Preventing anterior cruciate ligament injuries in sport: a biomechanically informed approach to training

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THIS THESIS IS PRESENTED FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

THE UNIVERSITY OF WESTERN AUSTRALIA

SCHOOL OF SPORT SCIENCE, EXERCISE AND HEALTH

2016
DECLARATION FOR THESES CONTAINING PUBLISHED WORK AND/OR WORK PREPARED FOR PUBLICATION

This thesis contains published work and/or work prepared for publication, some of which has been co-authored. The bibliographical details of the work are presented for each paper. The work involved in designing the studies described was performed primarily by Gillian Weir (candidate). The thesis outline and experimental design was planned and developed by the candidate, in consultation with Assistant Prof. Cyril J Donnelly, Associate Prof. Jacqueline Alderson and Emeritus Prof. Bruce Elliott (the candidate’s academic supervisors).

All participant recruitment and management was carried out by the candidate, Assistant Prof. Cyril Donnelly and Associate Prof. Jacqueline Alderson. In addition, the candidate was responsible for all data analysis. The candidate drafted the original thesis chapters as well as papers arising from this thesis that have been published or prepared for future publication. Assistant Prof. Cyril Donnelly, Associate Prof. Jacqueline Alderson and Emeritus Prof. Bruce Elliott provided guidance on data collection, data analysis and all drafts associated with the thesis until the examinable version was finalised.

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(Gillian Weir)

Principle & Coordinating Supervisor Signature........................................................................................................
(Dr Cyril J Donnelly)
ABSTRACT

Anterior cruciate ligament (ACL) injuries are arguably the most debilitating injury an athlete can sustain in sport. The majority of ACL injuries are non-contact and occur during sidestepping and single leg landing tasks. In-vivo, in-vitro and in-silico research has identified that combined knee extension, valgus and internal rotation moments elevate ACL strain and are therefore associated with an athlete's risk of sustaining an injury. There are two biomechanical approaches typically used to reduce the strain on the ACL; 1) modify an athlete’s technique in an attempt to reduce the external moments applied to the knee and; 2) improve the strength/activation of the musculature supporting the knee when external joint loading is elevated. With this in mind and upon review of an injury prevention framework specific to non-contact ACL injuries, a “biomechanically focused” injury prevention training program was developed.

Study one tested the effectiveness of the biomechanically focussed injury prevention program on the incidence of ACL injuries and athletic performance in elite female field hockey players (n=26) over two consecutive seasons. Injury incidence and athletic performance variables were measured across both seasons, with biomechanical risk factors assessed during Intervention Season 1. Training was successful in reducing both ACL and total lower limb injuries over two seasons, while maintaining and/or improving athletic performance. Coach and athlete compliance, training exposure and program design should be considered upon implementation into community level sport.

Following the successful implementation of the training program presented in Study one, it was important to explore the influence of training on the kinetic, kinematic and neuromuscular risk factors associated with ACL injury in Study two. Seventeen elite female hockey players participated in biomechanical testing of unplanned sidestepping manoeuvres at; baseline, following a 9 week intensive training phase and again following 16 weeks of maintenance...
training. In order to understand training on an individual level athletes were classified as responders (n=5) or non-responders (n=11) based upon changes in peak knee valgus moments following intensive training. Responder athletes possessed peak knee valgus moments that were 44% higher in magnitude to athletes within the non-responder group prior to the training and following training reduced these by 30%. While there were no changes to kinematics, elevated hip muscle activation and medially directed muscle co-contraction at the knee were found to complement the kinetic findings following intensive training phase in all athletes. These benefits were retained in the maintenance training phase. The results from this study supported those from Study one and provide evidence for targeting and measuring biomechanical factors associated with ACL injury, in parallel with injury rates, when implementing training programs.

Study three addressed current limitations associated with ACL injury risk screening by employing a cost-effective 2D motion analysis screening tool capable of identifying high risk techniques associated with ACL injury risk. Frontal and sagittal plane measures of full body kinematics in 2D were recorded concurrently with 3D measures of peak knee moments during unplanned sidestepping of junior (n=15) and senior (n=15) team sport athletes. Movement patterns such as high dynamic knee valgus, low knee flexion angle at foot strike, elevated trunk flexion range of motion (ROM), increased trunk lateral flexion, large peak hip abduction and knee flexion ROM, were effective in predicting peak knee moments during unplanned sidestepping. All 2D measures had good to excellent intra- and inter-rater reliability. The power of this screening tool will enable coaches, medical staff and trainers to: 1) identify athletes who are “high-risk” and 2) place these athletes into individualised injury prevention training programs.

The outcomes of this research have significant implications for the development of ACL injury prevention training paradigms. The first two studies (Chapters 3 and 4) provide a blue print for an ACL injury prevention program where exercise recommendations (see Appendix D) are body
weight based and therefore easily implemented in a wide variety of training environments. In order to identify those at risk of injury and direct injury prevention protocols toward these “high-risk” athletes, Study three (Chapter 5) provides a cost-effective and clinically relevant screening tool available to the community level athlete. These studies in combination have the potential to be translated into real world training environments and further bridge the gap between injury prevention research and practice.
ACKNOWLEDGEMENTS

A PhD is not only a thesis but a journey. One of which many people that surround me have contributed to.

To the people that inspire me...

Jon. Your passion, your rigour and your knowledge toward this topic and biomechanics in general is something I truly look up to. My favourite PhD past time is sitting in your office and talking science - you have taught me more than you will ever know. You have been an incredible supervisor and friend and I cannot wait for many more years of talking science with you.

Jacque. As a twenty year old I sat through your third year biomechanics course and found what I wanted to spend the rest of my life doing. As a twenty-seven year old I leave UWA on a path I thought I could only dream about. You have been the most incredible teacher, mentor and friend. I cannot put into words my admiration for you and the thanks for your belief in me.

Bruce. It has been a privilege to have been supervised by you both in honours and my PhD. You have taught me so much as a researcher working in a sport context. Your contribution throughout my candidature has truly shaped my research interests.

To Hockey Australia for their contribution to this thesis and to the field of ACL injury prevention research...

Dr Carmel Goodman, Claire Rechichi, Jen Cooke and Kate Starre. Jen for your impeccable organisation and scheduling. Kate for translating research into practise – a researchers dream! Your ability to make this program what it is today, is a reflection of your talent as a strength and conditioning coach. The medical and performance team as a whole – this program alongside your incredible output is reflected in the findings of Paper 1.

Hockeyroos. I first met most of you while exfoliating the skin overlying the surface of your right gluteus maximus for electrode placement, so thank you for staying for the next two hours of testing. Thank you for coming back for the additional testing sessions when I said last time would be the last time. Finally, thank you for travelling straight from the closing ceremony of the 2014 Commonwealth Games to Liverpool for more testing at LJMU. You work so incredibly hard to get Gold, and I really admire each and every one of you.

To the people that this project couldn’t have been possible without...

The UWA technical staff. Tony, Jared, Chunbo, Luke, Christian. Thank you for all of your help facilitating the methodology associated with this research.

Josh “Coach” Armstrong. Thank you for the initial development of the training program. You started this project from the ground up and the potential of the training program is exponential.
UWA Statistics. In particular Michelle Trevenen. Thank you for putting up with my many, many, many questions. The reflection of the findings of this thesis would not have been possible without your advice.

To the family and friends who help me do the life things...

Willis. This journey would not have been the same without you. To work alongside your best friend and someone you truly admire in all aspects is incredibly motivating. Your passion for what you do is incredible and I am so excited to see what you contribute to your field. You have helped me through so many things and I cannot express the gratitude for all the big and little things you do for me.

The Palace. Ash, Ben, Will, Dopo and Coops. You are the most wonderful people to come home to. Thank you for looking after me. Ash having a bedroom and an office next door to you has been an honour. You are someone I really look up to. Thank you for all the life advice.

Gal Pals. Thank you for the holidays, the nights out, the Monday morning photo/video reminders of the nights out and for being the most inspiring group of women I have been lucky enough to call my friends.

Wolfpack. Thank you for teaching me; 1) how to cook more than scrambled eggs, 2) how to look after a 188cm/90kg (sometimes 96kg) man and, 3) that I really really hate Gwyneth Paltrow. Some of my favourite memories will always be at 16 Bronzewing Loop.

Swannies. Thank you for giving me the opportunity to work in a place I call my home. The people I have met along the way will be people I will keep very close to my heart – Swoop, Rose, Jess, Angie, Erin, Karli, Shelley, Shannon, Aitchy, Pratty, Wes, Greg, Pete. Go ducks.

And finally to those who consistently enable me to reach my dreams...

My family. I am truly blessed to have two beautiful people as my parents. Everything I achieve is the product of your support, love and guidance. Charlotte (my big little sister), you have taught me many little lessons. A thank you will never be enough to explain the importance you all place in my life.
The following is a list of publications and abstracts to which I have contributed during the course of my candidature, arising both directly and indirectly from this thesis.

PEER REVIEWED PUBLICATIONS


ABSTRACTS

Weir, G.J., Smailes, N., Alderson, J., Elliott, B.C., Donnelly, C.J. A Two-Dimensional Video Based Screening Tool To Predict Peak Knee Loading and ACL Injury Risk in Female Community Level Athletes. In proceedings of the XXIV Congress of the International Society of Biomechanics, Natal, Brazil, August 4-9, 2013.


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Individual athlete peak knee valgus moments normalised to body mass and height at baseline and following intensive training and maintenance training phases for responder ($n=5$) and non-responder ($n=11$) athletes. Responders are signified by an “R” and athletes with previous ACLR are signified by an asterisk in the X axis.

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Peak knee valgus moments normalised to body mass and height for responder and non-responder athletes during the weight acceptance phase of unplanned sidestepping. Data presented is at baseline, post-intensive training and post-maintenance training. $a$ = Indicates a statistically significant difference ($p < 0.05$), $b$ = Indicates a greater than moderate effect size ($g \geq 0.60$), $c$ = Indicates a moderate effect size ($0.30 \leq g < 0.6$).
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<tr>
<td>°</td>
<td>Degrees</td>
</tr>
<tr>
<td>1RM</td>
<td>One Repetition Maximum</td>
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<tr>
<td>2D</td>
<td>Two Dimensional</td>
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<tr>
<td>3D</td>
<td>Three-Dimensional</td>
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<tr>
<td>ACL</td>
<td>Anterior Cruciate Ligament</td>
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<td>ACLR</td>
<td>Anterior Cruciate Ligament Reconstruction</td>
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<tr>
<td>AJC</td>
<td>Ankle Joint Centre</td>
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<td>ANOVA</td>
<td>Analysis Of Variance</td>
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<tr>
<td>ASIS</td>
<td>Anterior Superior Iliac Spine</td>
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<td>BF</td>
<td>Biceps Femoris</td>
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<tr>
<td>CAST</td>
<td>Calibrated Anatomical System Technique</td>
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<tr>
<td>CNS</td>
<td>Central Nervous System</td>
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<td>CoM</td>
<td>Centre Of Mass</td>
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<tr>
<td>d</td>
<td>Cohens D Effect Size</td>
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<tr>
<td>DCCR</td>
<td>Directed CO-Contraction Ratio</td>
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<tr>
<td>df</td>
<td>Degrees Of Freedom</td>
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<tr>
<td>F/E</td>
<td>Flexion/Extension</td>
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<tr>
<td>g</td>
<td>Hedges G Effect Size</td>
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<tr>
<td>Gmax</td>
<td>Gluteus Maximus</td>
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<tr>
<td>Gmed</td>
<td>Gluteus Medius</td>
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<tr>
<td>GRF</td>
<td>Ground Reaction Force</td>
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<tr>
<td>HAT</td>
<td>Head, Arms And Trunk</td>
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<td>HJC</td>
<td>Hip Joint Centre</td>
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<tr>
<td>Hz</td>
<td>Hertz</td>
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<tr>
<td>IC</td>
<td>Initial Contact</td>
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<tr>
<td>ICC</td>
<td>Intra-Class Correlations</td>
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<tr>
<td>IOC</td>
<td>International Olympic Committee</td>
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<tr>
<td>ISB</td>
<td>International Society Of Biomechanics</td>
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<tr>
<td>kg</td>
<td>Kilograms</td>
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<tr>
<td>KJC</td>
<td>Knee Joint Centre</td>
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<tr>
<td>LESS</td>
<td>Landing Error Scoring System</td>
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<tr>
<td>LG</td>
<td>Lateral Gastrocnemius</td>
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<tr>
<td>LoA</td>
<td>Limits Of Agreement</td>
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<tr>
<td>LSD</td>
<td>Least Significant Difference</td>
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<td>m</td>
<td>Metres</td>
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<td>ABBREVIATION</td>
<td>DEFINITION</td>
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<tr>
<td>M/L</td>
<td>Medial/Lateral</td>
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<tr>
<td>m/s</td>
<td>Metres Per Second</td>
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<tr>
<td>MG</td>
<td>Medial Gastrocnemius</td>
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<td>Number</td>
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<tr>
<td>Nm.kg.-1.m-1</td>
<td>Newton Metres Per Kilogram Per Second</td>
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<tr>
<td>NR</td>
<td>Non-Responder</td>
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<td>OSICS</td>
<td>Orchard Sport Injury Classification System</td>
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<tr>
<td>PC</td>
<td>Pre-Contact</td>
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<td>PKE</td>
<td>Peak Knee Extension</td>
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<td>PKIR</td>
<td>Peak Knee Internal Rotation</td>
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<td>Peak Knee Valgus</td>
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<td>PP</td>
<td>Pre-Planned</td>
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<td>R</td>
<td>Responder</td>
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<td>RF</td>
<td>Rectus Femoris</td>
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<td>RoM</td>
<td>Range Of Motion</td>
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<td>s</td>
<td>Seconds</td>
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<tr>
<td>SD</td>
<td>Standard Deviation</td>
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<td>sEMG</td>
<td>Surface Electromyography</td>
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<td>SLL</td>
<td>Single Leg Landing</td>
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<tr>
<td>SM</td>
<td>Semimembranosus</td>
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<td>SM/BF</td>
<td>Semimembranosus/Bicep Femoris</td>
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<tr>
<td>SS</td>
<td>Sidestepping</td>
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<tr>
<td>TCS</td>
<td>Technical Coordinate Systems</td>
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<td>TLF</td>
<td>Trunk Lateral Flexion</td>
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<tr>
<td>TMA</td>
<td>Total Muscle Activation</td>
</tr>
<tr>
<td>TRIPP</td>
<td>Translating Research Into Injury Prevention Practise</td>
</tr>
<tr>
<td>UP</td>
<td>Unplanned</td>
</tr>
<tr>
<td>UWA</td>
<td>University Of Western Australia</td>
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<tr>
<td>VDJ</td>
<td>A Vertical Drop Jump</td>
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<tr>
<td>vGRF</td>
<td>Vertical Ground Reaction Force</td>
</tr>
<tr>
<td>VL</td>
<td>Vastus Lateralis</td>
</tr>
<tr>
<td>VM</td>
<td>Vastus Medialis</td>
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<tr>
<td>WA</td>
<td>Weight Acceptance</td>
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<tr>
<td>WBCoM</td>
<td>Wholebody Centre Of Mass</td>
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<td>yrs</td>
<td>Years</td>
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<td>$\chi^2$</td>
<td>Chi Squared</td>
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CHAPTER ONE

