTs, such as allocation concealment or blinding of subjects or assessors (Sackett et al., 2000) and scored six out of ten on the PEDro scale (Physiotherapy Evidence Database scale used to evaluate trial quality). An RCT with a score of six can be considered of “good” quality (Score 9-10 = excellent, 6-8 good, 4-5 fair, <4 poor) (Teasell et al., 2003).

The purpose of the present study was to use a randomized controlled trial to compare a Core-PAC trained group to a control group for peak flexion angles and peak abduction moments at the knee during a side-cut and an unanticipated side-cut prior to kicking a soccer ball and a side-hop task after a six-week training program. It was hypothesized that a Core-PAC group would have greater peak flexion angles and lower peak abduction moments at the knee compared to a control group during a side-cut, an unanticipated side-cut, and a side-hop task after a six-week training program.
4.2 Methods

4.2.1 Design

This study was a randomized controlled trial, in which assessors were blinded to group assignment and subjects, although not blinded to group assignment, were unaware of the study hypothesis.

4.2.2 Subjects and recruitment

Figure 4.1 shows the flow of subjects through the study. In March 2007, coaches from two provincial-level female soccer teams (one U-15 and one U-16) were contacted and asked to distribute information sheets outlining the study to their players. U-16 teams consist of players that are 15 years old or have just turned 16 within the year. U-15 teams consist of players that are 14 years old or have just turned 15 within the year. Provincial-level players are the top players in the province. The players had the opportunity to discuss the study with their parents, and submit the consent form if they were interested in participating. Informed consent was provided for all subjects prior to testing (Appendix one). Ethical approval was granted by the University of British Columbia’s Clinical Research Ethics Board.
Figure 4.1 Consort diagram for study 3
4.2.2.1 Inclusion / exclusion criteria

As described in Study 1 (Chapter 2, page 50).

4.2.2.2 Randomization and allocation concealment

A research assistant screened for study eligibility and obtained informed consent; the same research assistant managed the recruitment and enrolment process. From the two teams approached, a total of twenty players meeting the inclusion criteria and providing consent were assigned a number code. Each subject was then randomly allocated to either the intervention (Core-PAC) group or the control (CON) group using concealed allocation. Research personnel testing subjects and analyzing data were also blinded to group allocation. The physiotherapists providing the training were not blinded. Concealment of group assignment was maintained until data were collected during the second set of post-training testing sessions (posttest 2).

We chose to randomize individual subjects (rather than teams) to either an intervention (Core-PAC) or a control (CON) group because our main study objective was to evaluate the effects of the Core-PAC and, therefore, internal validity was more important than external validity. Similar to other studies (Kato et al., 2008; Lim et al., 2009; Ortiz et al., 2010), we used a combination of physiotherapists and coaches to implement the program. Internal validity may be improved with the use of physiotherapists by ensuring the integrity of the content and program delivery is maintained. However, external validity may be compromised because coaches would normally implement such programs. The use of physiotherapists also allowed us to better control the amount and type of feedback provided to the subjects by the instructors, given the physiotherapists’ understanding of the study objectives.
4.2.3 Experimental protocol

The experimental protocol for this study is explained in detail in Study 1 (Chapter 2, pages 50-54). A brief summary and any points of difference from Study 1 will be provided here.

During baseline testing, subjects from both the Core-PAC and the CON groups performed three to five practice trials prior to performing nine consecutive test trials of each of the three performance tasks – SC, USC, and SH, using their own strategy. The same standardized instructions were provided to both groups (as described in Chapter 2, pages 52-53). Subjects were retested after the training program (posttest 1) with the same pretest instructions provided to both groups. After completing the three tasks, the subjects in both groups repeated the testing procedure a final time (posttest 2) with the only difference being a reminder provided to the Core-PAC group to perform the tasks using the Core-PAC that they trained during the six-week program.

Core-PAC instruction: The styrofoam ball was not used during the post-training testing sessions. This was done so that subjects were evaluated in more realistic conditions (i.e. they would not be using the styrofoam ball during training or games). After the reminder to perform the Core-PAC, the subjects would then practice the technique until they were comfortable with it. As this was a reminder of a strategy they had previously been taught during the six-week training program, the total time for review and practice varied between 2 to 3 minutes per subject. The subjects were reminded once every four trials to maintain the new strategy. To prevent fatigue, subjects adhered to a work / rest time ratio of at least 1:5 (Jacobs and Mattacola, 2005). On average, the testing procedures for the Core-PAC and the CON groups took approximately two hours to complete.

4.2.3.1 Performance tasks

The set-up and description of the performance tasks are provided in detail in Chapter 2, pages 51-54.
4.2.3.2 Training

The training program was implemented during a six-week period from June to July, 2007. These two particular teams were chosen because they trained at the same time and location as each other, allowing for a larger pool of players to draw from and yet still allow simultaneous warm-ups to occur prior to regular soccer practice. The simultaneous warm-ups were important in order to minimize potential contamination of the CON group by the Core-PAC group.

Subjects in each group performed a 20-minute warm-up program four times per week for six-weeks, replacing their regular warm-up prior to soccer practice (Appendix nine). Physiotherapists led the warm-up two times per week. Following attendance at a one-hour instruction session and after receiving training program instruction materials, coaches repeated the same warm-up routine with their teams another two times per week. The coaches were given the same cues and feedback instructions as were used by the physiotherapists (Appendix ten). So as to maintain consistency amongst the groups, the physiotherapists and coaches in both groups were told not to correct or provide their own feedback to individual athletes and to only use the standardized feedback provided. Players were allowed to communicate and provide feedback to each other (within their own group) as they observed each other perform the drills.

The warm-up program consisted of standard components recommended as part of effective injury prevention warm-up programs (Mandelbaum et al., 2005; Myklebust et al., 2003; Soligard et al., 2008). These components included core stability, balance, multidirectional running, and changes of direction (some of which were already part of the player’s regular warm-up). Subjects in the Core-PAC group wore the styrofoam ball during the physiotherapist-delivered sessions but not during the coach-delivered sessions. Both groups were told that they were receiving the same warm-up content but with different instructions and that the styrofoam ball used by subjects in the Core-PAC group was to allow better observation of movement by
the physiotherapist. The Core-PAC was reinforced throughout the warm-up with cues such as “move from the centre” and “lead with the belly button” (Appendix ten). No other instructions regarding technique (e.g. “bend your knees”, “keep your knee over your toes”) were provided to the Core-PAC group. The CON group was matched in the amount and frequency of feedback they received from the physiotherapists; the physiotherapists provided encouraging and general feedback such as “good work” and “keep your balance” which attempted to minimize potential biases and confounding variables by not positively or negatively affecting their movement strategy. An audit was conducted once per week to ensure the amount and frequency of feedback was equal between groups (Appendix eleven). Subjects were aligned in pairs, where possible, so that they could observe and correct each other’s Core-PAC technique. This method of partner observation and correction of each other’s technique has been used to good effect in previous studies (Myklebust et al., 2003). The three performance tasks that were tested in the laboratory were not included in the content of the warm-up.

4.2.4 Sample size

Prior to this exploratory RCT, we investigated the feasibility of conducting such a trial with a pilot study. Based on the results of the pilot study (SC mean difference in peak flexion angle = 6.4° (common SD = 5.3); SC mean difference in peak abduction moment = 0.25 Nm/kg (common SD = 0.22), 11 to 13 subjects per group would provide a power of 0.80, assuming an alpha of 0.05 (Appendix twelve). This is without correcting for multiple testing.

4.2.5 Statistical analysis

Statistical analyses were carried out using PASW Statistics 18 (SPSS Inc., Chicago IL). Subject characteristics were analyzed by descriptive statistics. Assumptions for normality of distribution for all variables were explored using the Shapiro-Wilk test of normality and by inspecting histograms and normal plots. Assumptions of homogeneity of variance and sphericity were also validated for the use of ANOVA analyses. A two-way mixed ANOVA with a between-subject factor of group and a within-subject factor of time was used to compare differences
between groups in peak knee flexion angle and peak abduction moment during the three tasks (Appendix thirteen). This was repeated six times for the two dependent variables (peak flexion angle and abduction moment) across the three tasks (SC, USC, and SH). Main effects for group and time and interaction effect of group x time were calculated. Time refers to the two testing sessions - posttest 1 and posttest 2. When significant interactions were identified, post hoc analyses using a univariate repeated measures ANOVA with a Bonferroni correction for multiple comparisons were conducted separately for the control and experimental groups. Analyses were performed with an intention-to-treat approach; that is all subjects were included despite compliance to protocol. Two-tailed probability tests were set at an a priori level of $P < 0.05$ unless otherwise stated. Effect sizes were calculated using Hedges’ $g$ and are provided in Appendix eight.

4.3 Results

4.3.1 Subjects

Subject characteristics are summarized in Table 4.1. At baseline there were no significant differences between groups on study characteristics (Table 4.3). Twenty subjects completed the baseline testing, with one subject being lost to injury from within the CON group. The average time between the end of the training program and the post-training sessions was 8.1 ± 6.2 days (mean ± SD). All subjects selected the right leg as their dominant leg. Therefore, biomechanical and statistical analyses were performed on the right lower limb only. The speeds for the groups in completing the three tasks were not significantly different between groups or between baseline and posttest 1 or posttest 2 (Table 4.3). After removing incomplete trials (e.g. missed force plate), we used an average of 7.6 SC trials, 7.5 USC trials, and 7.9 SH trials from the original nine trials captured for each subject. This represented 84% of all collected data.
Table 4.1 Subject characteristics for study 3 (mean ± standard deviation (range))

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Intervention (n = 10)</th>
<th>Control (n = 9)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>15.7±0.5 (15-16)</td>
<td>15.1±0.9 (14-16)</td>
</tr>
<tr>
<td>Height (m)</td>
<td>1.65±0.06 (1.57-1.78)</td>
<td>1.66±0.06 (1.55-1.75)</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>60.9±5.7 (52.6-72.6)</td>
<td>63.1±8.2 (52.3-78.0)</td>
</tr>
<tr>
<td>BMI (kg/m²)</td>
<td>22.3±1.9 (19.4-25.5)</td>
<td>22.8±1.8 (21.0-25.5)</td>
</tr>
</tbody>
</table>

4.3.2 Compliance

Subjects in the Core-PAC group completed 209 out of a potential 240 (87%) physiotherapist or coach led training sessions. Subjects in the CON group completed 190 out of a potential 216 (88%) physiotherapist or coach led training sessions.