INTRODUCTION

1.1 INTRODUCTION

Anterior cruciate ligament (ACL) injuries are arguably the most traumatic and debilitating injuries and athlete can sustain in team sport. These injuries often require surgical repair followed by extensive long-term rehabilitation upward of 9-12 months \(^1\) and as such, sporting seasons and often entire careers are prematurely halted for these athletes. Statistics show that only 63-81\% of athletes are able to return to the same level of competition following injury \(^3\). It is estimated that $75 million AUD is spent annually in Australia on reconstructive surgery \(^4\). Furthermore, when an ACL injury is accompanied by a meniscal injury, the probability an athlete will develop debilitating, and painful knee osteoarthritis within 10 to 15 years increases by 20-50\% \(^5\). Therefore, the long term musculoskeletal consequences associated with ACL injury may also affect their ongoing participation in physical activity over their lifespan \(^6\)-\(^7\). These statistics, combined with the cost of ACL reconstruction, suggest the impact ACL injuries have on worldwide healthcare systems are much greater than what has been previously reported in the literature.

The majority of ACL injuries occur during non-contact sporting tasks, such as sidestepping (SS) and single leg landings (SLL) \(^8\). Being non-contact injuries \(^8\)-\(^10\), it is possible to prevent these injuries through targeted neuromuscular training. Subsequently, a great deal of ACL injury research has been dedicated toward injury prevention strategies. However, before successful preventative efforts can be achieved the determinants of sports safety behaviours must be researched within models or frameworks \(^11\). The translating research into injury prevention practise (TRIPP) model first proposed by Finch et al. (2006) has been specifically applied to ACL injury prevention (Figure 1.1) \(^12\). The ACL injury prevention framework \(^12\) encompasses the
incidence and epidemiological evidence with the modifiable biomechanical factors associated with ACL injury. This model provides a rationale for the design of injury prevention programs with the goal of changing policy on how to prevent and manage these injuries on a national level.

Female athletes have been shown to have four to six times higher risk of ACL injury in comparison with age and sport matched male athletes (Stage 1). Combined knee joint extension, valgus and internal rotation moments during the weight acceptance phase of stance, when the knee is near full extension during SS and SLL, has been associated with elevated ACL strain and injury risk (Stage 2) \(^{14-17}\). Biomechanical countermeasures to reduce these factors associated with ACL injury should be focused around; 1) reducing the magnitude of externally applied moments to the knee by modifying an athlete’s technique \(^{18-20}\) and, 2) improving the strength and activation of the muscles that support the knee from these externally applied forces (Stage 3) \(^{21-23}\). Injury prevention training programs have had mixed success in reducing ACL injury risk and rates in “ideal” training environments and as such, the question remains as to whether these programs are effectively targeting the biomechanical mechanisms associated with the injury (Stage 4) \(^{24-30}\).

**Figure 1.1.** ACL injury prevention framework developed by Donnelly et al., (2012). Image adapted from Alderson and Donnelly \(^{31}\)
1.2 **Statement of the Problem**

Currently, the literature contributing to the ACL injury prevention framework described in Figure 1.1, provides us with an evidence base to conduct research within Stages 1-4, however it does not appear that this has been translated into practice given that global ACL injury rates remain unaffected, and in fact have increased among team sport athletes. Further research is required if we are to identify and develop effective training strategies (Table 1.1) for reducing ACL injury rates within “real-world” settings (Stage 5 & 6).

Injury occurs when the force applied to the tissue is greater than its ability to tolerate it. While the mechanism of an ACL injury doesn’t differ between genders, it has been shown that modifiable deficiencies in lower limb biomechanics are associated with elevated ACL injury risk (i.e., externally applied forces) and rates among female athletes. It is therefore important to target female athletes and/or those athletes (male or female) who display poor biomechanical patterns. This can be achieved by focusing training interventions around biomechanically informed goals and developing screening protocols which identify athletes predisposed to higher risk of injury. Both approaches are thought to be important factors for improving both the efficacy of training and coach/athlete adherence to injury prevention protocols.

To address the many multifaceted barriers associated with program implementation within real world training environments, the International Olympic Committee (IOC) have proposed the following guidelines, specifically when applied to female athletes.
Table 1.1. International Olympic Committee (IOC) identified important factors for a successful prevention program.

<table>
<thead>
<tr>
<th>IOC recommendations</th>
</tr>
</thead>
<tbody>
<tr>
<td>The program should include strength and power exercises, neuromuscular training, plyometric and agility exercises.</td>
</tr>
<tr>
<td>Design as a regular warm-up program increases adherence.</td>
</tr>
<tr>
<td>Focus should be on performance of the hip-knee-foot line and “kissing knees” should be avoided (excessive valgus strain).</td>
</tr>
<tr>
<td>Maintenance and compliance of prevention programs before, during and after the sports participation season are essential to minimise injuries.</td>
</tr>
<tr>
<td>The drop vertical jump test should be used to identify players at risk.</td>
</tr>
<tr>
<td>The program must be well received by coaches and players to be successful.</td>
</tr>
<tr>
<td>Evaluation of success or failure of a prevention program requires large numbers of athletes and injuries.</td>
</tr>
</tbody>
</table>

This thesis will specifically target these implementation strategies with the aim to contribute to stage 4/5 of the ACL injury prevention framework. 

1.2.1 Research Aims

The general aims of this thesis are to contribute meaningful neuromuscular and biomechanics related science to improve the design and effectiveness of ACL injury prevention training in reducing injury risk and incidence among female team sport athletes. More specifically, this research aims to; 1) test the effectiveness of a biomechanically informed and focussed injury prevention training program in reducing ACL injury risk, ACL injury incidence and physical performance measures among a group of elite female field hockey players, and 2) develop a two dimensional video screening tool capable of identifying the kinematic factors associated with an athlete’s peak knee moments (surrogate measure of ACL injury risk) during a clinically relevant and injury specific unplanned sidestepping movement task. This will be developed among a group of elite, and community level female field hockey players.

1.2.2 Research Significance

This thesis provides a rationale for the implementation of biomechanically informed and focussed injury prevention training for elite and community level sporting environments. Rather
than prescribing exercise genres (i.e., plyometric, balance, resistance, technique etc.), the philosophy of biomechanically informed training is to develop exercises within the program that purposefully and specifically target the movement patterns and muscle activation strategies related to elevated ACL injury risk or incidence of injury. A number of critical elements associated with the success of the training intervention that concurrently do not hinder performance, will also be investigated. These include athlete and coach compliance, athlete exposure to the training program and importantly identifying athletes at risk of injury prior to entry to the training intervention. To date, there are no easily implemented, task specific screening tools capable of identifying high risk athletes in community level sporting environments. This thesis will investigate the development of a cost-effective screening tool to identify “high-risk” athletes using 2D video analysis of unplanned sidestepping techniques with the goal to be used in large scale mass screening scenarios. The findings of this research will provide a template for future training paradigms, and add to the evidence base in ACL injury prevention in our efforts in continuing to bridge the gap between research and practice in the context of elite and community level team sport.

1.3 Thesis Outline
This thesis is presented as a series of papers that draw from specific components of the aforementioned ACL injury prevention framework\textsuperscript{12}. Focus is directed toward evaluating the development and implementation of biomechanically focussed training (Stage 4/5) and athlete screening (Stage 3). The decision of how to best design these injury prevention training strategies is described in the literature review, with emphasis placed upon biomechanical solutions to reduce peak knee loading and associated ACL injury risk during unplanned sidestepping tasks. Study one investigates the effect of biomechanically informed and focused injury prevention training on an athlete’s injury risk, injury incidence and performance among a group an elite level athletes. Study two investigates the effect of biomechanically informed and
focused injury prevention training program on the biomechanical (i.e. peak knee moments) and neuromuscular (i.e. technique and muscle activation strategies) factors related to ACL injury risk in sport. In order to better understand the ideal time/dose required for injury prevention training, study two also assessed the aforementioned biomechanical and neuromuscular variables over two training phases – an intensive training phase (4 x 20 minutes per/week for 9 weeks) and a maintenance training phase (3 x 10 minutes per/week for 16 weeks). Finally, Study three explores the development of a clinically relevant and cost-effective two-dimensional video screening tool to identify athletes at “high-risk” of injury based upon their whole body movement patterns during an unplanned sidestepping.

1.3.1 CHAPTER TWO – REVIEW OF THE LITERATURE

The literature review provides a comprehensive overview of previously published ACL related research and how it fits within the ACL injury prevention framework proposed by Donnelly et al., (2012). It is also meant to highlight the ‘gaps’ in the literature, providing a theoretical rationale for the research undertaken through this thesis.

1.3.2 CHAPTER THREE – STUDY ONE

INJURY PREVENTION AND ATHLETIC PERFORMANCE ARE NOT MUTUALLY EXCLUSIVE: A BIOMECHANICALLY INFORMED ANTERIOR CRUCIATE LIGAMENT INJURY PREVENTION PROGRAM

The aim of this study is to:

- assess the efficacy of a novel, biomechanically informed injury prevention training program on ACL injury incidence, ACL injury risk and athletic performance among elite female field hockey players.

It is hypothesised that:

- the training program will reduce ACL injury rates relative to a control season,
the training program will reduce peak valgus, extension and internal rotation knee moments following a 25 week intervention period in comparison to a control season,

there will not be any changes in athletic performance, as measured by a standard battery of tests relative to a control season.

1.3.3 CHAPTER FOUR – STUDY TWO

A 25-WEEK BIOMECHANICALLY INFORMED TWO PHASE INJURY PREVENTION TRAINING PROGRAM: IMPLICATIONS FOR ACL INJURY RISK AMONG ELITE FEMALE HOCKEY PLAYERS

The aims of this study are to:

verify the efficacy of a novel, biomechanically informed, nine week intensive injury prevention training program in reducing ACL injury risk factors (i.e., peak knee moments, kinematic solutions and muscle activation strategies) among a group of elite female field hockey players,

assess the effectiveness of a subsequent 16 week maintenance (intensity and type maintained, duration reduced) training phase in retaining any initial benefits brought about by the initial 9 week intensive training phase.