4.3.3 Kinematic and kinetic profile

Subjects in both the Core-PAC and CON groups demonstrated similar kinematic and kinetic profiles during baseline, posttest 1, and posttest 2 testing sessions. A typical kinematic profile across the three tasks showed subjects landing on the force plate in approximately 10-40° of knee flexion angle with the knee increasing to peaks of 55 - 75° flexion at mid-stance before decreasing to 10 - 30° flexion at the end of stance (Figure 4.2a-c). Peak knee flexion angles occurred at similar time points within mid stance for all three tasks. Subjects demonstrated a typical bimodal peak in abduction moment; the first, sharper peak was usually between 0.80 and 1.6 Nm/kg and occurred between heel contact and 20% of stance phase. A second more gradual peak of similar magnitude occurred at the end of stance during push-off phase (Figure 4.2d-f). Peak knee abduction moments always occurred within the first 20% of stance for all three tasks during baseline, posttest 1, and posttest 2 testing sessions.
4.3.4 Effect of the program

There were significant group by trial interactions for peak knee flexion angle during the SH ($P = 0.001$) and SC tasks ($P < 0.001$) (Table 4.2). Bonferroni corrected post hoc analyses revealed that the Core-PAC group demonstrated a significant increase in peak flexion angles during the SH task (Mean difference = 6.2°, 95% CI: 1.9-10.5°, ES = 1.01, $P = 0.034$) after the six-week training program (posttest 1) and during the SC (Mean difference = 8.5°, 95% CI: 4.8-12.2°, ES = 2.02, $P = 0.001$) and the SH (Mean difference = 10.0°, 95% CI: 5.7-14.3°, ES = 1.66, $P = 0.001$) tasks after reminding the subjects in the Core-PAC group to perform the tasks using the Core-PAC strategy (posttest 2). A comparison of changes in angles across tasks between a sample Core-PAC and CON subject during the posttest 1 testing session is demonstrated in Figure 4.1a-c. Scatterplots of raw data are provided in Appendix fourteen and interaction plots are provided in Appendix fifteen.

There was a significant main effect of time for peak knee abduction moment during the SC ($P = 0.022$) and USC ($P = 0.015$) (Table 4.2). Bonferroni corrected post hoc analyses did not demonstrate significant increases in peak knee abduction moments for the groups at posttest 1 or posttest 2 during SC and USC tasks.
Figure 4.2 Changes in peak flexion angle (a, b, c) and abduction moment (d, e, f) during the three movement tasks for a sample Core-PAC and a sample CON subject before and after the Core-PAC training program (posttest1). Flexion angles are greater in the negative direction and abduction moments are greater in the positive direction. After the training program, this Core-PAC subject shows increased flexion angles across all three tasks and decreased moments during the SH. Conversely, the CON subject shown here demonstrates decreased flexion angles across all three tasks, increased peak moments during the SC and SH tasks and decreased peak moments during the USC.
Side Hop

c) Flexion Angle (°)

-80 -60 -40 -20 0

Fraction of Stance Phase

0 0.2 0.4 0.6 0.8 1

f) Abduction Moment (Nm/kg)

-1.2 -1.0 -0.8 -0.6 -0.4 -0.2 0

Fraction of Stance Phase

0 0.2 0.4 0.6 0.8 1

Legend:
- Control (Pre)
- Control (Post)
- Intervention (Pre)
- Intervention (Post)
Table 4.2 ANOVA results and significance for group and time main effects and interaction effect

<table>
<thead>
<tr>
<th>Task</th>
<th>Group Effect</th>
<th>Time Effect</th>
<th>Interaction Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Side-cut</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peak Flexion Angle</td>
<td>$F(1, 17) = 5.062, P = 0.038^*$</td>
<td>$F(2, 34) = 5.262, P &lt; 0.01^*$</td>
<td>$F(2, 34) = 9.944, P &lt; 0.001^*$</td>
</tr>
<tr>
<td>Peak Abduction Moment</td>
<td>$F(1, 17) = 0.001, P = 0.976$</td>
<td>$F(2, 34) = 5.207, P = 0.022^*$</td>
<td>$F(2, 34) = 0.939, P = 0.373$</td>
</tr>
<tr>
<td><strong>Unanticipated Side-cut</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peak Flexion Angle</td>
<td>$F(1, 17) = 3.763, P = 0.069$</td>
<td>$F(2, 34) = 2.678, P = 0.101$</td>
<td>$F(2, 34) = 3.293, P = 0.066$</td>
</tr>
<tr>
<td>Peak Abduction Moment</td>
<td>$F(1, 17) = 0.049, P = 0.827$</td>
<td>$F(2, 34) = 4.806, P = 0.015^*$</td>
<td>$F(2, 34) = 0.774, P = 0.469$</td>
</tr>
<tr>
<td><strong>Side-hop</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peak Flexion Angle</td>
<td>$F(1, 17) = 4.220, P = 0.056$</td>
<td>$F(2, 34) = 5.521, P = 0.008^*$</td>
<td>$F(2, 34) = 8.109, P = 0.001^*$</td>
</tr>
<tr>
<td>Peak Abduction Moment</td>
<td>$F(1, 17) = 0.115, P = 0.739$</td>
<td>$F(2, 34) = 3.016, P = 0.062$</td>
<td>$F(2, 34) = 2.158, P = 0.131$</td>
</tr>
</tbody>
</table>

*Significant, $P < 0.05$
Table 4.3 Comparisons of peak knee flexion angles (°) and abduction moments (N·m/kg) between groups and across tasks for the three testing sessions (mean (standard deviation))

<table>
<thead>
<tr>
<th>Task</th>
<th>Baseline (n = 10)</th>
<th>Intervention Posttest1</th>
<th>Posttest2</th>
<th>Baseline (n = 9)</th>
<th>Control Posttest1</th>
<th>Posttest2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Side-cut Peak Flexion Angle *τφ</td>
<td>60.4 (5.7)</td>
<td>64.2 (7.2)</td>
<td>68.9 (4.1)</td>
<td>61.0 (5.5)</td>
<td>59.2 (4.7)</td>
<td>59.5 (3.5)</td>
</tr>
<tr>
<td>Unanticipated Side-cut Peak Flexion Angle</td>
<td>63.5 (6.2)</td>
<td>67.1 (5.3)</td>
<td>70.1 (4.5)</td>
<td>63.5 (5.0)</td>
<td>62.8 (6.3)</td>
<td>63.2 (4.9)</td>
</tr>
<tr>
<td>Side-hop Peak Flexion Angle*τ</td>
<td>62.6 (4.3)</td>
<td>68.8 (8.6)</td>
<td>72.6 (6.1)</td>
<td>64.3 (5.0)</td>
<td>63.2 (4.8)</td>
<td>63.5 (4.2)</td>
</tr>
<tr>
<td>Side-cut Peak Abduction Moment τ</td>
<td>1.13 (0.26)</td>
<td>1.27 (0.22)</td>
<td>1.23 (0.27)</td>
<td>1.05 (0.32)</td>
<td>1.25 (0.29)</td>
<td>1.32 (0.30)</td>
</tr>
<tr>
<td>Unanticipated Side-cut Abduction Moment</td>
<td>1.11 (0.36)</td>
<td>1.16 (0.38)</td>
<td>1.22 (0.49)</td>
<td>1.00 (0.24)</td>
<td>1.14 (0.32)</td>
<td>1.25 (0.44)</td>
</tr>
<tr>
<td>Side-hop Abduction Moment</td>
<td>1.20 (0.30)</td>
<td>1.25 (0.31)</td>
<td>1.18 (0.27)</td>
<td>1.11 (0.38)</td>
<td>1.35 (0.48)</td>
<td>1.30 (0.33)</td>
</tr>
<tr>
<td>Speed (average across tasks(m/s))</td>
<td>2.67 (0.17)</td>
<td>2.78 (0.23)</td>
<td>2.73 (0.26)</td>
<td>2.71 (0.22)</td>
<td>2.80 (0.18)</td>
<td>2.78 (0.21)</td>
</tr>
</tbody>
</table>

* Significant Interaction Effect
τ Significant Time Effect
φ Significant Group Effect
♦ Flexion Angle in Posttest2 is greater than Baseline
■ Flexion Angles in Posttest1 and Posttest2 are greater than Baseline
Table 4.4 Changes in peak knee flexion angles (°) and abduction moments (N·m/kg) for the intervention group relative to the control group across tasks for the three testing sessions (mean difference between groups (confidence interval))

<table>
<thead>
<tr>
<th>Task</th>
<th>Intervention to control group difference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Baseline to Posttest1 Baseline to Posttest2 Posttest1 to Posttest2</td>
</tr>
<tr>
<td>Side-cut Peak Flexion Angle</td>
<td>5.6 (9.6-1.6) 10.0 (13.4-6.6) 4.4 (7.7-1.1)</td>
</tr>
<tr>
<td>Unanticipated Side-cut Peak Flexion Angle</td>
<td>4.3 (8.6-0.03) 6.9 (12.2-1.6) 2.6 (5.8-0.63)</td>
</tr>
<tr>
<td>Side-hop Peak Flexion Angle</td>
<td>7.3 (12.4-2.2) 10.8 (12.1-2.5) 3.5 (10.7-3.9)</td>
</tr>
<tr>
<td>Side-cut Peak Abduction Moment</td>
<td>-0.06 (0.16- -0.28) -0.17 (0.21- -0.33) -0.11 (0.08- -0.19)</td>
</tr>
<tr>
<td>Unanticipated Side-cut Abduction Moment</td>
<td>-0.09 (0.10- -0.28) -0.14 (0.14- -0.32) -0.05 (0.08- -0.25)</td>
</tr>
<tr>
<td>Side-hop Abduction Moment</td>
<td>-0.19 (0.03- -0.41) -0.21 (0.01- -0.39) -0.02 (0.02- -0.36)</td>
</tr>
</tbody>
</table>
Table 4.5 Change in peak knee flexion angles (°) and abduction moments (N·m/kg) for the intervention and the control groups across tasks for the three testing sessions (mean difference (confidence interval))