It is hypothesised that:

peak knee moments associated with injury risk will be reduced, and technique and lower limb muscle activation strategies known to mitigate ACL risk will improve following the intensive training phase, and that

improvements in peak knee moments, technique and lower limb muscle activation strategies brought about by intensive training will not change during the maintenance phase of the training program.
1.3.4 Chapter Five – Study Three

A video based screening tool for sidestepping clinical movement assessments: Predicting peak knee moments and ACL injury risk in female team sport athletes

The aim of this study is to:

- develop a reliable 2D video analysis screening tool that can be used to identify the kinematic factors associated with an athletes peak knee moments during unplanned sidestepping in female team sport athletes of different levels of maturation and skill.

It is hypothesised that:

- selected two-dimensional measures of upper and lower body kinematics in the frontal and sagittal plane during unplanned sidestepping will be predictive of peak knee extension, valgus and internal rotation moments, and that the selected 2D kinematic measures will be repeatable both within (intra) and between (inter) testers.

1.3.5 Chapter Six – Synthesis of Findings and Conclusion

The final chapter aims to provide an overall synthesis of results presented throughout the thesis, integrating the major findings from each study and their contribution to the ACL injury prevention framework. It will highlight the broader conclusions of the research in the context of elite and community level sport and provide guidelines for future research directions.

1.3.6 Thesis as a Series of Papers

The University of Western Australia supports the submission of PhD theses that comprise a series of papers prepared for publication. This structure has been adopted by the candidate in the submission of this thesis. As such, while the theoretical linking between the studies (i.e. papers) should be made clear for the examiner, each study must be stand-alone in content. Consequently, theses adopting a series of papers approach sometimes result in repetition of methodology from study to study. Please note that where possible reference to previous papers
(i.e. previous studies) has been undertaken, however at times the examiner may find some repeated methodology redundant in the course of reading. Additionally, extended methods are presented in Appendix D to provide thorough detail of the processes undertaken within the three studies. Readers will be directed where to find these materials within the text of each chapter.

1.4 LIMITATIONS AND DELIMITATIONS

1.4.1 LIMITATIONS

The following limitations should be acknowledged when interpreting the results of this research:

General limitations:

- it is assumed that the sample is representative of all elite female team sport athletes, and junior female community level team sport athletes,
- it is assumed that the laboratory based running and sidestepping testing procedures are representative or the sporting situation in which non-contact ACL injuries occur,
- it is assumed that a projector screen displaying a 30cm arrow is an ecologically valid signal to initiate an unanticipated sidestepping condition.

Study one limitations:

- due to the sample being of the entire Australian national women’s hockey team, a control group was not possible unless the intervention programme was undertaken internationally, which required testing and training access to another international Olympic level female field hockey team. The research team did not have such access and testing would not have been feasible regardless.
- due to retirement, player load management and injury, six athletes were lost to follow up.
Study two limitation:

- surface electromyography (sEMG) data provides information only about the electrical activity produced during a muscle contraction, and not the force generated through the musculo-tendon unit. Care should be taken when using sEMG data to represent the magnitude of muscle support provided to a joint when external loads are applied.

Study three limitations:

- video sampling rate was 50Hz to reflect standard video cameras available to the wider community. It was assumed this sample rate was sufficient to capture movement in the weight acceptance phase of stance,

- SiliconCoach software was used to manually digitise anatomical landmarks in two-dimensional footage and greater error levels are associated with this procedure when compared with automated digitising.

1.4.2 Delimitations

The following delimitations were imposed, limiting the generality of the findings:

General delimitations:

- only female field hockey players aged 14-31 were included and the findings may not be transferrable to males and other team sport athletes,

- all participants conducted unplanned sidestepping tasks with an approach velocity of 4.5-5.5m.s\(^{-1}\) and changed direction along a 45±10° line,

- during unplanned sidestepping tasks, athletes were signalled to change direction when they were approximately 1.5m from the force plate which corresponded with contralateral leg foot off.
Study one and two delimitations:

- all athletes wore size appropriate “Asics Gel Kayano 19” model shoes during biomechanical testing for all testing sessions,
- all training was delivered by two qualified advanced strength and conditioning coaches who were employees of Hockey Australia.

Study three delimitation:

- Video data were only captured in the frontal and sagittal planes.
1.5 REFERENCES


CHAPTER TWO

REVIEW OF THE LITERATURE

2.1 INTRODUCTION

The structure of this literature review and thesis purposefully aligns with the non-contact anterior cruciate ligament (ACL) injury prevention framework developed by Donnelly and colleagues (2012) (Figure 1.1, Chapter 1), which was adapted from the more general Translating Research into Injury Prevention Practice framework proposed by Finch (2006).

In the first part of this review, evidence contributing to the development of biomechanically informed injury prevention strategies will be presented. Specifically, this portion of the review will focus on effective kinematic approaches to reduce external loading applied and injury risk to the knee and ACL, as well as neuromuscular strategies to improve the strength and support of the musculature surrounding the knee when these external loads are high. It has been shown that training is more effective when targeted toward “high-risk” populations. Therefore, to further investigate program efficacy, methods to screen and identify “high-risk” athletes are described in the latter part of this review.

2.2 EPIDEMIOLOGY OF ACL INJURY

Anterior Cruciate Ligament injuries account for over half of all knee injuries. The majority of ACL injuries occur during sport, with over half (56%) occurring during either non-contact sidestepping (SS) or single leg landing (SLL) tasks. This, in combination with improved injury surveillance and increased sports participation and exposure, may explain why ACL injury rates have appeared to double over the past decade. An Australian study performed by Janssen and colleagues showed these rates to be as high as 52/100,000 people per year (2003-2008), which are currently the highest in the world. Approximately 70% of athletes are unable to return to the same level of competition post-injury and are at increased risk of developing radiographic
diagnosed osteoarthritis later on in life. The implications of ACL injury may therefore have a much greater effect on long term athlete physical activity participation, wellbeing and consequently, our health care systems.

2.3 MECHANISMS OF NON-CONTACT ACL INJURIES
The ultimate mechanism of an injury to the musculoskeletal system is the inability of the tissues within it to sustain the loads applied to them. Multiple research strategies (\textit{in-vivo}, \textit{in-silico} and in-lab) have been implemented to better understand the internal (knee joint morphology) and external (forces applied to the knee joint) mechanisms of sport related non-contact ACL injuries.

The main function of the ACL is to prevent the anterior translation of the tibia relative to the femur. The antero-medial and postero-lateral bundles of the ACL are under peak tension during weight bearing conditions when the knee is flexed at 15-30 degrees and 15 degrees respectively. This overlap in antero-medial and postero-lateral peak tension therefore places the ACL at highest risk when the knee is near full extension. This mechanism is consistent with qualitative video analysis of non-contact ACL rupture events, where the majority occur immediately following foot contact with the knee joint near full extension. The ACL also supports the knee under valgus and internal rotation loading conditions. However, knee extension, valgus and/or internal rotation moments place the ACL at the highest strain when applied in combination.

When comparing three-dimensional (3D) biomechanics of SS with straight-line running, peak extension knee moments are similar, however valgus and internal rotation knee moments are significantly greater during SS manoeuvres. Both \textit{in-silico} and \textit{in-vivo} research have shown that valgus knee moments must be present in combination with extension knee moments to strain the ACL ligament to a level likely to cause a rupture (>2000N). Literature has identified valgus and internal rotation knee moments, in combination with low knee flexion angles during...
controlled in-lab analyses of SS $^{19,21}$ and SLL $^{22-24}$, as the probable loading pattern, knee joint posture and phase of the sporting movement where an ACL injury event occurs.

2.4 ACL INJURY RISK IN FEMALE ATHLETES
Adolescent female athletes who participate in team sports involving pivoting and/or jumping have been shown to have a four to six times greater risk of an ACL injury event when compared with age and sport matched male athletes $^{7,25}$. In support, Whiteside et al. (1980) reported that while overall injury rates for men and women are relatively similar, serious knee injuries were found to occur 10 times more often among women than men during team sports such as basketball, soccer and volleyball.

Though the mechanism of ACL injury does not differ between males and females, Hewett and colleagues $^{26}$ described anatomical, hormonal and neuromuscular differences as likely contributors to the observed discrepancy in injury rates among adolescent females versus male athletes. Anatomical factors are generally non-modifiable. Additionally, the extent to which hormonal factors influence ACL injury risk still remain unclear. Several studies have attempted to define a common menstrual cycle phase during which females are at highest risk of injury. However valid measures of menstrual cycle phase status are needed to establish links between cycle phase, acute effect of sex hormones and risk of ACL injury $^{27-32}$. Literature has shown that gender differences in hip and knee neuromuscular control may be a contributing biomechanical factor associated with elevated ACL injury risk $^{26}$ and rates $^{22}$ observed among athletic female populations. More specifically, female athletes have been shown to have higher hip and knee extension angles at foot strike as well as larger dynamic knee valgus angles during landing and sidestepping tasks $^{33}$. This may explain the elevated incidence of ACL injuries among adolescent females, particularly at this stage of maturation.
2.5 **COUNTERMEASURES**

The most logical intervention to reduce ACL injury rates among sporting populations would be to improve the capacity of the ligamentous tissue itself to withstand external loading. However, this is currently not achievable for healthy mature ligamentous tissues\(^{34,35}\). Consequently, ACL injury prevention strategies have focused on decreasing the magnitude of force applied to the tissue during high risk sporting manoeuvres when these injuries are known to occur. Biomechanically, this can be achieved in two ways; the first is to change an athlete’s technique to reduce external joint loading, and the second is to increase the strength and support of the surrounding musculature of the knee joint when external loading is high.

### 2.5.1 MOTOR CONTROL STRATEGIES DURING SIDESTEPPING

Team-based sports require athletes to perform dynamic movements in response to external stimuli (i.e., a ball, team member, opposing player etc.). These external stimuli require rapid and precise reactions in order to gain possession of a ball, evade an opponent or carry out a team tactic. Time constraints associated with these dynamic movements may cause unplanned anticipatory adjustments and as a consequence, lead to altered joint biomechanics\(^{36-38}\). In the context of ACL injury in sport, carrying out an unplanned SS has been shown to almost double peak knee valgus moments when compared to a planned SS task\(^{36}\).

Patla et al. (1999) described online steering or whole body centre of mass (WBCoM) control during change of direction tasks as an interplay between two factors; 1) an early foot position strategy, where change of direction is initiated prior to ipsilateral foot contact (planned sidestepping) and, 2) upper body centre of mass (CoM) reorientation (unplanned sidestepping). As a third on-line steering strategy, Dempsey (2007) identified a late wide foot position, which is likely related to deficits in trunk and hip strength. Postural control and reorientation differences during planned and unplanned sidestepping has also been reported by Houck et al.
(2006) who found anticipation to affect both lateral trunk orientation and foot placement (Figure 2.1).

Figure 2.1. Mean and SDs of trunk and pelvis kinematics and foot placement during planned and unplanned change of direction tasks. Adapted from Houck et al. 39.

Patla et al. (1999) showed that when cues are provided early (i.e. planned movements), re-directing the CoM is primarily accomplished using a foot position strategy, where the contralateral foot is placed away from the body’s midline to initiate a re-orientation of the upper body to the intended direction of travel. However, with late cues or during unplanned movements, reorientation of the CoM is accomplished by adopting a trunk strategy, where the trunk is flexed laterally away from the intended direction of travel 39 40. Dempsey et al. (2009) reported that during high velocity tasks like running, there is a late foot position strategy, where ipsilateral foot placement away from the body’s midline is used to re-direct the CoM toward the intended direction of travel. He also showed that both a laterally flexed trunk away from the desired direction of travel and a wide ipsilateral foot placement are directly related to increased valgus knee moments 41.

When perturbations are applied during dynamic movements, the central nervous system (CNS) is capable of adjusting muscle activation patterns to oppose these destabilising forces 42. However, it is suggested that reactive muscle activity must occur with sufficient magnitude
within 30 to 70 milliseconds after the onset of joint loading (i.e. foot strike), which may not be enough time to effectively support the knee and ACL. Consequently, when tasks are unplanned there may not be adequate time for the CNS to plan appropriate muscle activation strategies to support the knee from elevated external loading and injury risk. This has been found in unplanned SS where muscle activation levels increased by 10-20% compared with planned SS. During these tasks however, valgus and internal rotation moments increased by 70%, suggesting that muscle activation strategies with reduced preparatory time may not be effective in supporting the knee from the consequent elevated peak loading. By understanding the effect of preparatory time on muscle activation and kinematic solutions, we may be able to modify the outcome of these motor control strategies. This can be achieved by; 1) increasing dynamic control of the trunk and hip to effectively control WBCoM reorientation to reduce valgus and internal rotation knee moments, and 2) improve the strength and activation of muscles crossing these joints during unanticipated change of direction tasks.

2.5.2 TECHNIQUE MODIFICATION

Three general kinematic strategies have been proposed to counter elevated peak knee moments and associated ACL injury risk in sport; 1) control of WBCoM, 2) increasing knee flexion angle at foot strike, and 3) preventing dynamic knee valgus postures of the lower limb.

Seventy percent of a person’s mass is located in the head, arms and trunk (HAT), which is located two thirds of their height above the ground. As WBCoM control is fundamental to balance and stability during gait, the dynamic control and potential for the upper body to influence the loading of distal segments in the kinetic chain is substantial. During SS, techniques such as a wide foot position relative to WBCoM, lateral trunk flexion and rotation in the opposite direction to travel, and constraining the arms have also been shown to increase knee valgus moments. Recent in-silico research has supported these experimental studies and has identified re-
positioning of an individual’s WBCoM toward the desired direction of travel as a preferred posture during SS to reduce knee valgus moments. Dempsey and colleagues (2009) showed that an athlete’s knee valgus moments can be decreased by almost 40% if the athlete was capable of maintaining a vertical trunk posture during unplanned SS. The mechanistic rationale for these observed changes was that the motion of the trunk away from the stance leg and the direction of travel causing the centre of pressure to move laterally to keep the WBCoM within the athlete’s base of support. This increases the perpendicular distance between the GRF and knee joint centre that in turn causes the observed increases in internal rotation and valgus knee moments. It is therefore important to both assess and target trunk stability during preventative programs.

Increasing knee flexion angle at foot strike has been shown to be associated with reduced combined transverse and frontal plane knee moments during SS. Inversely, reduced knee flexion angle at foot strike has been observed during video analysis of ACL injury events. Both of these findings are congruent with cadaveric research, which has shown peak ACL strain is observed at low knee flexion angles (<20°). As such, focus should be placed on encouraging athletes to land and change direction with a flexed knee. Strength training is recommended in this flexed knee posture, so an athlete can effectively accommodate or accomplish this proposed technique modification.

Dynamic knee valgus postures of the lower limb have been associated with elevated peak knee valgus moments and ACL injury among female athletes. In a lab context, Kipp et al. (2011) showed that poor hip flexion-extension neuromuscular control resulted in elevated peak knee valgus moments during a single-leg land and cut manoeuvre. These 'dynamic' knee valgus postures consist of combined knee flexion and hip internal rotation, which can signify poor hip external rotator strength. As such, particular attention should be placed upon hip neuromuscular control when designing intervention programs.
By identifying the kinematic factors associated with elevated external knee loads, we can similarly investigate the neuromuscular adaptations required to facilitate modifying an athlete’s technique to adopt safe SS and SLL movement patterns.

2.5.3 **Muscle Strength and Support**

Increasing the strength and activation of the lower limb musculature is another avenue that has been explored to reduce sport related ACL injury risk. There is no single muscle crossing the knee capable of simultaneously supporting the joint from anterior drawer, valgus and internal rotation knee moments in parallel. It is therefore difficult to design a best practice training intervention that effectively strengthens the lower limb musculature in a manner that effectively supports the knee when these combined knee loads are elevated. For this reason, multiple muscle activation strategies can be used to reduce ACL injury risk during non-contact change of direction sporting scenarios. The first of these generalised strategies involves “selected activation” of muscles with moment arms able to counter the aforementioned applied external loads. Examples of this include musculature with medial moment arms such as the sartorius and gracilis muscles and medial hamstrings and quadriceps muscles, which all possess functional moment arms capable of supporting knee valgus moments. The second strategy is “generalised co-contraction”, where co-contraction of muscle groups, such as the quadriceps and hamstring muscle groups occur. Co-contraction of the quadriceps with the hamstrings has also been shown to elevate knee joint compression further when compared with quadriceps muscle force alone in simulated landing. Cadaveric research has shown that increasing eccentric quadriceps muscle force in the pre-contact phase of landing significantly reduced the forces applied to the ACL during weight acceptance (WA), when the knee is in at least 20 degrees of flexion.
While quadriceps and hamstring co-contraction has been widely investigated within the literature, quadriceps and gastrocnemii co-contraction has recently been identified as a plausible strategy to increase knee joint compression\(^{56,60-62}\). The gastrocnemii muscle group primarily functions to plantar-flex the foot, which has a crucial role in generating the support moment (sum of all sagittal plane hip, knee and ankle moments) required for dynamic stability during running, landing and change of direction sporting manoeuvres\(^\text{63}\). Recent simulation based evidence has proposed a second function, which is to co-contract with the quadriceps to elevate joint compression and thus protect the knee and ACL from external joint loading\(^{56}\). This is desirable as research has shown that joint compression achieved by elevated muscle contraction can limit translation forces\(^{56,64}\).

The majority of research exploring the role of muscle coordination and support in ACL injury prevention has investigated those that cross the knee joint. However, muscle activity of the trunk and hip precedes the activation of muscles crossing distal joints lower in the kinematic chain during single leg sporting tasks\(^{46,65}\). More specifically, the CNS has been shown to initiate contraction of trunk musculature in a feedforward manner prior to lower limb movement\(^{65}\). This top down strategy suggests that control of the trunk and hip musculature is paramount in maintaining an athlete’s WBCoM positioning within their base of support during dynamic movement. Of the 13 muscles crossing the hip and knee, which act to provide structural support and direct movements at the knee; five are bi-articulate with attachments at the pelvis and/or sacrum\(^{66}\). Therefore, if muscle activation of the trunk and hip is unable to support medio-lateral control of the CoM, they can also function synergistically with muscles further down the kinetic chain to support the knee joint.

Not only is strength of these muscles important, but so is the timing of their activation. Peak external loading to the knee is observed during WA, which is when the muscles crossing the knee are needed to support and protect its internal structures from injury. It is thought that
increased ACL strain during unplanned SS is in part, a result of the inability of the surrounding musculature to generate force and increase joint compression at the appropriate time. It is thought that increased ACL strain during unplanned sidestepping is in part, a result of the inability of the surrounding musculature to generate force and increase joint compression in time as the result of; 1) peak knee moments occurring during WA which occurs within 40ms following foot strike, 2) electromechanical delay is approximately 60ms and subsequently, 3) the inability of reflexive or voluntary muscle activation. It is therefore vital that an athlete has adequate muscle support or training is focused upon increasing muscle support during WA to support the knee during unanticipated sporting manoeuvres when elevated joint loading is observed.

In summary, consideration of aforementioned neuromuscular and biomechanical factors can facilitate the design of effective training interventions to mitigate peak knee moments and ACL injury risk. The neuromuscular factors that should be specifically targeted in ACL injury prevention programs through technique and multifactorial strength and stability training include; 1) improving the control of WBCoM through targeted hip and trunk stability training, 2) increasing knee flexion angle at foot strike through external cues, and improving eccentric quadriceps strength, 3) preventing dynamic knee valgus postures of the lower limb by strengthening hip external rotators and, 4) increasing the strength and activation of the gastrocnemius muscle group to elevate knee joint compression.

### 2.6 ACL Injury Prevention Focused Training Interventions

ACL injury prevention protocols can be classified into four general categories; 1) plyometric training, 2) balance training, 3) technique training, and 4) resistance training. Training interventions have been found to be both effective and ineffective in reducing ACL injury rates among general athletic populations. Though injury prevention is a complex multifaceted problem, one could argue that not all injury prevention programs are targeting the
biomechanical and neuromuscular factors related to peak loading and injury risk. Few studies have measured these factors in parallel and as such the biomechanical mechanisms underpinning why the success or otherwise of these interventions is unclear. This may also suggest that it is not the type of training used (i.e. plyometric, balance, technique and resistance), but rather the focus of the injury prevention protocol that influences the effectiveness of such interventions. Successful training interventions performed by Hewett et al. (1999) and Mandelbaum et al. (2005) both contained technique components that focused on trunk and hip neuromuscular control and increasing knee flexion at foot-ground impact, in combination with plyometric exercises, which may have unintentionally targeted the gastrocnemius muscle group. This evidence supports the design of training protocols that are focused on the kinematic and neuromuscular factors associated with elevated knee valgus and internal rotation knee moments and the subsequent elevated injury risk. Coach and athlete compliance to injury prevention protocols is also an important consideration in attempting to understand the quantity of training required to observe a treatment effect, and whether maintenance programs are required following the intensive 6-12 weeks programs as commonly reported in the literature.

2.6.1 MAINTENANCE TRAINING AND MULTIPHASE PROGRAMS

Due to competition schedules, pre-season training loads and injuries, athletes are frequently required to adjust to fluctuating training volumes and intensities over a season of play. Training duration and intensity is often lower in the non-playing season compared with pre- and in-competition training schedules, which may result in detraining effects. Detraining is defined as the partial or complete loss of adaptations in response to insufficient training stimulus. In as early as four weeks post-training, detraining effects can be observed in the form of reduced; muscle strength, physiological function (e.g. capillary density, arterial-venous oxygen difference, oxidative enzymes activities, VO\textsubscript{2max}) and task-specific proprioception. This is
an important consideration when researchers implement short intensive training interventions commonly found in the ACL injury prevention literature. These programs typically span from 4-12 weeks and then assess injury rates following long periods (i.e. 12 months) post-intervention. Consequently, the effect of exercise-based interventions may be transient following one year of discontinuing injury prevention training programs. Immediate improvements in biomechanical and neuromuscular characteristics after an injury prevention training program suggest that function has been improved, however motor learning of the new skills and techniques prescribed in the intervention may take longer periods to achieve and/or maintain.

To maintain initial positive biomechanical and neuromuscular adaptations from an intensive training phase, a number of studies have implemented maintenance phase programs immediately following an intensive injury prevention training program. However, there has been little research in understanding the effect on ACL injury risk/rates following each component of the entire program and this limits our capacity to assess the efficacy of maintenance training programs in isolation following intensive training phases.

2.6.2 OTHER FACTORS INFLUENCING EFFECTIVE PROGRAM DESIGN

We must in part acknowledge that while sound neuromuscular and biomechanics information serves as the backbone to effective injury prevention research, it is crucial that injury prevention paradigms are approached in a multi-disciplinary manner. Previous research has identified practical problems when implementing training protocols in “real-world” scenarios (Stage 5 of the TRIPP framework). The most apparent of which are athlete compliance and adherence to the training interventions. Chappell and Limpisvasti (2008) found that 10-15 minutes of neuromuscular training adjunct to preseason soccer training was effective in decreasing valgus knee moments during a double-leg stop-jump task. The proposed success of this investigation
was likely due to high athlete compliance (100%) which was in part attributed to a high coach to athlete ratio (2:33). While Donnelly and colleagues (2012) conducted a similar in season training protocol with a community based football program, they had low athlete compliance (<45%) and a low coach to athlete ratio (1:40) and consequently reported that balance and technique training intervention were not effective in decreasing valgus knee moments and injury risk during planned or unplanned SS. The importance of a low athlete to coach ratio may be explained by the ability to ensure each individual athlete is performing training tasks and technique modifications are immediate and precise so that the intended focus of the training protocol is appropriately translated from the laboratory to real-world settings. Another strategy suggested to counter barriers associated with community level implementation based research is athlete screening \(^1\). As such, there is enhanced rationale to participate and comply to training if an athlete is identified as high risk, and interventions can be modified to target an individual’s specific biomechanical and/or neuromuscular deficiencies.

2.7 Athlete Screening

Screening and identifying athletes who are at higher risk of ACL injury, may improve the effectiveness of injury prevention training protocols by firstly, improving coach intent to implement these programs and secondly, improving the specificity of the intervention itself \(^1\)\(^88\)\(^89\). Myer and colleagues (2007) found that following a seven week neuromuscular training program, athletes identified as high-risk reduced their peak knee valgus moments by 13% in comparison with low-risk athletes, and a control group, who experienced no change. These findings suggest that by implementing screening prior to injury prevention training we can further refine the protocols delivered to an individual athlete. However, implementing screening strategies alongside injury prevention training protocols is not yet considered cost-effective in community sport settings \(^89\)\(^90\). This can be attributed to three key factors; 1) specificity and sensitivity of the task(s) used within the screening tool to movements associated with the injury
eliciting event, 2) validity and reliability of the measures recorded, and 3) feasibility of implementation in community level sport and mass-screening scenarios.