<table>
<thead>
<tr>
<th>Task</th>
<th>Intervention (n = 10)</th>
<th>Control (n = 9)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Baseline to Posttest1</td>
<td>Baseline to Posttest2</td>
</tr>
<tr>
<td>Side-cut Peak Flexion Angle</td>
<td>3.8 (-0.9 - 8.6)</td>
<td>8.5 (4.3 - 12.8)</td>
</tr>
<tr>
<td>Unanticipated Side-cut Peak Flexion Angle</td>
<td>3.6 (-1.3 - 8.5)</td>
<td>6.6 (-0.1 - 13.4)</td>
</tr>
<tr>
<td>Side-hop Peak Flexion Angle</td>
<td>6.2 (0.3 - 12.1)</td>
<td>10 (5.1 - 15.0)</td>
</tr>
<tr>
<td>Side-cut Peak Abduction Moment</td>
<td>0.14 (-0.01 - 0.29)</td>
<td>0.1 (-0.09 - 0.29)</td>
</tr>
<tr>
<td>Unanticipated Side-cut Abduction Moment</td>
<td>0.05 (-0.15 - 0.26)</td>
<td>0.11 (-0.08 - 0.31)</td>
</tr>
<tr>
<td>Side-hop Abduction Moment</td>
<td>0.05 (-0.16 - 0.25)</td>
<td>-0.02 (-0.23 - 0.18)</td>
</tr>
<tr>
<td>Speed (average across tasks (m/s))</td>
<td>0.11</td>
<td>0.06</td>
</tr>
</tbody>
</table>
4.4 Discussion

There is a need for randomized controlled trials to discern the separate effects of training components contained within multimodal injury prevention training programs. Training effects demonstrated without a control group have been shown to inflate effect sizes as compared to controlled trials (Lipsey and Wilson, 1993). Our study design provided strong evidence that the changes in knee flexion angles observed in the intervention group were a result of the Core-PAC. Several RCTs have demonstrated improvements in biomechanical risk factors during high-risk athletic movements (Cochrane et al., 2010; Herman et al., 2008; Kato et al., 2008; Lim et al., 2009; Onate et al., 2005; Ortiz et al., 2010). RCTs that have focused on the effects of multimodal team warm-up sessions on biomechanical variables (Kato et al., 2008; Lim et al., 2009; Ortiz et al., 2010) have not, to date, investigated the separate effects of individual training components. RCTs that have investigated the separate effects of individual training components (Cochrane et al., 2010; Herman et al., 2008; Onate et al., 2005) often include subjects trained or instructed in a laboratory or gym environment rather than on the field. Given that a team warm-up may be the most practical and consistent opportunity to implement and enhance compliance of an injury prevention program (Soligard et al., 2010), investigating the effects of individual training components that are implemented within team warm-ups is necessary. Controlled field-based studies are an extension of those performed in the laboratory. As we improve our external validity with field-based interventions (i.e. training on the field vs. the lab and training in groups or teams vs. individuals), we compromise our internal validity because of the increased number of potential confounding factors. However, the controlled field-based study is also performed in “ideal conditions” (Finch, 2006). Finch (2006) cautions that the artificial environments created by targeted and controlled interventions involving players and coaches that are provided reminders and incentives for their participation do not necessarily continue within amateur sports teams after the study is completed.

Our findings partially support our hypothesis that the Core-PAC would improve biomechanical risk factors at the knee during a SC, USC, and a SH task after a six-week
training program. The Core-PAC group demonstrated significant increases in peak knee flexion angle of 10% during a SH task after the six-week training program. The effects of the Core-PAC instruction were even greater after a reminder to perform the tasks using the Core-PAC movement strategy with a 14% increase during SC and a 16% increase during SH tasks. Peak knee abduction moments for the SC and USC tasks increased across testing sessions for both groups. This was an unexpected finding that we cannot explain. This is the first randomized controlled trial to demonstrate improvements in biomechanical risk factors for ACL injury as a result of isolated movement training implemented within a team warm-up.

The potential strain on the ACL is decreased with increasing knee flexion angles (Chapter 1, pages 2-4). An increase in knee flexion angle may offer the ACL enough of a protective mechanism to influence the combination of joint positions and forces that may contribute to an ACL injury. As explained previously, we do not know how much change in knee flexion angle is clinically significant, especially when combined with the interaction of other protective and strain-inducing factors. An increase in knee flexion angle may indicate that forces are being transferred to the large muscle groups (gluteus maximus, quadriceps femoris) in the sagittal plane rather than inert ligamentous structures such as the ACL and the medial collateral ligament (MCL) in the frontal plane (Hewett et al., 2002; Pollard et al., 2006). However, we found no significant change in peak abduction moment during the three tasks. Therefore, relative to the two dependent variables we investigated (peak knee flexion angle and abduction moment), there may be a net positive effect but we must be cautious of making such inferences based on limited information.

The increase in peak flexion angles combined with the lack of an effect on peak abduction moments found in our study is similar to other study results (Cochrane et al., 2010; Dempsey et al., 2009; Lim et al., 2009). Dempsey et al. (2009) investigated the effects of a six-week individualized training program aimed at modifying whole body side-cutting technique. They demonstrated a 36% decrease in valgus moments during the weight acceptance phase of
stance but did not observe a change in flexion angles at the knee (opposite to our results). Lim et al. (2009) demonstrated increased knee flexion angles ($P = 0.023$) but also increased abduction moments ($P = 0.043$) in an experimental group that completed an eight-week, multimodal training program in a group setting, as compared to a control group. Increased peak valgus moments have been reported in a control group of male subjects during a side-cutting task (Cochrane et al., 2010). The authors suggested that the increase in valgus moments may have been a result of random variation or typical in-season conditioning after the twelve week period between testing sessions.

In our study, the Core-PAC group did not decrease peak abduction moments after the reminder. This is in contrast to our previous findings (Chapter 2) where we demonstrated significant decreases in peak abduction moments after immediate instruction. One of the main differences between our two studies was the higher level of soccer played by the subjects in the present study (provincial level) compared to the previous study (community level). Sigward and Powers (2006) compared abduction moments produced by experienced and novice soccer players during a side-cutting task. They found that experienced players had greater abduction moments at the knee as compared to their less experienced counterparts and suggested these increases may be consistent with the principles of skill acquisition where a pattern of decreased co-contraction and increased moments occur with increased movement efficiency (Sigward and Powers, 2006). The lack of effect on peak abduction moments in response to our reminder may also be a result of providing this information after six weeks of Core-PAC training rather than as a novel instruction as it was in our previous study. If the critical difference in the new movement is not clearly conveyed, the reminder may become "redundant" because the information that is provided is no different than what subjects perceive themselves to be doing already (Newell, 2003).

Finally, the lack of improvement in the CON group despite performing the same injury prevention exercises within the warm-up is consistent with other studies. Pollard et al. (2006)
demonstrated no changes in knee flexion or valgus angles in adolescent female soccer players after a season-long training program implemented within a team warm-up, although they did show improvements in kinematics at the hip. Vescovi and VanHeest (2009) conducted an RCT and found no performance improvements in speed, jump height, or agility between adolescent female soccer players undergoing an injury prevention warm-up and those that did not after 6 and 12 weeks. The lack of an effect within our CON group and within other studies (Ortiz et al., 2010; Pollard et al., 2006; Vescovi and VanHeest, 2009) further supports our hypothesis that the improvements observed in the intervention group were a result of the Core-PAC.

4.4.1 Limitations

Our study was prone to Type II error because of our small sample size and the large variance in our data. Despite the small sample, we were able to demonstrate a significant improvement in peak knee flexion angle during the SH task. The risk of Type I error in our study, as a result of multiple comparisons, was controlled for with the use of a Bonferroni correction. We acknowledge the potential for contamination within our subjects. However, we controlled for contamination by having subjects blinded to the study hypothesis (i.e. the most advantageous group). We did not screen for high-risk or low-risk subjects. Myer et al. (2007) showed that female soccer and basketball players classified as “high-risk” were able to significantly decrease abduction moments at the knee during a drop jump after a training program whereas those athletes classified as “low-risk” were not. The improvements observed in our study may have been higher if we had screened for and only included high-risk athletes.

4.4.2 Future directions

The Core-PAC shows promise in providing a means of modifying technique in high-risk movements for ACL injury. The Core-PAC should be evaluated with and against other forms of technique modification and included in the most time-efficient, yet comprehensive, multimodal training programs. As has been appropriately suggested, the next step should be to evaluate the transfer of biomechanical improvements seen in the laboratory to the competitive sporting
environment and to combine these studies with large-scale epidemiological studies evaluating incidence of ACL injury (Dempsey et al., 2009).

4.5 Conclusion

The results of this study suggest that the Core-PAC may be one method of modifying high-risk movements such as side-cutting and single-leg landing. Young female soccer players demonstrated improvements in peak knee flexion angle following completion of a six-week movement training program that was implemented within a team warm-up. Our results support the inclusion of Core-PAC instruction as part of a comprehensive ACL injury prevention program.
5 Overall Discussion, Synthesis, and Future Directions

5.1 Overview

The Core Position and Control movement strategy (Core-PAC) was originally developed by our group in 1997 as a clinical technique to treat recalcitrant lumbo-pelvic-hip conditions. It was based on scientific evidence and theory (Hodges and Richardson, 1997a; Kibler et al., 2006; Putnam, 1993; Richardson and Jull, 1995) and applied to the rehabilitation of various musculoskeletal conditions, including anterior cruciate ligament (ACL) rehabilitation. As a result of clinical experience and a review of the scientific literature, the application of this technique in ACL injury prevention was considered.

We initiated this series of studies in 2004 by reviewing the literature (Chapter 1 - Introduction) and recognized the increasing scientific support for training programs as effective means of modifying high-risk movement patterns and decreasing ACL injury (Griffin et al., 2000; Hewett, 2000). A common mechanism of ACL injury in young female soccer players occurs during side-cutting movements when the athlete’s centre of mass (COM) is at a distance from the base of support (BOS) combined with potentially insufficient proximal control (Boden et al., 2000; Olsen et al., 2004). The athlete lands with a relatively straight knee combined with valgus loading (decreased knee flexion and increased abduction moment) (Krosshaug et al., 2007a). There was very little research on proximal control or technique training at this time. The Core-PAC was thought to have a potential role in modifying these high-risk movements.