2.7.1 Screening Specificity and Sensitivity

In order to improve the specificity of injury screening, the ability to predict one’s risk of injury should be measured within the injurious task itself, as these tasks better approximate the accelerations and forces related to the injury event. While some screening tests incorporate sport specific injurious task manoeuvres such as SS and SLL, others do not and go on to include surrogate tasks such as single leg squats, drop vertical jump, drop landing, tuck jumps and isokinetic knee extensor/flexor strength. Secondly, the dependent variables chosen to assess movements within a screening tool must be associated with neuromuscular or biomechanical factors associated with injury risk as highlighted within section 2.5 of this chapter. As elevated combined peak knee extension, valgus and internal rotation moments have been associated with ACL injury risk and rates, direct measurement of these during the high risk manoeuvres is ideal. Peak knee valgus moments measured during a vertical drop jump (VDJ) landing task have been found to be capable of predicting ACL injury with 73% specificity and 78% sensitivity, where 2D dynamic knee valgus angle measures provided a predictive $R^2$ of 0.88 for injury in female athletes. In contrast, Smith et al. (2012) screened 5,047 male and female high school and college athletes using a VDJ task and failed to identify any two dimensional (2D) measures of lower limb motion associated with injury among the 28 injured athletes analysed when compared with 64 matched controls. This may be due to the screening task being double leg, rather than SLL (i.e. not mimicking forces and accelerations of injurious tasks). Additionally, their analysis was restricted to a single plane, which does not take into consideration the multi-planar dynamics of SLL and unplanned SS sporting tasks. Krosshaug et al. (2016) measured 3D lower limb kinetics and kinematics and GRFs in 782 elite handball players and found only dynamic knee valgus to be associated with increased risk of ACL...
injury. Sidestepping has been shown to have five times higher peak knee valgus moments when compared with a VDJ\textsuperscript{98}, suggesting that VDJ may not be a mechanically demanding enough task to elicit injurious levels in the biomechanical risk factors associated with ACL injury risk or injury\textsuperscript{98,99}.

2.7.2 Screening Validity and Repeatability

Kinematics and muscular activation patterns selected for analysis during movement screening protocols must be associated with the biomechanical mechanisms (i.e. peak knee moments) of ACL injury in order for the tool to be sensitive enough to detect change and/or discriminate between high and low risk individuals. Screening tools currently reported in the literature incorporate dynamic knee valgus\textsuperscript{94,100-102}, hip and knee flexion angles\textsuperscript{102}, EMG pre activity of knee flexors/extensors\textsuperscript{86} and isokinetic concentric quadriceps/hamstring strength\textsuperscript{62}.

Due to differences in kinematic modelling approaches, tester experience and movement assessment protocol differences, it is important for these methods to first be described in detail so that test protocols can be reliably replicated. Secondly, in order to describe the robustness of the tool it should be compared across testing centres. Inter-laboratory reliability of a single-leg cross jump task screening tool was found to have moderate to high reliability for kinematics, and high reliability for kinetics when utilising each centres’ individual equipment and staff\textsuperscript{103}.

The Landing Error Scoring System (LESS) screening tool has been found to have good-excellent intra- and inter-rater reliability and has predictive validity in identifying ACL injury events. However this is only within a young athlete population\textsuperscript{102}. The Clinic Based Algorithm employs a combination of anthropometric measures (i.e. tibia length and body mass index), landing mechanics and isokinetic knee extensor/flexor strength ratio to predict high knee valgus moments in female athletes. This tool has good predictive value, with lab-based measures explaining 83% of the variance in peak knee valgus moments. However, 3D analysis of landing
and isokinetic strength limits this tool to laboratory settings. Two dimensional measures of dynamic knee valgus have been shown to predict peak knee moments and have good within and between day reliability\textsuperscript{100, 101}. However, the success of these tools when translated across heterogeneous sporting populations is limited, likely as a consequence of the lack of consideration of both upper and lower body multi-planar biomechanical and neuromuscular patterns. Therefore emphasis should be placed on sound mechanical links to ACL injury mechanisms (i.e. peak knee loading) and investigating upper and lower body biomechanics across all three planes of motion when developing ACL screening tools.

2.7.3 Screening Feasibility

Though an established and reliable measurement tool, 3D motion capture systems are both cost and computationally expensive, limiting their utility for the mass screening of athletes within community level training environments. To address the practical research question of feasibility of implementation, 2D video based motion capture may be a cost effective solution by which to assess an athlete’s technique and associated ACL injury risk during dynamic sporting movements\textsuperscript{101, 102}. Two-dimensional video based measures have been shown to be reliable in their measurement of lower limb kinematics\textsuperscript{91}. Research therefore needs to investigate the use of reliable 2D screening measures of upper and lower body mechanics in multiple planes during SS and SLL in heterogeneous athletic populations, in order to develop sensitive measures of ACL injury risk for large-scale screening environments.

2.8 Summary

Using a multidisciplinary approach (i.e., \textit{in-vivo}, \textit{in-vitro} and in-silico research), it believed non-contact ACL injures occur when combined externally applied flexion, valgus and internal rotation moments are applied to the knee while it is in an extended posture during the weight acceptance phase of unplanned SS or SLL (Stage 2\textsuperscript{57}). However, while the underlying mechanisms of an ACL injury is established, there is little research describing the specific techniques and
neuromuscular support strategies associated with elevated injury risk in sport (Stage 3). Consequently, training interventions (Stage 4/5) and screening methods (Stage 3) are still being developed. As such, these injury prevention strategies are yet to be moved out of the laboratory environment and widely adopted in community level training environments (Stage 5/6). With the sound evidence behind the mechanisms and countermeasures of ACL injury, biomechanically informed content must therefore be incorporated in the development of injury prevention training and screening protocols. The research within this thesis will aid stages 3 and 4 of the ACL injury prevention framework, to inform community focused real world interventions (Stage 5) and policy surrounding ACL and lower limb injury prevention research (Stage 6), in order to effectively facilitate real-world ACL injury rate reductions (Stage 1).
2.9 References


CHAPTER THREE

INJURY PREVENTION AND ATHLETIC PERFORMANCE ARE NOT MUTUALLY EXCLUSIVE: A BIOMECHANICALLY INFORMED ANTERIOR CRUCIATE LIGAMENT INJURY PREVENTION PROGRAM.

This manuscript was prepared for *The American Journal of Sports Medicine*.

Conference abstract pertaining to this manuscript is provided in Appendix E of this thesis.


The PhD candidate, Gillian J Weir, accounted for 80% of the intellectual property associated with the final manuscript. Collectively, the remaining authors contributed 20%. The formatting and references of this chapter follow the guidelines for submission to *The American Journal of Sports Medicine*.
As identified in Chapter Two, there lies a gap between injury prevention research and practise in real world implementation. While there is significant evidence surrounding the biomechanical mechanisms of ACL injury, this is yet to be translated into global ACL injury rate reductions. Injury prevention training interventions that typically focus on different combinations of training modality (i.e. resistance, balance, plyometric, technique) have reported mixed success. The following study investigates a new training philosophy which focuses on the biomechanical mechanisms associated with ACL injury and its efficacy in reducing lower limb and ACL injury rates. Simultaneously, this study investigates the effect of injury prevention training on athletic performance measures. This paper presents a blueprint for ACL injury prevention training program design with body-weight based exercise recommendations such that it can be incorporated into any elite or community level training environment.
3.1 Abstract

Background: There has been mixed success following the implementation of injury prevention training programs in reducing anterior cruciate ligament (ACL) injury rates. Coach and athlete perceptions toward injury prevention and time taken away from skills/performance training have been associated with limited adherence in time-poor sporting environments.

Aim: To verify the efficacy of a novel biomechanically informed training intervention in reducing the incidence of ACL injuries and its effect on athletic performance.

Methods: Twenty-six elite female field hockey players participated in a biomechanically informed and focussed injury prevention training program for two consecutive seasons. Injury incidence (i.e. lower limb and ACL) and athletic performance (i.e. strength, speed and aerobic power) were measured during a control season, and following two intervention seasons. Known biomechanical risk factors for ACL injuries (i.e. peak extension, valgus and internal rotation knee moments) during an unplanned sidestepping task were also assessed prior to, and following two training phases within intervention season one.

Results: Biomechanically informed training was effective in reducing the incidence of lower limb and ACL injuries while maintaining and/or improving athletic performance following two intervention seasons. Peak knee valgus and internal rotation moments (surrogate measures of ACL injury risk) assessed in intervention season 1 decreased, supporting the injury incidence findings.

Conclusions: Biomechanically informed injury prevention training in parallel with an elite training and medical environment, was successful in reducing the incidence of lower limb and ACL injuries over two seasons, while maintaining and/or improving the athletic performance among a group of elite female field hockey players.
3.2 INTRODUCTION

Anterior cruciate ligament (ACL) injuries are arguably the most debilitating knee injury an athlete can sustain in sport. The majority (56-80%) of these injuries occur during non-contact sporting tasks such as sidestepping and single-leg landing \(^{14}\), indicating that these injuries are preventable \(^5\)\(^-\)\(^7\). In-vivo, in-silico and ex-vivo research have identified combined externally applied peak knee extension, valgus and internal rotation knee moments as a surrogate measure of ACL strain and subsequent ACL injury risk in sport \(^{18}\)\(^-\)\(^{11}\). Significant research attention has been dedicated toward the development of a multitude of clinical methods to reduce ACL injury rates, including the prescription of various training modalities (e.g. balance, plyometric, strength and technique) \(^7\)\(^\)\(^8\)\(^\)\(^12\)\(^\)\(^13\)\(^\)\(^18\). However, there have been conflicting findings regarding the effectiveness of these interventions \(^7\)\(^\)\(^12\)\(^\)\(^13\), thereby raising the question: are these interventions effectively targeting the biomechanical mechanisms associated with ACL injury risk? \(^2\)\(^4\)

The origin and insertion of the ACL is non-linear and subsequently, no single external moment or force in isolation is capable of rupturing the ACL. Two biomechanical strategies can be adopted to reduce an athlete’s risk of sustaining an ACL injury during sport participation. The first is to modify an athlete’s technique in an effort to reduce externally applied forces to the knee, which are known mechanical risk factors to an ACL injury event \(^{14}\)\(^-\)\(^{16}\). The second is to improve the strength and activation of the muscles that support the knee when external joint loading is elevated \(^{17}\)\(^-\)\(^{20}\).

Recent evidence has focused on the following biomechanical strategies associated with mitigating ACL injury risk; 1) increasing knee flexion angle at foot strike to reduce combined peak valgus and internal rotation knee moments \(^{21}\), 2) improving dynamic control of the trunk and upper body to reduce peak valgus knee moments \(^9\)\(^\)\(^{16}\), 3) improving the strength of the gastrocnemius muscle group to elevate joint compression \(^{20}\) and finally, 4) increased hip external rotator strength, which can prevent athletes from attaining “dynamic knee valgus” postures \(^{11}\). Consideration of these biomechanical factors can facilitate the design of training interventions
to target the biomechanical mechanisms associated with an ACL injury event. When translating laboratory findings into real-world training environments, a number of other factors may limit the success of interventions. Training exposure, coach/athlete adherence and compliance, and coach/athlete perceptions of training time and its influence on athletic performance, are key concerns within this research stream.\textsuperscript{22-24}

The aim of this study was to assess the efficacy of a novel, biomechanically informed and focussed injury prevention training program on reducing ACL injury risk, ACL injury incidence and athletic performance among elite female field hockey players. We hypothesised the training program would reduce ACL injury risk and rates in this cohort following two intervention seasons when compared with a control season. We further hypothesised that any changes brought about by the training intervention would not have a detrimental effect on overall athlete performance.

3.3 Methods

3.3.1 Study Design and Participants

The biomechanically informed injury prevention training program was assessed over three consecutive seasons (control, intervention season 1, intervention season 2) among the Australian National women’s field hockey team (Hockeyroos) (Figure 3.1). The first season (2012-2013) was treated as the baseline/control season, then a 9 week intensive-training phase was implemented and immediately followed by a maintenance-training phase in the first intervention season (2013-2014), which continued through a second intervention season (2014-2015). Injury incidence were measured across all three seasons. Athletic performance was assessed on four occasions; 1) at the end of the control season, 2) following the intensive-training, 3) following the first intervention season and 4) following the second intervention season. Biomechanical injury risk factors (i.e. peak knee moments) were assessed on three occasions; at the end of the control season, and again at the completion of both phases of the training program in the first intervention season.
Twenty-six elite female hockey players (age: 22.1 ± 2.3 years, height: 1.68 ± 0.09 m, mass: 63.30 ± 7.00 kg) participated in this study. Due to retirement, player availability and injury, not all players completed all biomechanical and performance testing sessions and/or in each seasons injury incidence measurements. Written informed consent was obtained from all participants approved by the University of Western Australia’s Human Research Ethics Committee (See Appendix A.1).