We established adequate test-retest reliability during a preplanned (SC) and an unanticipated (USC) soccer-specific side-cut and a side-hop (SH) task for peak knee flexion angle and abduction moment (Chapter 2). We conducted a single-group pretest-posttest study (Chapter 3) to evaluate our hypotheses that implementing a Core-PAC training program into a team warm-up prior to regular soccer practice would be feasible, and that the Core-PAC would improve peak knee flexion angles and abduction moments in a cohort of female youth soccer players after immediate instruction and after a four-week training program. We found that the
Core-PAC was easily understood and accepted by the subjects and incorporated into their warm-up activities and self-directed homework sessions with good compliance. The Core-PAC also demonstrated significant improvements in peak knee flexion angles and abduction moments after immediate instruction and showed improvement in some individuals after a four-week training program. Based on these findings, we conducted a randomized controlled trial (RCT) (Chapter 4) to further investigate the effects of Core-PAC training within a team setting on peak knee flexion angles and abduction moments during the same three high-risk movements. The Core-PAC-trained group demonstrated significant increases in knee flexion angles during the SH task after a six-week training program and during the SC and SH tasks after a reminder to use the Core-PAC. The control group showed no significant changes across tasks after completing the same training program without the Core-PAC instruction and feedback.

5.2 Improving the effectiveness of injury prevention training programs

There is evidence that training programs can change muscle activation patterns, improve balance, decrease landing forces, improve biomechanics, and, most importantly, decrease ACL injury incidence (Hewett et al., 2007). However, despite an intense research focus, non-contact ACL injury rates have not demonstrated an overall decline and females remain at greater risk than their male counterparts (Agel et al., 2005). Hewett et al. (2007) have suggested this may be due to a lack of widespread programs and overall awareness. Given the demonstrated effectiveness of specific ACL injury prevention programs, compliance and uptake of the programs may be a critical factor in decreasing ACL injuries overall (Finch, 2006; Soligard et al., 2010). Finch (2006) suggests that athletes, coaches, and sports administrators will only adopt injury prevention strategies once they are convinced that the proposed strategies will actually prevent injuries, will not change the nature or enjoyment of the sport, will enhance rather than negatively affect performance, and are easy to do (Eime et al., 2004). In youth soccer, coaches are often the decision makers and potential implementers of injury prevention programs. Coaches are less likely to implement injury prevention programs if they are not soccer-specific
or take too much time away from regular practice (Soligard et al., 2010). Therefore, effective ACL injury prevention training programs must accomplish two goals: 1) improve known risk factors and 2) be adopted by coaches and athletes and performed on a consistent and ongoing basis. The results of this dissertation will be summarized in this context.

5.3 The Core-PAC movement strategy may improve biomechanical risk factors

In this section, I will compare and synthesize the significant results demonstrated in Study 2 (Chapter 3) and our results from Study 3 (Chapter 4) and relate them to the test-retest reliability results of Study 1 (Chapter 2) and their clinical relevancy.

5.3.1 Training

After training, Study 2 graphs demonstrated a trend to increased peak flexion angles and decreased peak abduction moments across all three tasks in a single group pretest-posttest study of female adolescent soccer players. This was not confirmed by the RCT in Study 3 except for the SH task. The Core-PAC group in Study 3 demonstrated a significant increase in peak flexion angles after training that was greater than the standard error of measurement (SEM) for the SH task reported in Study 1. Although the graphs in Study 2 are only descriptive in nature, the robustness of the SH task was demonstrated within the more rigorous RCT. The main differences in the SH task compared to the SC and USC tasks were 1) hopping rather than striding and 2) not having to kick the soccer ball during the SH task. It may have been easier for subjects to transfer the Core-PAC to the SH task without the distraction of having to kick the soccer ball in the SC and USC tasks.

5.3.2 Immediate instruction / reminder

After immediate instruction in Study 2, significant improvements in peak knee flexion angles and peak abduction moments were observed across all three tasks. All outcome measures except peak abduction moments during the USC and SH tasks were above estimated SEM values from Study 1. As discussed in Chapter 4, page 99, the single-group pretest-posttest design in Study 2 demonstrated inflated effects as compared to the results from our RCT (Study
3). After reminding subjects to use the Core-PAC in the RCT, significant improvements were only demonstrated for peak knee flexion angles during the SH and SC tasks, both of which were well above estimated SEM values. The USC did not demonstrate a significant improvement in peak flexion angles during the RCT.

5.3.3 Unanticipated side-cut task

Although the USC did not demonstrate a significant improvement in peak flexion angles during the RCT, the interaction effect ($P = 0.066$) and group effect ($P = 0.069$) were near significance and suggests the study may have been underpowered to detect these changes. The addition of an unanticipated component to a task has been shown to create increases in biomechanical risk factors (i.e. risk factors worsened) in other laboratory-based studies (Besier et al., 2001a; Sell et al., 2006). However, we did not see a significant difference in peak flexion angles or abduction moments between the preplanned (SC) and the unanticipated (USC) tasks across our three studies. The lack of difference between preplanned and unanticipated side-cutting tasks has been observed in another study (Dempsey et al., 2009). In our study the lack of difference produced by the reaction component in the USC may have been a result of the constrained movement of the tasks (single-step and end-point target of the ball in the SC and USC) that restricted the variability in response. Another possibility is that either the onset of the direction cues was delayed sufficiently to allow the subjects to preplan their movement, or the subjects adjusted their speed to allow more time to respond. Timing was not significantly different between the SC and USC tasks for most subjects, suggesting the unlikelihood of the latter explanation.

5.3.4 Summary and implications of results

As explained in (Chapter 3.4.4, page 94), we don’t know how much or what combination of changes may be clinically important in side-cutting tasks. Applying the prospective findings of Hewett et al. (2005a) (2.5 times greater abduction moments and 10.5° less knee flexion angle in injured vs. non-injured athletes) during a drop jump task may not be valid for interpreting
changes during the side-cutting tasks in our study. However, these results may suggest that clinically important differences between subjects are quite large and may be greater than the thresholds indicating change above measurement error that are established in statistical estimates by our SEMs. Although we did not calculate the minimal detectable change (MDC = SEM x Z value x \sqrt{2}) from our SEM estimates, this could have been calculated to provide an indicator of changes that were above measurement error. For example, we could be confident at the 95% confidence level that a true change occurred for an individual that improved greater than 5° (1.9 x 1.96 x \sqrt{2}) and that this was not due to measurement error.

In this dissertation, the Core-PAC demonstrated an overall positive effect on kinematic (flexion angles) and, to a lesser extent, kinetic (abduction moments) risk factors for ACL injury at the knee after immediate instruction and after a reminder to use the strategy. The improvements were less evident when the subjects were not reminded or instructed prior to completing the tasks and were, therefore, transferring training effects from a more practical, field-based soccer warm-up (i.e. they performed the task with their existing strategy). Others have found similar difficulty in transferring training effects from field-based multimodal training to the laboratory (Ortiz et al., 2010; Pollard et al., 2006; Vescovi and VanHeest, 2009). Previous studies have demonstrated improvements after individual training and then testing the same movement (Dempsey et al., 2009; Hewett et al., 1996; Onate et al., 2005), often with video feedback and other effective but not readily accessible equipment or methods. Evaluating the effects of practical training programs implemented in the field that use group rather than individual instruction, assists in bridging the gap between the field and the laboratory. An important and novel finding in this dissertation was the significant improvement in peak knee flexion angle demonstrated during the SH task after training. Forces that have been shown to increase strain on the ACL, such as anterior translation and frontal and transverse plane moments, are reduced with increasing knee flexion angles (Hame et al., 2002; Markolf et al., 1995). This improvement was demonstrated within the rigors of an RCT, wherein subjects were not reminded to transfer the Core-PAC strategy that had been trained within a team warm-up.
5.4 Strengths of this research

5.4.1 Methodology

This dissertation provides the first RCT to evaluate the effects of an individual training component implemented in a practical, team-based warm-up program on biomechanical risk factors for ACL injury. This study design helped control for selection bias and confounding variables (e.g. minor injuries and training effects). Randomization to individual subjects instead of teams improved the internal validity of the study. The nature of the tasks investigated was intentionally constrained to accentuate a reaching movement if it was present and more clearly observe the potential effects of the Core-PAC. The kicking of a soccer ball after side-cutting and the inclusion of an unanticipated component improved the sport-specificity and ecological validity of the tasks. The evaluation of both immediate instruction / reminders and transfer of the independent effects of a movement strategy (Core-PAC) after training was another strength and novel aspect of this research.

5.4.2 Core-PAC program

Technique modification using a movement strategy, such as the Core-PAC, that is implemented within a team warm-up shows promise for increasing compliance in coaches and athletes based on the following criteria:

**Time-efficient** - The Core-PAC was implemented within a 20-minute team warm-up and, therefore, did not take more time than the subjects’ regular warm-ups. Studies show that prevention strategies requiring additional dedicated time within gym-based programs may have decreased compliance (Finch, 2006). The warm-up provides a consistent, dedicated opportunity to train movement; just as the players will practice soccer-specific skills such as passing and shooting, cutting and landing are skills that must also be practiced to prevent injury.

**Cost-effective** - Similar to other multimodal ACL injury prevention soccer warm-up programs (PEP, FIFA 11+), the implementation of the Core-PAC did not require additional equipment beyond standard soccer equipment (i.e. cones, the styrofoam ball is optional).
Soccer-specific and performance-enhancing - The Core-PAC is a movement strategy which extends beyond a simple description of the movement pattern and includes with it: how the learner organizes motor, sensory, and perceptual information necessary to perform the tasks in different environments (Shumway-Cook and Woollacott, 2007). Therefore, the movement strategy can readily be incorporated into soccer-specific drills within a soccer practice and during soccer games; such incorporation offers increased opportunity to practice the Core-PAC in a dynamic, sport-specific environment. Further, it has direct application to proper technique in various soccer-specific skills such as engaging in a tackle (Figure 5.1) and kicking a ball (Putnam, 1993), which may encourage coaches and players to more readily adopt the strategy (Soligard et al., 2010).