**Figure 3.1.** Biomechanically informed injury prevention program study design and sample size flow chart.

### 3.3.2 Intervention

During the intervention seasons, all athletes participated in injury prevention training sessions adjunct to their regular in-season warm-up and gym sessions, which were delivered by the team strength and conditioning coaches (see Appendix D.6). A high coach to athlete ratio of 1:13 was implemented in attempts to maximise athlete adherence and compliance to the training protocol\textsuperscript{18,26}. Irrespective of the exercise genre (resistance, balance, plyometric and technique),
the overriding goal or focus of the intervention was to target four key biomechanical factors associated with ACL injury risk and/or incidence; 1) increase knee flexion angle at foot strike\textsuperscript{21}, 2) to improve the dynamic control the trunk and upper body\textsuperscript{9,27}, 3) to strengthen the hip external rotators to prevent athletes from attaining “dynamic knee valgus” postures\textsuperscript{11,14,18}, and 4) to increase the strength of the gastrocnemius muscle group\textsuperscript{20} (see Table D.3, Appendix D). From this, the strength and conditioning coach designed each session to best suit the training environment. During the first intervention season a 25 week training program was implemented and split into two phases; 1) Intensive-Training (Weeks 1-9) and 2) Maintenance-Training (Weeks 9-25). The intensive-training phase consisted of 4 x 20 minute sessions per week which progressed in intensity every two weeks. While intensity and type of exercise remained the same, only training duration was reduced in the maintenance training phase (3 x 10 minute sessions per week). The maintenance-training phase was then continued throughout the second intervention season. During each session of the intensive-training phase, attendance, and coach ratings of compliance and athlete engagement were measured\textsuperscript{28}. Attendance and compliance were 81.1±25.0% and 88.2±19.7% respectively, with attendance only missed due to injury as advised by team medical staff. Athlete engagement was high with 89.2±11.5%. Athlete commitment, 89.9±11.2% motivation and 91.9±9.9% perseverance, which are components of athlete engagement throughout the intervention, were also high.

3.3.3 Injury Rates

All lower limb injuries occurring during pre-season, in-season training and competitive games over the control (2012-2013) and intervention seasons (Intervention Season 1: 2013-2014 and Intervention Season 2: 2014-2015) were collected by the same team doctor and physiotherapist using the Orchard Sport Injury Classification System (OSICS)\textsuperscript{29}. Total lower limb injuries (all injuries sustained to the lower limbs excluding contusions), total knee injuries (ligament, tendon and cartilage), total knee ligament injuries and ACL injuries were recorded. All injuries were verified by either the team doctor or physiotherapist and was defined as an event that caused a
player to cease training/playing and seek medical attention. Injury incidence per 1,000 player hours was calculated by dividing the number of injuries by exposure (number of athletes x number of hours of training/games per season) and multiplied by 1,000 (equation 3.1).

\[
\text{Injury Incidence} = \frac{\text{Injuries}}{\text{Number of Athletes} \times \text{Season Exposure}} \times 1000 \tag{3.1}
\]

To evaluate differences in injury rates per season, expected injury rates were calculated for each season as the same proportion of total injuries as that season’s exposure hours were of the total hours\(^{30}\) (Equation 3.2).

\[
\text{Expected Injuries} = \frac{\text{Season Exposure}}{\text{Total Exposure}} \times \text{Total Injuries} \tag{3.2}
\]

### 3.3.4 Athletic Performance

Athletic performance measures were recorded during the control season and following the intensive training phase, post-intervention season 1 and post-intervention season 2. Strength performance tests included one repetition maximum (1RM) strength normalised to body mass for the bench press, bench pull and back squat\(^{31}\). Speed was assessed with 40m sprint times (split at 10m and 40m) and aerobic power assessed using the beep test\(^{32}\).

### 3.3.5 Biomechanical Testing

To assess biomechanical injury risk factors a subset of athletes completed a laboratory based unplanned sidestepping (UPSS) functional movement assessment\(^1\) \(^8\) \(^33\). Kinematic marker trajectories were collected using a 12 camera Vicon\(^*\) MX and 10 camera Vicon\(^*\) T40 (Oxford Metrics, Oxford, UK) system operating at 250 Hz, which was synchronised with an AMTI force
plate, recording at 2,000 Hz (Advanced Mechanical Technology Inc., Watertown, MA). These data and a reliable full body customised kinematic model\textsuperscript{33 34} were used to calculate peak knee extension, valgus and internal rotation knee moments via inverse dynamics procedures in Bodybuilder (Vicon, Exford Metrics, Oxford, UK). Peak knee moments were analysed during the weight acceptance phase of UPSS, and normalised to body weight (N) and height (m)\textsuperscript{8 11}. More detailed descriptions of the experimental protocol and modelling approach have been described in Donnelly et al. (2012).

3.3.6 Statistical Analysis

Chi square analysis (\(\alpha=0.05\)) was used to assess the difference between observed and expected injuries between control season, intervention season 1 and intervention season 2. All performance and biomechanical variables were analysed according to the intention-to-treat principle with a linear mixed model. Time (control season, post-intensive training, post-intervention season 1 and post-intervention season 2) was input as a fixed factor. Hedge’s ‘\(g\)’ effect sizes were calculated between and within groups after intensive-training, intervention season 1 and intervention season 2, and were employed as to account for the differences in sample sizes across seasons. All statistical analyses were conducted in SPSS, and an alpha of 0.05 was used (IBM SPSS Statistics 22, SPSS Inc., Chicago, IL).

3.4 Results

Exposure increased following the control season (6,749.1 hours), for intervention season 1 (7,609.2 hours) and intervention season 2 (7,143.4 hours) with a total of 21,501.7 hours over all three seasons. Total knee injury incidence increased in intervention season 1 (2013-2014) but was reduced following intervention season 2 (2014-2015). Of most significance, total lower limb, knee ligament and ACL injury incidence were reduced following the implementation of the
training program following intervention season 1, and were further reduced following intervention season 2 (Table 3.1).

**Table 3.1.** Injury incidence (number of injuries per 1,000 player hours) for total lower limb, knee, knee ligament and ACL injuries for the control season (2012-2013) and intervention seasons (1: 2013-2014, 2: 2014-2015).

<table>
<thead>
<tr>
<th>Season</th>
<th>Lower Limb</th>
<th>Knee</th>
<th>Knee Ligament</th>
<th>ACL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>23.0</td>
<td>2.1</td>
<td>0.6</td>
<td>0.4</td>
</tr>
<tr>
<td>Intervention season 1</td>
<td>15.7</td>
<td>2.9</td>
<td>0.3</td>
<td>0.0</td>
</tr>
<tr>
<td>Intervention season 2</td>
<td>5.2</td>
<td>1.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Observed total lower limb injuries were significantly lower than expected during intervention season 2 ($\chi^2=61.1$, $p<0.001$, df=2). Observed ACL injuries were higher than expected in the control season and lower than expected in the intervention seasons, with zero injuries occurring following the intervention period ($\chi^2=7.0$, $p=0.03$, df=2) (Table 3.2).

**Table 3.2.** Observed and expected total lower limb, knee, knee ligament and ACL injuries for the control season (2012-2013) and intervention seasons (1: 2013-2014, 2: 2014-2015).

<table>
<thead>
<tr>
<th>Season</th>
<th>Observed</th>
<th>Expected</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Lower Limb</td>
<td>Knee</td>
</tr>
<tr>
<td>Control</td>
<td>155.0</td>
<td>14.0</td>
</tr>
<tr>
<td>Intervention season 1</td>
<td>124.0</td>
<td>23.0</td>
</tr>
<tr>
<td>Intervention season 2</td>
<td>48.0</td>
<td>9.0</td>
</tr>
</tbody>
</table>
Improved 1RM strength was observed for bench press (+Δ7.9%, p=0.001) and bench pull 1 (+Δ9.8%, p=0.013) following intervention season 1 relative to the control season, and these strength gains were maintained following intervention season 2. Back squat 1RM improved from the control season following intervention season 2 (+Δ4.34%, p=0.046) (Figure 3.2).

**Figure 3.2.** Absolute 1RM scores during the control season and following the intensive training intervention, intervention season 1 and intervention season 2. *Denotes significant differences, p<0.05.
Ten metre split time for 40m sprint efforts improved relative to the control season following intervention season 1 (Δ0.7%, p=0.013). Times increased (+2.4% p=0.011) from intervention season 1 to intervention season 2. However, there were no differences in 10m split time from the control season to intervention season 2 (p=0.353). Improvements in 40m sprint time were observed between post-intensive training and post-intervention season 1 (Δ2.7%, p=0.026) and at post-intervention season 2 from the control season (Δ0.17%, p=0.004) (Figure 3.3).

Figure 3.3. 10m split and total 40m sprint times during the control season and following the intensive training intervention, intervention season 1 and intervention season 2. *Denotes significant differences, p<0.05.
Beep test scores improved by 7.5% following intervention season 1 \((p<0.001)\) and a further 6.2% following intervention season 2 \((p=0.002)\) (Figure 3.4).

**Figure 3.4.** Beep test decimal scores during the control season and following the intensive training intervention, intervention season 1 and intervention season 2. *Denotes significant differences, \(p<0.05\).
There were no changes in peak knee extension moments following intensive training, however there was a statistical trend associated with a +Δ8.2% increase from post-intensive training to post-maintenance training (g=0.534, p=0.060). There were no statistically significant changes in peak valgus knee moments during the intensive phase of the training intervention, however a trend existed for a -Δ20.9% reduction from the control season to the end of intervention season 1 (g=0.400, p=0.580). A trend also existed for a reduction in peak internal rotation moments from the control season to intervention season 1 (-Δ19.7%, g=0.419, p=0.480) (Figure 3.5).

**Total Group Knee Moments**

![Graph showing total group knee moments](image)

*Figure 3.5. Peak knee extension, valgus and internal rotation moments normalised to body weight and height during the weight acceptance phase of unplanned sidestepping during the control season, following the intensive training phase and following the maintenance training phase of intervention season 1. *) Denotes moderate effect sizes (0.30 ≤ d < 0.6).*

3.5 **DISCUSSION**

Biomechanically informed injury prevention training successfully reduced lower limb and ACL injury incidence among elite level female field hockey players. In addition, though time was taken away from skills/performance training, selected performance measures were not compromised, and for some measures, improvements were observed. Overall results support the efficacy of biomechanically informed and focussed injury prevention training, as both an ACL and lower limb injury prevention training prescription.
While training exposure increased following the control season, both total lower limb injury incidence (control season: 23, intervention season 2: 5.2) and ACL injury incidence (control season: 3, intervention season 2: 0) were reduced (Table 2). As outlined by previous injury prevention research, it is important to assess effectiveness of these programs on not only injury rates, but also biomechanical injury mechanisms (i.e. peak knee moments). In line with these findings, there was a trend observed for a 20.9% reduction in peak valgus (\(g=0.400, p=0.530\)) and a 19.7% reduction in peak internal rotation (\(g=0.419, p=0.480\)) knee moments following intervention season 1 (Figure 5). Although not statistically significant, these trends suggest that the program has displayed some success in targeting the biomechanical factors associated with ACL and lower limb injury risk.

Though some ACL injury prevention training interventions have been successful\(^{25-37}\), the majority have been unsuccessful in reducing ACL injury rates among general athletic populations\(^{7,12,13,38,41}\). In the prospective analysis of the effect of a 6 week neuromuscular training program among 1,263 male and female team sport athletes, Hewett et al. found that untrained athletes had a 2.4-3.6 higher incidence of serious knee injuries than the trained group. The “Prevent Injury and Enhance Performance” program\(^{37}\) delivered as a warm up in female soccer players included strength, plyometric and agility exercises with a strong instructional focus on landing technique. There was an 88% reduction in ACL injuries in year 1 and 74% reduction in year 2 following this training regime. It is difficult to understand the mechanisms by which these interventions were effective/ineffective in reducing ACL injury rates, as biomechanical risk factors were not measured in parallel. It is likely that successful training interventions may have intentionally or unintentionally targeted the biomechanical factors associated with injury risk.

While training design may be similar to the aforementioned studies, Myklebust et al. (2003) found no reductions in ACL injuries following a year of balance, plyometric and technique training. Training was revised in the second intervention season following coach/athlete feedback and coach/trainer education on the intended outcomes of the program was provided.
As a result, compliance increased from 42% to 50% for elite division teams, which corresponded to reductions in ACL injury events in the second intervention season. Donnelly and colleagues (2012) found balance and technique training to be ineffective in reducing biomechanical risk factors among community-level Australian Rules football players where player attendance in the training was 45±22% and coach to athlete ratio recorded at 1:44. These studies are in contrast to the present study where 81.1±25.0% attendance and 88.2±19.7% compliance and a low coach to athlete ratio of 1:13 were exhibited. This highlights three key factors in the design of injury prevention training research: (1) coach autonomy (2) low coach to athlete ratios and, (3) high athlete attendance and compliance to gain optimal exposure. By delivering a training “message” rather than a specific prescription of individual exercises, coaches are provided with education and choice surrounding the specifics of program implementation that on face value appears to have improved athlete compliance. These research design factors appear to be crucial in understanding the effect of preventative training on the biomechanical factors associated with ACL injury risk and the subsequent reduction in ACL injury rates.

A number of limitations to this study should be noted. A control cohort to the same level of competition (i.e. national team) as our sample could not be obtained. However, following the success of this feasibility study, a larger-scale RCT is recommended. With only one available team at the time of testing, we admittedly possessed a relatively small sample size. This small sample size limited our ability to interpret the biomechanical findings, although effect sizes indicate practical significance that can be used to inform future research. To further understand the effects of biomechanically informed training, research should identify athletes who are at high risk of injury prior to entry into interventions, in order to increase the sensitivity of biomechanical findings and improve coach commitment to injury prevention training for “high-risk” individuals.

With the power of biomechanical research in injury prevention, it is important to disseminate this into community level sport settings in a multidisciplinary manner. In addition, athlete and
coach adherence and compliance are key to the success of injury prevention research\textsuperscript{5} \textsuperscript{16} \textsuperscript{26} \textsuperscript{44}, and the design of future interventions should incorporate strategies designed to enhance participant engagement\textsuperscript{43} \textsuperscript{45}. For example, rather than prescribing specific exercise programs that may not be suited to different training regimes, educating coaches on key biomechanical factors associated with ACL injury risk may be more effective. These biomechanical training messages are; 1) to increase knee flexion angle at foot strike\textsuperscript{21}, 2) to control the trunk and upper body during dynamic movement \textsuperscript{9} \textsuperscript{27}, 3) to strengthen the hip external rotators and avoid “dynamic knee valgus” postures \textsuperscript{11} \textsuperscript{18} and, 4) to increase strength of the gastrocnemius muscle group\textsuperscript{20}. By offering various exercises that target these four pillars of training, coaches and sport science staff are enabled and empowered to develop injury prevention sessions that best fit their program environment and structure. Anecdotally, perhaps this aspect of the program is one of the reasons why the Australian national women’s hockey program have continued to use this training approach independently since its implementation in 2013, well beyond their commitment to this research study.

3.6 CONCLUSION

A biomechanically informed injury prevention training program implemented in conjunction with an elite training and medical environment was successful in reducing both total lower limb and ACL injuries among elite female hockey players over two seasons while maintaining and/or improving athletic performance measures. Biomechanical injury risk factors, that of peak knee moments \textsuperscript{14}, were also reduced. These findings support delivering a training “message” rather than a training “genre” for effective implementation of ACL injury prevention training.
3.7 References


20. Morgan KD, Donnelly CJ, Reinbolt JA. Elevated gastrocnemius forces compensate for decreased hamstrings forces during the weight-acceptance phase of single-leg jump landing:


CHAPTER FOUR

A 25-WEEK BIOMECHANICALLY INFORMED TWO PHASE INJURY PREVENTION TRAINING PROGRAM: IMPLICATIONS FOR ACL INJURY RISK AMONG ELITE FEMALE HOCKEY PLAYERS

This manuscript was prepared for Medicine and Science in Sports and Exercise.

Conference abstracts pertaining to this manuscript are provided in Appendix E of this thesis.


The PhD candidate, Gillian J Weir, accounted for 80% of the intellectual property associated with the final manuscript. Collectively, the remaining authors contributed 20%. The formatting and references of this chapter follow the guidelines for submission to Medicine and Science in Sports and Exercise.
FOREWORD

The previous chapter (Study one) demonstrated the efficacy of biomechanically informed and focussed training in reducing total lower limb and ACL injury rates while maintaining/improving athletic performance. It was then important to understand how this intervention modified an athlete’s injury risk profile. This can be achieved through two biomechanical approaches; the first is to change an athlete’s technique to reduce external joint loading, and the second is to increase the strength and support of the surrounding knee joint musculature when external loading is high. This study will investigate the influence of training on peak knee moments, full body kinematics and lower limb muscle activation strategies during unplanned sidestepping. It was also important to determine how much training was required in the long term to maintain any observed neuromuscular or biomechanical adaptations. As such all neuromuscular and biomechanical measures were taken prior to and following an initial nine week intensive training phase, and again following a 16 week reduced volume maintenance phase. Previous research has shown injury prevention training to have differential effect in “high” vs “low” risk populations ¹, and consequently this study also investigates the effect of biomechanically informed training at an individual level. This study, in combination with Study one provides evidence for the efficacy of biomechanically informed and focused training reducing ACL injury risk and rates among elite team sport athletes.
4.1 Abstract

Purpose: The aim of this study was to assess the efficacy of a novel, biomechanically informed injury prevention program, which was focussed on modifying an athlete’s kinematics, kinetics and muscle activation in efforts to reduce their risk of anterior cruciate ligament (ACL) injury in sport. This was appraised by way of an intensive training phase (9-weeks, 4x20mins p/wk) and a maintenance training phase (16-weeks, 3x10mins p/wk).

Methods: Seventeen elite female hockey players participated in a two-phase, 25-week, injury prevention training program. Biomechanical measures associated with ACL injury risk were recorded during unplanned sidestepping at; baseline, following an intensive training phase and following a maintenance training phase. Athletes were classified as responders (n=5) if they recorded a moderate-large effect size reduction in peak knee valgus (PKV) moments or non-responders (n=11) following the intensive training phase.

Results: Intensive training: PKV moments among the total training group (i.e. both responders and non-responders) did not change over the intervention period, however when considered in isolation, the responder group displayed a 29.5% reduction (p=0.045). At baseline these athletes possessed 43.8% higher PKV moments than non-responders (p=0.007). No kinematic changes were observed, however desirable muscle activation strategies were adopted (i.e., elevated gluteal total muscle activation (TMA) and medially directed co-contraction for muscles crossing the knee). Maintenance training: While there were no significant changes in kinematic variables over the intervention phase, responders continued to decrease (-Δ32.8%, g=0.590, p=0.286) their PKV moments. Initial increases in gluteal TMA for responder athletes were maintained, however medially directed lower limb muscle co-contraction ratios returned to a lateral activation strategy and were not significantly different from baseline (p=0.580) at the completion of the maintenance phase.
**Conclusion:** Biomechanically informed injury prevention training was successful in reducing PKV moments and subsequent ACL injury risk for an identified responder elite athlete cohort. While there were no changes to investigated sidestepping technique variables, elevated total muscle activation of the hip musculature, and medially directed muscle co-contraction at the knee, were found to complement kinetic results following the 9-week *intensive* training phase. These benefits were retained following a reduced session volume/frequency *maintenance* training program. Screening to identify “high-risk” athletes to improve training efficacy and to determine optimal training volume should be important factors that researchers consider when designing injury prevention training programs.
4.2 INTRODUCTION

It has been well documented that female athletes participating in team sports suffer anterior cruciate ligament (ACL) injuries at a four to six fold higher rate than their male counterparts. Additionally, females competing in a higher level of competition have been shown to display significantly higher peak knee valgus moments when compared with novice athletes. These injuries place a high financial and lifestyle burden on the athlete. Costs associated with surgery are upward of $5,000 AUD, and these injuries remove athletes from competition for 12 months, with only 70% able to return to the same level of competition. Injury prevention training programs may present a cost-effective solution for this global problem. Research has investigated the effect of training programs such as balance, plyometric, resistance, flexibility and/or a combination thereof in injury prevention training programs, however these interventions have had mixed success in reducing ACL injury rates among general athletic populations. As these programs failed to measure the biomechanical mechanisms of injury in parallel with injury rates, conclusions cannot be drawn upon whether these training programs adequately targeted them.

Non-contact ACL injuries occur when the knee is in an extended posture and combined, externally applied flexion, valgus and internal rotation moments are experienced at the knee joint. In-silico and in-vivo research has shown that the ACL is at greatest risk of injury during the weight acceptance (WA) phase of stance, where valgus knee moments are the greatest. Two biomechanical strategies an athlete can adopt to counter elevated peak knee moments in an effort to reduce ACL injury risk are; 1) to modify their technique to reduce the peak external forces applied to the knee, and 2) to improve the muscular strength and activation to support the knee joint when these forces are elevated. More specifically, recent evidence has identified the following countermeasures for reducing ACL injury predisposition; 1) increasing knee flexion angle at foot strike to reduce combined peak valgus and internal...
rotation knee moments, 2) improving dynamic control of the trunk and upper body to reduce peak valgus knee moments, 3) increased hip external rotator strength, which can prevent athletes from attaining “dynamic knee valgus” postures and, 4) improving the strength of the gastrocnemius muscle group to elevate joint compression. With these four biomechanically informed training pillars, clinicians and coaches are now in a position to design injury prevention training programs that effectively target the biomechanical mechanisms associated with ACL injury risk.

A number of other limitations exist that inhibit the translation of laboratory based findings to real-world training environments. These include athlete compliance, coach perceptions of the program and the trainer to athlete ratios. To combat these barriers it is important to identify athletes who are high-risk in the first instance, as these cohorts have been shown to respond more positively to focused injury prevention training. While some injury prevention training research has been successful in reducing ACL injury risk/rates in the short term (4-12 weeks), there is little to no evidence for the retention of these initial benefits in the longer term. Further, there are no guidelines outlining optimal intensity and duration levels for injury prevention training to be successful in reducing injury rates over a season of play. In the absence of sufficient training stimuli, it is questionable if athletes can maintain any neuromuscular and biomechanical benefits gained once dedicated injury prevention training is discontinued. As such, research is warranted investigating the effect of a maintenance training phase following the implementation of an initial targeted injury prevention program has been completed.

This study aimed to verify the efficacy of a novel, biomechanically informed, 9 week intensive injury prevention training program in reducing ACL injury risk factors (i.e. peak knee moments, kinematic solutions and muscle activation strategies) among elite female field hockey players. Our secondary aim was to assess the efficacy of a subsequent 16 week maintenance training
phase that immediately followed the *intensive* program, where training intensity and type were maintained but session duration was reduced. We hypothesised that peak knee moments associated with ACL injury risk would be reduced, and technique and lower limb muscle activation strategies known to mitigate ACL injury risk would improve following the *intensive* training phase. We further hypothesised that these improvements would be preserved during the *maintenance* phase of the training program.

### 4.3 Methods

#### 4.3.1 Participants

Seventeen elite international female hockey players (age = 22.1 ± 2.3yr, height = 1.68 ± 0.09m, mass = 66.30 ± 7.00kg) were recruited for this study. A power analysis from a previous study revealed significant reductions in peak valgus knee moments following 6 weeks of technique training, indicating that for 80% power with the alpha set to 0.05, a minimum of 14 subjects were required. All 17 athletes were injury free at the time of testing. Four athletes had previous ACL reconstruction (ACLR), but had returned to full competition at least 12 months prior to testing. This study was approved by the human research ethics committee at the University of Western Australia (See Appendix A.1) and informed written consent was obtained from all participants prior to study’s commencement.

#### 4.3.2 Experimental Design

All athletes participated in a 25-week biomechanically focussed injury prevention training program. The training program was partitioned into two phases; 1) *intensive* training (Weeks 1-9) and, 2) *maintenance* training (Weeks 10-25). To test the effectiveness of each phase of the program in reducing ACL injury risk factors (i.e. peak knee moments, joint kinematics and muscle activation strategies), biomechanical analyses of participants completing a previously published unplanned sidestepping movement assessment were collected three times; prior to the
intervention (baseline), following the *intensive* training phase, and following the *maintenance* training phases (Figure 4.1).

**Figure 4.1** Biomechanically informed training intervention design, with both intensive and maintenance phases highlighted. Biomechanical testing sessions outlining sample size and participant stratification are also noted.
4.3.3. TRAINING PROGRAM

Irrespective of the exercise genre (resistance, balance, plyometric and technique) the overriding goal or focus of the intervention was to target four key biomechanical factors proven to be associated with ACL injury risk. These were; (1) to increase knee flexion angle at foot strike, (2) improve dynamic control of the trunk and upper body, (3) strengthen the hip external rotators to prevent athletes from exhibiting “dynamic knee valgus” postures and, (4) increase the strength of the gastrocnemius musculature. A high coach to athlete ratio of 1:13 was adopted in efforts to maximise athlete adherence and compliance to the training protocol.