Figure 5.1 - Soccer tackle technique demonstrating a) a “reaching” strategy and b) a Core-PAC strategy.

Non-fatiguing – A team warm-up must not induce fatigue or it may then contribute to an increased risk of injury and decreased performance (Alentorn-Geli et al., 2010; Gilchrist et al., 2008). Other important neuromuscular training components for injury prevention, such as plyometrics and strength, must be of sufficient intensity to overload the neuromuscular system
and provide a physiological training effect (Myer et al., 2006). These are high demand activities that may place excessive stress on adolescents that already have demanding training and conditioning programs (Hewett et al., 2007). Therefore, the primary benefit of a team warm-up may not be in improving strength and power (Vescovi and VanHeest, 2009) but in providing a neuromuscular stimulus that increases the response of muscles prior to playing or training (Fradkin et al., 2006). The Core-PAC is less physiologically demanding on the athlete than some of these other training components and, in fact, is focused more on "how" rather than "what" is being performed in the warm-up.

**Simple instruction and monitoring** - Subjects found the goal of "moving from the centre" easy to understand and perform (Chapter 3.4.1, page 91). Informal feedback from the coaches in Study 3 suggested that the instructions and monitoring of the Core-PAC during the warm-up was simple and practical from a coach’s perspective. We have previously observed that even trained physiotherapists may have difficulty in identifying valgus alignment of the knee during dynamic athletic tasks (Ekegren et al., 2009). In a setting in which those responsible for injury prevention may not have the frame of reference of a trained physiotherapist, a strategy’s simplicity and ease of practical application may have a meaningful impact on its success.

### 5.5 Limitations of this research

Although they provide valuable information, a limitation of laboratory-based experiments such as ours is inferring injury risk through the evaluation of non-injurious movements performed in a controlled setting (McLean, 2008). The relationship between ACL strain and external joint loading also remains unclear (Sell et al., 2006). Although we measured a core set of clinically relevant biomechanical risk factors, there were many others that could have been measured (e.g. biomechanics of the hip and trunk and muscle activation patterns). We had a small sample size, as was acknowledged in Studies 2 and 3, and were therefore prone to type II error. Finally, we do not know how well the positive effects we did find would transfer to a competitive, “real-world” sport setting or if they are maintained at long-term follow-
5.6 Future directions

Training components that are most consistently included in effective injury prevention training programs and are evidence-based include plyometrics, balance, strength, and technique modification (Hewett et al., 2007). However, no isolated training component has been shown to decrease ACL injury except technique modification (Ettlinger et al., 1995; Griffis et al., 1989). Established movement patterns, such as those used by an athlete to perform a side-cutting task, are often difficult to change and may require a catalyst to facilitate change (Newell, 2003). Furthermore, each athlete may respond differently or require a different catalyst to induce such change. It was important in this dissertation to evaluate the efficacy of this novel movement strategy (Core-PAC) in isolation but, in practical application, the Core-PAC should be complemented by other, existing instruction techniques. It is not clear which instructions and techniques are most effective at changing high-risk movement for ACL injury. We also don’t know how long it takes to modify these movements or the appropriate age to start such movement training. With the established importance of technique training to change high-risk movement patterns for ACL injury, future studies should focus on these issues and questions.

Technique modification may be most effective using a more individualized and interactive process (Dempsey et al., 2009; Onate et al., 2005) and individualized evaluation and instruction should be considered if sufficient resources permit. However, team or group training remains the most feasible means of implementing injury prevention training, especially in youth sports. Therefore, future studies should investigate methods of technique modification in these settings with coaches implementing the programs. Screening and real-time feedback using marker-less motion capture and wearable motion sensors to evaluate and monitor movements during competitive training and games may prove valuable in the future (McLean, 2008).
References


Appendices
Appendix one: Subject consent form

THE UNIVERSITY OF BRITISH COLUMBIA

School of Rehabilitation Sciences
Faculty of Medicine
T325-2211 Wesbrook Mall
Vancouver, British Columbia V6T 2B5

Consent Form - Subjects

The effectiveness of a novel warm-up in decreasing risk factors for anterior cruciate ligament injury in female youth soccer players.

Principal Investigator: Dr. Susan R. Harris, School of Rehabilitation Sciences, UBC, Phone 604-822-7944

Co-Investigator(s): Mr. Rick Celebrini (PhD Candidate), Drs. Janice Eng, William Miller and Donna MacIntyre, School of Rehabilitation Sciences, UBC.

Purpose:

Soccer is a great sport but over the last few years an increasing number of young women are sustaining serious knee injuries. We are trying to investigate different methods of preventing these injuries. We are conducting a research project to assess the effect of a warm-up on changing some of the movement patterns thought to contribute to these serious knee injuries.

You are invited to participate in this study because you are a healthy, 14-17 year old female soccer player. The information contained in this sheet will provide you with more details about the study so that you can decide whether you wish to participate.

Study Procedures:

If you choose to participate in this study, you will be contacted to further explain the details of the study, answer any questions you may have, ensure that you qualify for the study, and to set up an initial testing session at the GF Strong Rehabilitation Center.

The testing will consist of a 10-minute warm-up on a stationary cycle, followed by reflective markers and electrodes attached by tape to the leg, hip, and pelvis of your dominant side. Electrodes and markers will be applied by Rick Celebrini or his assistant.
You will then be asked to perform 3 movements. First, you will stand in an athletic ready position and react as quickly as possible to a set of lights by planting your dominant leg on a platform and then kicking a soccer ball to the left or right. Next, you will stand beside the platform and step onto it with your dominant leg. Finally, you will jump off a 30 cm box onto the platform. You will do each of these movements 7 times after practicing several times. These movements will be assessed for the position and the forces on your knee joint and the activity of your muscles through video and electrical monitoring instruments. You will not be identifiable from the video data collected.

Part 1. The first part of this study is called a reliability study. That means that we will do the same tests more than once to evaluate how consistent the measures are from time to time. To do this we will then take off all of the markers and electrodes and give you a break. After this, we will put the markers back on and you will repeat the same movements again. Finally, you will be given specific instructions to do the movements and we will test you a third time.

The three testing sessions will take approximately 1.5 hours for each of the first two and 1/2 hour for the last one. The warm-ups will be 10 minutes each session and there will be breaks. You will be notified immediately of any changes that may affect your decision to continue participating in the study.

Part 2. The second part of the study will assess the effect of a warm-up on the 3 movements that we are testing and that have been described above. By the flip of a coin you will be assigned to one of two groups within your soccer team, each led by a physiotherapist before each practice and game. One group will be instructed to move from the trunk first during a series of athletic tasks. The other group will be instructed to move with their usual athletic movements during the same tasks.

After six weeks of this training you will be asked to return to the GF Strong Rehabilitation Center for retesting of the same 3 movements. This last testing session will take approximately 1.5 hours and the warm-up will be 10 minutes before the testing session. You will be notified immediately of any changes that may effect your decision to continue participating in the study.

Exclusion Criteria:
You will not be eligible to participate in this study if you 1) have had a severe back or lower extremity injury in the past, 2) have had any injury during the six weeks prior to the study, or 3) are presently using a supplemental exercise based training program such as a gym workout.

Risk Section:
One of the movements that you will be tested on is a quick reaction, cutting maneuver that could cause injury. You will complete a warm-up and perform several practice trials to minimize any risk of injury. **Signing this consent form in no way limits your legal rights against the sponsor, investigators, or anyone else.**

There will be no direct clinical benefit from participating in this study.
Stipend:

You will be given a stipend of $50.00 to cover transportation, parking, and for your participation in each of the two lab testing sessions (approx. 6 hours) for a total of $100.00.

Confidentiality:

Your identity will be kept confidential. All documents will be identified only by code number and kept in a locked filing cabinet.

Your confidentiality will be respected. No information that discloses your identity will be released or published without your specific consent to the disclosure. However, research records and medical records identifying you may be inspected in the presence of the Investigator or his or her designate by representatives of Health Canada, and the UBC Research Ethics Board for the purpose of monitoring the research. However, no records, which identify you by name or initials, will be allowed to leave the Investigators’ offices. The only people having access to this information will be the investigators mentioned above and the research assistants.

Contact for information about the study:

If you have any questions or desire further information with respect to this study, you may contact Dr. Donna MacIntyre or Rick Celebrini at 604-822-0799.

Contact for concerns about the rights of research subjects:

If you have any concerns about your treatment or rights as a research subject, you may contact the Research Subject Information Line in the UBC Office of Research Services at 604-822-8598.
Part 1 Consent for Reliability Study: For parent/guardian if subject less than 19 years of age

Your daughter’s participation in this study is entirely voluntary and she may refuse to participate or withdraw from the study at any time without jeopardy to her place within the team. You do not have to provide any reasons for your decision. Unless specified otherwise she may be contacted in the future for related studies. At that time she can refuse to participate and her name will be removed from future correspondence. If she decides to participate in future studies, she will be asked to sign another consent form specific to that study.

Your signature below indicates that you have received a copy of this consent form for your own records. Your signature does not waive any of your/your daughter’s legal rights.

Your signature indicates that you consent for your daughter to participate in this study.

Please return this portion of the consent form in the self addressed envelope and keep the rest of the form for your records.

I consent to my daughter’s participation in this study.

__________________________________________________________  ____________________________________________________________
Name of Parent/guardian  (Please Print)  Name of Witness (Please Print)

__________________________________________________________  ____________________________________________________________
Signature of Parent/guardian  Date  Signature of witness  Date

__________________________________________________________
Name of Investigator  (Please Print)

__________________________________________________________
Signature of Investigator  Date

I wish to be contacted for future studies - YES____  NO____
Part 1 Assent for Reliability Study: For subjects less than 19 years of age

I have had the opportunity to read this consent form, to ask questions about my participation in this research, and to discuss my participation with my parents. All my questions have been answered. I understand that I may withdraw from this research at any time, and that this will not interfere with the availability to me of other health care. I have received a copy of this consent form. If I write and sign my name below, it means that I agree to be in the study.

_______________________________________________________
Printed name of subject

_______________________________________________________  _____________
Signature  Date
Part 2 Consent for Warm-up Study: For parent/guardian if subject less than 19 years of age

Your daughter’s participation in this study is entirely voluntary and she may refuse to participate or withdraw from the study at any time without jeopardy to her place within the team. You do not have to provide any reasons for your decision. Unless specified otherwise she may be contacted in the future for related studies. At that time she can refuse to participate and her name will be removed from future correspondence. If she decides to participate in future studies, she will be asked to sign another consent form specific to that study.

Your signature below indicates that you have received a copy of this consent form for your own records. Your signature does not waive any of your/your daughter’s legal rights.

Your signature indicates that you consent for your daughter to participate in this study.

Please return this portion of the consent form in the self addressed envelope and keep the rest of the form for your records.

I consent to my daughter’s participation in this study.

____________________________________  __________________________________
Name of Parent/guardian (Please Print)  Name of Witness (Please Print)

____________________________________  __________________________
Signature of Parent/guardian  Date  Signature of witness  Date

____________________________________
Name of Investigator (Please Print)

____________________________________
Signature of Investigator  Date

I wish to be contacted for future studies - YES____

NO____
Part 2 Assent for Warm-up Study: For subjects less than 19 years of age

I have had the opportunity to read this consent form, to ask questions about my participation in this research, and to discuss my participation with my parents. All my questions have been answered. I understand that I may withdraw from this research at any time, and that this will not interfere with the availability to me of other health care. I have received a copy of this consent form. If I write and sign my name below, it means that I agree to be in the study.

__________________________________________
Printed name of subject

______________________________  ________________
Signature                    Date
Appendix two: Checklist for subject scheduling

Name:

Questions to ask before scheduling:

1. Check inclusion/exclusion criteria:

<table>
<thead>
<tr>
<th>Inclusion</th>
<th>√ or X</th>
<th>Exclusion:</th>
<th>√ or X</th>
</tr>
</thead>
<tbody>
<tr>
<td>14-17 years</td>
<td></td>
<td>1) have had a severe back or lower extremity injury in the past,</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>2) have had any injury during the six weeks prior to the study, or</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>3) are presently using a supplemental exercise based training program such as a gym workout.</td>
<td></td>
</tr>
</tbody>
</table>

2. Check activity level:

<table>
<thead>
<tr>
<th>Activity</th>
<th>Duration</th>
<th>Frequency (days/wk)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
3. Check availability:

<table>
<thead>
<tr>
<th>M</th>
<th>T</th>
<th>W</th>
<th>Th</th>
<th>F</th>
<th>Sat</th>
<th>Sun</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Appendix three: Testing information sheet for research subjects

THE UNIVERSITY OF BRITISH COLUMBIA

School of Rehabilitation Sciences
Faculty of Medicine
T325-2211 Wesbrook Mall
Vancouver, British Columbia V6T 2B5

Testing Information for research subjects

Dear Soccer Player,

Thank you for agreeing to be part of the Soccer study. Your first testing session has now been scheduled and will take place at:

GF Strong Rehabilitation Centre

4255 Laurel St.
Vancouver, BC, V5Z 2G9

From the main entrance of GF Strong you will turn left down the long corridor behind the elevators. Look out for the overhead sign saying Research Laboratory and turn right.

What to wear

You will be provided with a pair of lycra shorts to wear during testing. These will have a small hole cut out over the right hip. Please wear your own white T-shirt and runners with low-cut socks. You will be asked to wear the same pair of runners for the 2nd testing session in approximately 6-12 weeks time.

What to bring

You may wish to bring a bottle of water and some snacks.

Testing procedures

The testing should take no more than two hours. First we will measure you, weigh you and check your alignment. After this you will perform a 10-minute warm-up on a stationary cycle and then Rick and Christina will attach reflective markers and electrodes to your right leg, hip and pelvis. These markers are completely pain-free. You will then perform a series of soccer-like movements.

Contact for information about the study:

If you have any questions or desire further information with respect to this study, you may contact Dr. Donna MacIntyre at 604-822-0799.

Thank you for participating. We look forward to seeing you.

Kind regards,

Rick Celebrini (PT, PhD candidate) and Christina Ekegren (PT, MSc candidate)
Appendix four: Subject information sheet

Data Sheet
Athlete to complete

Name: _______________________________ Date of birth: ___________
(yyyymm/dd)

Address: ___________________________________________________________

Postal code: _______________________________________________________

Home phone: _____________________ Cell: ___________________________

E-mail: ___________________________________________________________________

Next of kin (eg. parent’s name): _________________________________________

Relationship to you: _______________________________________________

Phone no: daytime: ___________________ evening: _______________________

Leg dominance
Which leg would you feel most comfortable kicking a ball with?  R  L

Injuries
Have you had any injuries/conditions/surgeries that have interfered with sport? Yes  No  Unsure

For each injury/condition/surgery:
Description (include side of injury)  Date  Any residual problems?

______________________________________________________________

______________________________________________________________

______________________________________________________________

______________________________________________________________

______________________________________________________________

______________________________________________________________

______________________________________________________________

______________________________________________________________

______________________________________________________________

______________________________________________________________

______________________________________________________________

______________________________________________________________

Data collection sheet Version 1

31/01/07
ID #

**Tester to complete**

<table>
<thead>
<tr>
<th>Date:</th>
<th>Measurements (cm):</th>
</tr>
</thead>
</table>
| (dd/mm/yyyy) | **Foot:**
|  | h | Length: | Heel to toe |
| | P1 | Perimeter: | Min near ankle |
| | P2 | Perimeter: | Arch |
| | P3 | Perimeter: | Ball |
| **Leg:** |  | Length: | Knee centre to ankle centre |
| | P1 | Perimeter: | Knee |
| | P2 | Perimeter: | Max |
| | P3 | Perimeter: | Min near ankle |

Leg Tested: __________
Weight (kg): __________
Height (cm): __________

Data collection sheet Version 1

31/01/07
### Appendix five: IRED marker placements

<table>
<thead>
<tr>
<th>IRED no.</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Head of 5th metatarsal</td>
</tr>
<tr>
<td>2</td>
<td>Dorsal foot (midpoint of metatarsals and ankle joint)</td>
</tr>
<tr>
<td>3</td>
<td>Lateral heel</td>
</tr>
<tr>
<td>4</td>
<td>Lateral malleolus</td>
</tr>
<tr>
<td>5</td>
<td>Mid-shank (anterior aspect of tibia, midpoint of ankle &amp; knee)</td>
</tr>
<tr>
<td>6</td>
<td>Head of fibula</td>
</tr>
<tr>
<td>7</td>
<td>Middle of tibia</td>
</tr>
<tr>
<td>8</td>
<td>Lateral femoral condyle</td>
</tr>
<tr>
<td>9</td>
<td>Lower thigh</td>
</tr>
<tr>
<td>10</td>
<td>Greater trochanter</td>
</tr>
<tr>
<td>11</td>
<td>Medial femoral condyle</td>
</tr>
<tr>
<td>12</td>
<td>Middle of femur</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Digitised points</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Head of 2nd MTP</td>
</tr>
<tr>
<td>2</td>
<td>Medial malleolus</td>
</tr>
<tr>
<td>3</td>
<td>Medial tibial condyle</td>
</tr>
<tr>
<td>4</td>
<td>Medial femoral condyle</td>
</tr>
<tr>
<td>5</td>
<td>Right ASIS</td>
</tr>
<tr>
<td>6</td>
<td>Left ASIS</td>
</tr>
<tr>
<td>7</td>
<td>Right superior iliac crest</td>
</tr>
</tbody>
</table>
Appendix six: Formulae for ICC, SEM, and Bland and Altman

**ICC Formula**

\[
ICC_{3,k} = \frac{BMS - EMS}{BMS}
\]

Where,  
- \( BMS \) = between subjects mean square (from ANOVA)  
- \( EMS \) = error mean square  
  (Portney and Watkins, 2000 p. 565)

**SEM Formula**

\[
SEM = s\sqrt{1 - r}
\]

Where,  
- \( s \) = sample standard deviation  
- \( r \) = reliability coefficient (ICC)  
  (Portney and Watkins, 2000 p. 578)

**Bland and Altman Formula**

- \( BRDiff \) = Baseline score - retest score  
- \( BRMean \) = \( \frac{Baseline + retest}{2} \)  
  
- Mean Difference = \( \frac{\sum BRDiff}{n} \)  
- Limits of agreement = mean difference ± (2xSD(BRDiff))  
  (Bland and Altman, 1986)
Appendix seven: Core-PAC questionnaire for feasibility study

Core-PAC Questionnaire for Feasibility Study:

1) Did you have any injuries / illnesses or other conditions that affected the training program?

Circle one: yes  no

If “yes”, please explain:

____________________________________________________________________________
____________________________________________________________________________
____________________________________________________________________________

2) Did you start any other training or exercise programs during the last 4 – 6 weeks?

Circle one: yes  no

If “yes”, please explain (i.e. when, what, and how often?):

____________________________________________________________________________
____________________________________________________________________________
____________________________________________________________________________

3) What did you find most difficult about the training program?

Circle all that apply:

Technique required  Physically taxing  Time to do it

Explain:
____________________________________________________________________________
____________________________________________________________________________
____________________________________________________________________________

4) Did you feel you had adequate time to practice the technique?

Circle one: yes  no

Explain:
____________________________________________________________________________
____________________________________________________________________________
____________________________________________________________________________
5) Did you feel you had enough instruction for the technique?
Circle one: yes no
Explain:
________________________________________________________________________
________________________________________________________________________
________________________________________________________________________

6) Did you feel you had clear instruction for the technique?
Circle one: yes no
Explain:
________________________________________________________________________
________________________________________________________________________
________________________________________________________________________

7) Do you feel like you have improved in how you move during the exercises?
Circle one: yes no
Explain:
________________________________________________________________________
________________________________________________________________________
________________________________________________________________________

8) Do you feel like you have improved in how you move during other activities (i.e. soccer)?
Circle one: yes no
Explain:
________________________________________________________________________
________________________________________________________________________
________________________________________________________________________

9) How did the warm-up compare to your regular warm-up?
Circle one:
Easier Same Harder
Explain:
________________________________________________________________________
________________________________________________________________________

10) Do you feel this is an important skill to have as an athlete?
Circle one: yes no
Explain:
________________________________________________________________________
________________________________________________________________________
Appendix eight: Bias corrected (Hedges’ g) effect sizes (CI)

<table>
<thead>
<tr>
<th>Study 2</th>
<th>Pretest to Immediate Instruction</th>
<th>Pretest to Posttest</th>
</tr>
</thead>
<tbody>
<tr>
<td>Side-cut Peak Flexion Angle</td>
<td>1.14* (0.15-2.14)</td>
<td>0.63 (-0.44-1.70)</td>
</tr>
<tr>
<td>Unanticipated Side-cut Peak Flexion Angle</td>
<td>0.61* (-0.34-1.55)</td>
<td>0.43 (-0.63-1.49)</td>
</tr>
<tr>
<td>Side-hop Peak Flexion Angle</td>
<td>1.07* (0.08-2.06)</td>
<td>0.11 (-0.94-1.16)</td>
</tr>
<tr>
<td>Side-cut Peak Abduction Moment</td>
<td>-1.04* (-2.02- -0.05)</td>
<td>-0.73 (-1.81-0.35)</td>
</tr>
<tr>
<td>Unanticipated Side-cut Abduction Moment</td>
<td>-0.69* (-1.64-0.26)</td>
<td>0.82 (-1.91-0.27)</td>
</tr>
<tr>
<td>Side-hop Abduction Moment</td>
<td>-0.67* (-1.62-0.28)</td>
<td>-0.61 (-1.68-0.46)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Study 3</th>
<th>Baseline to Posttest1</th>
<th>Baseline to Posttest2</th>
<th>Posttest1 to Posttest2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Side-cut Peak Flexion Angle</td>
<td>0.98 (0.03-1.93)</td>
<td>2.03* (0.92-3.14)</td>
<td>0.94 (-0.01-1.89)</td>
</tr>
<tr>
<td>Unanticipated Side-cut Peak Flexion Angle</td>
<td>0.72 (-0.21-1.65)</td>
<td>0.90 (-0.05-1.84)</td>
<td>0.58 (-0.34-1.50)</td>
</tr>
<tr>
<td>Side-hop Peak Flexion Angle</td>
<td>1.01* (0.05-1.96)</td>
<td>1.66* (0.62-2.70)</td>
<td>0.75 (-0.18-1.69)</td>
</tr>
<tr>
<td>Side-cut Peak Abduction Moment</td>
<td>-0.20 (-1.10-0.70)</td>
<td>-0.47 (-1.39-0.44)</td>
<td>-0.60 (-1.52-0.32)</td>
</tr>
<tr>
<td>Unanticipated Side-cut Abduction Moment</td>
<td>-0.37 (-1.28-0.53)</td>
<td>-0.48 (-1.39-0.44)</td>
<td>-0.23 (-1.13-0.68)</td>
</tr>
<tr>
<td>Side-hop Abduction Moment</td>
<td>-0.68 (-1.61-0.24)</td>
<td>-0.83 (-1.77-0.11)</td>
<td>-0.13 (-1.03-0.77)</td>
</tr>
</tbody>
</table>

* Significant change
Appendix nine: Injury prevention and warm-up program and log

British Columbia Soccer Association
Under 16 Girls Provincial Team Program

INJURY PREVENTION PROGRAM
UBC KNEE INJURY STUDY

Prepared by: Markus Reinkens
BCSA Player Development / Soccer Science Staff Coach
Under 16 Girls Provincial Team Program Head Coach
WARM-UP AND INJURY PREVENTION PROGRAM
To be done 4 to 5 times a week and will be completed prior to our regular training sessions.

EXERCISE

SLOW JOG
1 Lap full field

DIAGONAL PUSH OFFS
1 Lap full field with:
  › End Lines = Stop and Go from one leg Balance
  › Side Lines = Cutting from a jog

CORE ROTATIONS
3 Sets of 10 Reps
  › 1 Rep = Rotation Right and Left

CORE CROSSBAR
Hold for 10 Seconds and repeat 3 Times

LATERAL SHUTTLE
Shuttle Left and Right = 1 Rep
  › 4 Rep Slow
  › 3 Rep Faster
  › 2 Rep Fast
  › 1 Rep Fast

FORWARD BACKWARD SHUTTLE
Shuttle Forward and Backward = 1 Rep
  › 1 Rep Slow
  › 3 Rep Faster
  › 2 Rep Fast
  › 1 Rep Fast

BALANCE WITH ROTATIONS
2 Sets on both right and left Leg
  › Hold for 20 seconds
  › Hop from Right and Left Leg

*ALTERNATE

DIAGONAL LUNGES or AGILITY CONES
2 x Width of field
2 x Narrow / 2 x Wide

*ALTERNATE

LATERAL HOPS or DIAGONAL HOPS
3 x 10 Hops
3 x 10 Hops
UBC Soccer Study Warm-up and Home Program Content – S

- To be done 4-5 x / week

<table>
<thead>
<tr>
<th>Warm-up:</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Slow jog</td>
<td>x 1 lap (full field)</td>
</tr>
<tr>
<td>Add diagonal push offs</td>
<td>x 1 lap (end lines = stop and go from one leg balance / side lines = cutting from a jog)</td>
</tr>
<tr>
<td>Core Rotations</td>
<td>3 x 10 (left and right = 1)</td>
</tr>
<tr>
<td>Core cross bar</td>
<td>3 x 10 second hold</td>
</tr>
<tr>
<td>Lateral shuttle</td>
<td>4 (slow) / 3 (faster), 2 (fast), 1 (fast) (left and right = 1)</td>
</tr>
<tr>
<td>Forward / backward shuttle</td>
<td>1 (slow) / 3 (faster), 2 (fast), 1 (fast) (fwd and bkwd = 1)</td>
</tr>
<tr>
<td>Balance with rotation</td>
<td>2 x 20 sec / each leg – quick hop between</td>
</tr>
</tbody>
</table>

Alternate:

|                  |                  |
| Diagonal lunges  | 2 widths         |
| Agility cones    | 2 x narrow / 2 x wide |

Alternate:

|                  |                  |
| Lateral hops     | 3 x 10 hops      |
| Diagonal hops    | 3 x 10 hops      |

Stretch as needed

- Can be done prior to other sports/practices for time efficiency
- Try to maintain the STRATEGY with these drills AND everything that you do!
# Training Log:

## Week 1:

<table>
<thead>
<tr>
<th>Mon</th>
<th>Tues</th>
<th>Wed</th>
<th>Thurs</th>
<th>Fri</th>
<th>Sat</th>
<th>Sun</th>
</tr>
</thead>
<tbody>
<tr>
<td>Check</td>
<td>Check</td>
<td>Check</td>
<td>Check</td>
<td>Check</td>
<td>Check</td>
<td>Check</td>
</tr>
<tr>
<td>Comments:</td>
<td>Comments:</td>
<td>Comments:</td>
<td>Comments:</td>
<td>Comments:</td>
<td>Comments:</td>
<td>Comments:</td>
</tr>
</tbody>
</table>

Questions? __________________________________________

Feedback? ____________________________________________

Checked by: ____________________________

Signature

*continues for six weeks.*
Appendix ten: Standardized instructions for physiotherapists and coaches

<table>
<thead>
<tr>
<th>Pre-practice Instruction for Core-PAC Group</th>
<th>Pre-practice Instruction for Control Group</th>
</tr>
</thead>
<tbody>
<tr>
<td>The following exercises will be done before practices and games. These exercises will help to improve your strength, balance, agility, and body control. This will contribute to improved performance and less chance of injury while playing soccer. You will be expected to keep a log of how often you complete these exercises. We will test you before and after six weeks of these exercises.</td>
<td>The following exercises will be done before practices and games. These exercises will help to improve your strength, balance, agility, and body control. This will contribute to improved performance and less chance of injury while playing soccer. You will be expected to keep a log of how often you complete these exercises. We will test you before and after six weeks of these exercises.</td>
</tr>
</tbody>
</table>

* Prior to all of the following exercises, core muscle recruitment (described as follows) will be initiated first and then sustained throughout the movement:

1. Neutral lordosis in supine with knees bent up
2. Train central and lateral costal diaphragm breathing control.
3a. Maintaining neutral lordosis, gently and slowly draw in your lower abdomen below your navel without moving your upper stomach, back or pelvis with a ‘mild’ effort (Urquhart et al., 2005).
Or:
3b. Facilitate the ‘drawing up and in’ contraction of the pelvic floor and lower and middle fibres of transversus abdominus with gentle controlled lateral costal diaphragm breathing and without global muscle substitution (O’Sullivan et al., 2000).

2 minutes will be spent reviewing this prior to each session.

Coaches version: Perform the kegel exercise while tucking your belly button in and maintain relaxed breathing.

* Prior to the following exercises, the control group will be instructed to bulge or contract the abdominal wall and focus on global muscles that produce the sit up or crunch type movement. They will be asked to feel how these muscles tense to produce the curling. They will not be asked to focus on this contraction during the movements to follow. Instead this will equate the groups on instructor interaction, attention and abdominal exercises. 2 minutes will be spent reviewing this prior to each session.

Standardized Instructions for Instructors:

Instruction/Feedback to be provided 1x before / 2x during / 1x after each exercise. Choose from the following list depending on the task and the

<table>
<thead>
<tr>
<th>Standardized Instructions for Instructors:</th>
<th>Standardized Instructions for Instructors:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Instruction/Feedback to be provided 1x before / 2x during / 1x after each exercise. Choose from the following list depending on the task and the</td>
<td>Instruction/Feedback to be provided 1x before / 2x during / 1x after each exercise. Choose from the following list depending on the task and the</td>
</tr>
<tr>
<td>Intervention Terms:</td>
<td>Control Terms:</td>
</tr>
<tr>
<td>-----------------------------------------------------------------------------------</td>
<td>--------------------------------------------------------------</td>
</tr>
<tr>
<td>“move from the centre”</td>
<td>“work hard”</td>
</tr>
<tr>
<td>“push into the ground (off the back foot)”</td>
<td>“make sure you get to the line”</td>
</tr>
<tr>
<td>“lead with the ball / belly-button”</td>
<td>“keep going”</td>
</tr>
<tr>
<td>“get the ball over your foot”</td>
<td>“get across side to side”</td>
</tr>
<tr>
<td>“keep yourself set through the core”</td>
<td>“keep your balance”</td>
</tr>
<tr>
<td>“Great job / Good work / Excellent Effort / etc.”</td>
<td>“Great job / Good work / Excellent Effort / etc.”</td>
</tr>
</tbody>
</table>

Demonstration to reinforce the movement between sets / within each drill.

1) Core set – **core recruitment** then curl up until the shoulders come off the ground – pause for 3 seconds and then slowly return to the ground.

2) Core cross bar – **core recruitment** then lift up with a straight back **leading with the belly button** – pause for 10 seconds and then slowly return to the ground.

3) Diagonal push-offs – Stop and Go: from a jog, balance briefly on one leg **with core recruitment then push off the back leg and lead with the belly button** to jog in diagonal direction. Cutting from a jog: same as above except cut diagonally without stopping.

1) Crunch - curl up until the shoulders come off the ground – pause for 3 seconds and then slowly return to the ground.

2) Cross bar - lift up with a straight back– pause for 10 seconds and then slowly return to the ground.

3) Diagonal push-offs – Stop and Go: from a jog, balance briefly on one leg then jog in diagonal direction. Cutting from a jog: same as above except cut diagonally without stopping.
4) **Lateral shuttle** - core recruitment then push off the back leg and lead with the belly button to side step 3 steps. **Always push from the back foot rather than reach with the lead leg. Make sure the center gets over the foot on change of direction.** Three steps across and three steps back is one.

5) **Forward / backward shuttle** - run forward and backward 2 metres without stopping in between. **Core recruitment then push off the back leg and lead with the belly button forward and push off the front leg on the way back. Make sure the center gets over the foot on change of direction.** Forward and back is one.

6) **Balance rotation** - core recruitment then balance on one leg with a bent knee and the other leg as straight as possible. The body should be as close to horizontal as possible. **Initiating the movement from the pelvis,** rotate the body on the planted leg without the planted leg moving. 

Alternate:

7) **Diagonal strides** - core recruitment then push off the back leg and lead with the belly button to stride diagonally and land in a balanced position. From the stance leg push off again and lead with the belly button to stride diagonally landing on the other leg.

**OR**

7) **Agility cones** - core recruitment then push off the back leg and lead with the belly button to move diagonally from cone to cone. **Make sure belly button gets to the cone and not just the outside foot.** 

Alternate:

8) **Lateral Hops** - core recruitment then push off the back leg and lead with the belly button to hop laterally and land in a balanced position. From the balance leg push off again and lead with the belly button to hop laterally landing on the other leg.

**OR**

8) **Diagonal Hops** - hop diagonally and land in a balanced position. From the balance leg, hop
8) Diagonal Hops - **core recruitment then push off the back leg and lead with the belly button** to hop diagonally and land in a balanced position. From the balance leg **push off again and lead with the belly button** to hop diagonally landing on the other leg. diagonally again to land on the other leg.
Appendix eleven: Instructor audit

Instructor Audit:

Instructor used non-standardized instructions / feedback ________ (frequency)
Details:
____________________________________________________________________________
____________________________________________________________________________
____________________________________________________________________________
____________________________________________________________________________
____________________________________________________________________________

Instructor provided instructions / feedback at standardized frequency (1x before / 2x during / 1x after each exercise) - Yes  No
Details:
____________________________________________________________________________
____________________________________________________________________________
____________________________________________________________________________
____________________________________________________________________________
____________________________________________________________________________

Instructor used demonstration as instruction / feedback tool __________ (frequency)
Details:
____________________________________________________________________________
____________________________________________________________________________
____________________________________________________________________________
____________________________________________________________________________
____________________________________________________________________________

Instructor demonstrated appropriate energy and enthusiasm?   Yes    No
Details:
____________________________________________________________________________
____________________________________________________________________________
____________________________________________________________________________
____________________________________________________________________________
____________________________________________________________________________
Appendix twelve: Sample size calculation for the randomized controlled trial

Sample size needed for comparing the means of two normally distributed samples of equal size using a two-sided test with significance level $\alpha$ and power $1-\beta$:

$$n = \left( \sigma_1^2 + \sigma_2^2 \right) \left( z_{1-\alpha/2} + z_{1-\beta} \right)^2 / \Delta^2 = \text{sample size for each sample}$$

where $\Delta = \mu_2 - \mu_1$. The means and variances of the two respective variances are $(\mu_1, \sigma_1^2)$ and $(\mu_2, \sigma_2^2)$ (Rosner, 1986 p. 264).
Appendix thirteen: SPSS syntax codes

SPSS syntax codes for the repeated measures analyses of Chapter 4

GLM SCF1 SCF2 SCF3 BY Group
   /WSFACTOR=Time 3 Polynomial
   /METHOD=SSTYPE(3)
   /PLOT=PROFILE(Time*Group)
   /PRINT=DESCRIPTIVE ETASQ HOMOGENEITY
   /CRITERIA=ALPHA(.05)
   /WSDESIGN=Time
   /DESIGN=Group.

GLM USCF1 USCF2 USCF3 BY Group
   /WSFACTOR=Time 3 Polynomial
   /METHOD=SSTYPE(3)
   /PLOT=PROFILE(Time*Group)
   /PRINT=DESCRIPTIVE ETASQ HOMOGENEITY
   /CRITERIA=ALPHA(.05)
   /WSDESIGN=Time
   /DESIGN=Group.

GLM SHF1 SHF2 SHF3 BY Group
   /WSFACTOR=Time 3 Polynomial
   /METHOD=SSTYPE(3)
   /PLOT=PROFILE(Time*Group)
   /PRINT=DESCRIPTIVE ETASQ HOMOGENEITY
   /CRITERIA=ALPHA(.05)
   /WSDESIGN=Time
   /DESIGN=Group.
GLM SCM1 SCM2 SCM3 BY Group
   /WSFACTOR=Time 3 Polynomial
   /METHOD=SSTYPE(3)
   /PLOT=PROFILE(Time*Group)
   /PRINT=DESCRIPTIVE ETASQ HOMOGENEITY
   /CRITERIA=ALPHA(.05)
   /WSDESIGN=Time
   /DESIGN=Group.

GLM USCM1 USCM2 USCM3 BY Group
   /WSFACTOR=Time 3 Polynomial
   /METHOD=SSTYPE(3)
   /PLOT=PROFILE(Time*Group)
   /PRINT=DESCRIPTIVE ETASQ HOMOGENEITY
   /CRITERIA=ALPHA(.05)
   /WSDESIGN=Time
   /DESIGN=Group.

GLM SHM1 SHM2 SHM3 BY Group
   /WSFACTOR=Time 3 Polynomial
   /METHOD=SSTYPE(3)
   /PLOT=PROFILE(Time*Group)
   /PRINT=DESCRIPTIVE ETASQ HOMOGENEITY
   /CRITERIA=ALPHA(.05)
   /WSDESIGN=Time
   /DESIGN=Group.
Appendix fourteen: Scatterplots of raw data for randomized controlled trial

Distribution of knee flexion angles during the side-cut task at baseline vs. posttest 1 for subjects in the Core-PAC group (asterisk) and the CON group (circle).
Distribution of knee flexion angles during the side-cut task at baseline vs. posttest 2 for subjects in the Core-PAC group (asterisk) and the CON group (circle).
Distribution of knee flexion angles during the unanticipated side-cut task at baseline vs. posttest 1 for subjects in the Core-PAC group (asterisk) and the CON group (circle).
Distribution of knee flexion angles during the unanticipated side-cut task at baseline vs. posttest 2 for subjects in the Core-PAC group (asterisk) and the CON group (circle).
Distribution of knee flexion angles during the side-hop task at baseline vs. posttest 1 for subjects in the Core-PAC group (asterisk) and the CON group (circle).
Distribution of knee flexion angles during the side-hop task at baseline vs. posttest 2 for subjects in the Core-PAC group (asterisk) and the CON group (circle).
Distribution of knee abduction moments during the side-cut task at baseline vs. posttest 1 for subjects in the Core-PAC group (asterisk) and the CON group (circle).
Distribution of knee abduction moments during the side-cut task at baseline vs. posttest 2 for subjects in the Core-PAC group (asterisk) and the CON group (circle).
Distribution of knee abduction moments during the unanticipated side-cut task at baseline vs. posttest 1 for subjects in the Core-PAC group (asterisk) and the CON group (circle).
Distribution of knee abduction moments during the unanticipated side-cut task at baseline vs. posttest 2 for subjects in the Core-PAC group (asterisk) and the CON group (circle).
Distribution of knee abduction moments during the side-hop task at baseline vs. posttest 1 for subjects in the Core-PAC group (asterisk) and the CON group (circle).
Distribution of knee abduction moments during the side-hop task at baseline vs. posttest 2 for subjects in the Core-PAC group (asterisk) and the CON group (circle).
Appendix fifteen: Interaction plots for randomized controlled trial

Side-Cut Flexion Angle

![Estimated Marginal Means of MEASURE_1](image-url)
Unanticipated Side-Cut Flexion Angle

Estimated Marginal Means of MEASURE_1

-72.000
-70.000
-68.000
-66.000
-64.000
-62.000

1 2 3

Time

Group
Control
Intervention
Side-hop Flexion Angle

Estimated Marginal Means of MEASURE_1

Group
- Control
- Intervention

Estimated Marginal Means
-62.500
-65.000
-67.500
-70.000
-72.500

Time
1
2
3
Side-cut Moment

Estimated Marginal Means of MEASURE_1

- Group
- Control
- Intervention

Time

Estimated Marginal Means

1 2 3
Unanticipated Side-cut Moment

Estimated Marginal Means of MEASURE_1

Group
- Control
- Intervention

Time

Estimated Marginal Means

1.0000
1.1000
1.2000
1.3000

1 2 3
Side-hop Moment

Estimated Marginal Means of MEASURE_1

Group
- Control
- Intervention

Estimated Marginal Means

1.1000
1.1500
1.2000
1.2500
1.3000
1.3500
1.4000

1 2 3

time