The intensive training phase consisted of 4 x 20 minute sessions per week which progressed in intensity every two weeks. Intensity was progressed in five stages; Stage 1 - Master basic techniques through unilateral tasks; Stage 2 - Integration of additional component or direction to the task to decrease stability; Stage 3 - Introduction of secondary perturbation; Stage 4 - Increase explosiveness of multidirectional tasks and respond to quick external perturbations; Stage 5 - Maintain responses and techniques to rapid external perturbations. The maintenance training phase comprised 3 x 10 minute sessions per week conducted during the warm up of skills training sessions. During these sessions the same intensity and type of exercises were performed from Stage 4 above with only the time (i.e. duration) dedicated to the specific training reduced.

4.3.3 BIOMECHANICAL TESTING

Three-dimensional (3D) motion analysis of each participant completing a previously published unplanned sidestepping protocol were recorded at baseline, following intensive training, and again following maintenance training. All sidestepping tasks were performed using the athletes’ self-selected preferred limb. Participants were fitted with retroreflective makers as per a customised kinematic marker set and model. Marker trajectories were recorded using a 24 camera Vicon® motion analysis system (12 Vicon® MX and 10 Vicon® T40 cameras) (Oxford
Metrics, Oxford, UK) operating at 250 Hz. Cameras were synchronized with a 1.2m x 1.2m force plate (AMTI, Watertown, MA) recording at 2,000Hz. These data, with a reliable full body customised model fully compliant with International Society of Biomechanics (ISB) standards for the reporting of data, were used to calculate full body kinematics and peak knee moments via inverse dynamics procedures in Vicon® Bodybuilder software through the Vicon® Nexus software pipeline (Vicon, Oxford Metrics, Oxford, UK).

Muscle activation was measured with surface electromyography (sEMG) using a 16-channel telemetry system (Telemyo2400 G2, Noraxon, Scottsdale, Arizona) at 1,500Hz. Using bipolar 30mm disposable surface electrodes (CleartraceTM Ag/AgCl, ConMed, Utica, NY), with an inter-electrode distance of 30mm, nine pairs of electrodes were placed over the muscle bellies of nine muscles crossing the knee and hip. These muscles were chosen as they can be analysed in a manner that provides knee and ACL injury risk information during sidestepping sporting tasks. These included the gluteus maximus (GMax), gluteus medius (GMed), semimembranosus (SM), biceps femoris (BF), vastus lateralis (VL), vastus medialis (VM), rectus femoris (RF), medial gastrocnemius (MG), and lateral gastrocnemius (LG). The signal processing of these signals included, first removing direct current offsets from the signal, then band-pass filtered between 30 and 500 Hz with a zero-lag, 4th order Butterworth digital filter, full-wave rectification and then linearly enveloped using a low pass with a zero-lag, 4th order Butterworth filter at 6 Hz.

Muscle activation was amplitude normalised to the maximal activation observed for each muscle during either a single leg squat, single leg countermovement jump or sidestepping trial and expressed as 0 – 100% maximal voluntary contraction. Muscle activation patterns were assessed using mean total muscle activation (TMA) and directed co-contraction ratios (DCCR) as per Donnelly et al.

4.3.4 ANALYSIS

The mean of three unplanned sidestepping trials for each participant were used in the analysis. Approach velocity and change of direction angles were measured to ensure task completion did
not differ across testing sessions. Peak knee extension (PKE), peak knee valgus (PKV) and peak knee internal rotation (PKIR) moments (normalised to body mass and height) were calculated during WA alongside trunk flexion range of motion (RoM), peak trunk lateral flexion, peak hip abduction, knee flexion RoM and mean knee flexion angles. Knee flexion angle and foot to centre of mass (CoM) were measured at foot strike.

Mean TMA of the gluteal, quadriceps, hamstrings and gastrocnemius muscle groups were calculated, as well as for all muscles crossing the knee. Directed co-contraction ratios (DCCR) were calculated for flexion/extension (F/E) muscle groups, medial/lateral (M/L) muscle groups, and the semimembranosus/bicep femoris muscles (SM/BF). A DCCR>0 indicated co-contraction was directed toward muscles with flexion and/or medial moment arms, while a DCCR<0 indicated co-contraction was directed toward muscles with extension and/or lateral moment arms. A DCCR=0 indicated maximal co-activation. All muscle activation variables were measured during pre-contact (PC) (50 milliseconds before foot strike) and WA.

Following the intensive training phase of the intervention a “responder-analysis” was performed. A responder athlete was defined as one who returned a moderate to large effect size reduction in PKV moments (n=5), and a non-responder as an athlete who did not display a reduction in PKV moments (n=11).

4.3.5 Statistical Analyses

All dependant variables were analysed across time according to the intention-to-treat (ITT) principle using a linear mixed model. ITT analysis includes all observations for each participant and ignores dropout. Therefore, during the second phase of the intervention unequal samples were compared with missing data entered. Time (Baseline, post-intensive training and post-maintenance training) and response (responder and non-responder) were input as fixed factors. Least significant difference (LSD) post-hoc analysis was used to assess for significant main effects and interactions. All statistical analyses were conducted in SPSS (IBM SPSS Statistics 22, SPSS
Inc., Chicago, IL), with an $\alpha = 0.05$. Hedge’s ‘$g$’ effect sizes which account for differences in sample sizes, were calculated between and within groups at baseline, after intensive training, and following maintenance training.

### 4.4 Results

There were no differences in approach velocity or cut angle between any of the three biomechanical testing sessions (Table 4.1).

<table>
<thead>
<tr>
<th></th>
<th>Baseline</th>
<th>Post-intensive training (9 wks)</th>
<th>Post-maintenance training (25 wks)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Approach velocity (m/s)</td>
<td>4.4 (0.3)</td>
<td>4.7 (0.3)</td>
<td>4.3 (0.4)</td>
</tr>
<tr>
<td>Change of direction angle (°)</td>
<td>26.5 (9.2)</td>
<td>27.9 (8.5)</td>
<td>26.2 (10.3)</td>
</tr>
</tbody>
</table>
There were no statistically significant reductions in PKE (p=0.060), PKV (p=0.530) and PKIR (p=0.480) moments across time for the total group (Figure 4.2). There was a moderate effect size for increased PKE moments between post-intensive training to post-maintenance training (+Δ8.2%, g=0.534), however values did not differ from baseline. A moderate effect size also existed for a -Δ18.9% reduction in PKV moments from baseline to post-maintenance training (g=0.397). There was a reduction in PKIR moments from baseline to post-maintenance training (-Δ19.7%, g=0.419).

**Figure 4.2.** Peak knee extension, valgus and internal rotation moments normalised to body mass and height for the total group (responder and non-responder athletes) during the weight acceptance phase of unplanned sidestepping. Data presented is at baseline, post-intensive training and post-maintenance training. *a* = Indicates a statistically significant difference (p < 0.05), *b* = Indicates a greater than moderate effect size (g ≥ 0.60), *c* = Indicates a moderate effect size (0.30 ≤ g < 0.6).
Five of the initial 16 athletes displayed a moderate effect size reduction (0.30 ≤ d < 0.6) in PKV moments following the intensive training phase and were classified into the responders cohort (Figure 4.3). One athlete (Participant 12) displayed a net 0.062 Nm.kg⁻¹.m⁻¹ increase in PKV moments following intensive training, which was atypical. This athlete, however displayed a 36.6% reduction in PKV moments following the combined intensive and maintenance training phases. Participant 4 displayed a 120.5% increase in PKV moments following the maintenance phase of training, however this athlete sustained a navicular stress fracture and did not complete all maintenance training sessions.

![Individual Responses to Training](image)

**Figure 4.3.** Individual athlete peak knee valgus moments normalised to body mass and height at baseline and following intensive training and maintenance training phases for responder (n=5) and non-responder (n=11) athletes. Responders are signified by an “R” and athletes with previous ACLR are signified by an asterisk in the X axis.
No significant group and time interactions were observed for PKE moments, however a moderate effect size was observed following intensive training for responder athletes (-Δ8.9%, g=0.467). Non-responder athletes displayed an increase in PKE moments following maintenance training (+Δ7.8%, g=-0.532). In contrast, the responder group saw an 8.8% reduction in PKE moments (g=0.534) following the intensive training phase (Figure 4.4).

**Figure 4.4.** Peak knee extension moments normalised to body mass and height for responder and non-responder athletes during the weight acceptance phase of unplanned sidestepping. Data presented is at baseline, post-intensive training and post-maintenance training. *a* = Indicates a statistically significant difference (p < 0.05), *b* = Indicates a greater than moderate effect size (g ≥ 0.60), *c* = Indicates a moderate effect size (0.30 ≤ g < 0.6).
A group and time interaction was observed for PKV moments (p=0.047). Post-hoc analyses showed that following *intensive* training, responders reduced their PKV moments by 29.5% (g=0.668, p=0.045). No significant differences were observed following *maintenance* training, however a further 32.8% reduction was supported by a moderate effect size (g=0.590). Non-responders experienced a 19.8% increase in PKV moments (g=-0.386) following *intensive* training. At baseline, responders displayed 43.8% higher PKV moments than non-responders (g=0.626, p=0.007) (Figure 4.5).

**Figure 4.5.** Peak knee valgus moments normalised to body mass and height for responder and non-responder athletes during the weight acceptance phase of unplanned sidestepping. Data presented is at baseline, post-intensive training and post-maintenance training. *a* = Indicates a statistically significant difference (p < 0.05), *b* = Indicates a greater than moderate effect size (g ≥ 0.60), *c* = Indicates a moderate effect size (0.30 ≤ g < 0.6).
Responder athletes reduced their peak internal rotation moments following the intensive training phase of the intervention (Δ17.7%, g=0.430) and from baseline to post-maintenance training (Δ24.6%, g=0.596) (Figure 4.6).

Figure 4.6. Peak knee internal rotation moments normalised to body mass and height for the responder and non-responder athletes during the weight acceptance phase of unplanned sidestepping. Data presented is at baseline, post-intensive training and post-maintenance training. a = Indicates a statistically significant difference (p < 0.05), b = Indicates a greater than moderate effect size (g ≥ 0.60), c = Indicates a moderate effect size (0.30 ≤ g < 0.6).

There were no between group responder and non-responder kinematic differences for investigated variables and as such all data presented are for the total group (Table 4.2). Following both the intensive and maintenance training phases of the intervention there were no statistically significant changes, however some moderate effect sizes were observed in relevant kinematic variables associated with ACL injury risk. There was a 4.2⁰ reduction in peak hip abduction following intensive training (g=0.572), which returned to baseline values following maintenance training (g=0.649). Mean knee flexion decreased (g=0.774), while foot-pelvis distance increased (d=0.583), across both training phases.
Table 4.2. Mean (SD) kinematics during unplanned sidestepping at baseline, post-intensive training and post-maintenance training for the total group (n=16).

<table>
<thead>
<tr>
<th></th>
<th>Baseline</th>
<th>Post-intensive training (9 wks)</th>
<th>Post-maintenance training (25 wks)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trunk Flexion RoM (°)</td>
<td>10.0 (1.7)</td>
<td>9.2 (2.5)</td>
<td>9.1 (2.2)</td>
</tr>
<tr>
<td>Peak trunk lateral flexion (°)</td>
<td>10.1 (6.3)</td>
<td>12.74 (8.2)</td>
<td>12.11 (3.8)</td>
</tr>
<tr>
<td>Peak hip abduction (°)</td>
<td>15.9 (7.5)</td>
<td>11.7 (7.5)</td>
<td>16.0 (5.7)</td>
</tr>
<tr>
<td>Knee flexion (IC) (°)</td>
<td>19.3 (4.8)</td>
<td>18.5 (5.2)</td>
<td>18.0 (5.0)</td>
</tr>
<tr>
<td>Knee flexion mean (°)</td>
<td>36.3 (4.4)</td>
<td>34.3 (5.5)</td>
<td>33.2 (3.7)</td>
</tr>
<tr>
<td>Knee flexion RoM (°)</td>
<td>37.1 (3.7)</td>
<td>35.6 (4.9)</td>
<td>36.4 (5.1)</td>
</tr>
<tr>
<td>Foot-pelvis distance (cm)</td>
<td>26.9 (3.3)</td>
<td>27.9 (3.1)</td>
<td>28.8 (3.1)</td>
</tr>
</tbody>
</table>

* Indicates a greater than moderate effect size (g ≥ 0.60) from baseline
* Indicates a greater than moderate effect size (g ≥ 0.60) from post-intensive training
* Indicates a moderate effect size (0.30 ≤ g < 0.6) from the baseline
* Indicates a moderate effect size (0.30 ≤ g < 0.6) from post-intensive training

There were no between group responder and non-responder muscle activation differences and as such all data were combined and presented as a total group (Table 4.3). During WA, mean gluteal TMA increased by 30% following intensive training (g= 0.609, p=0.015). No other statistically significant differences in TMA were observed. A moderate effect size was observed for a reduction in gluteal TMA following maintenance training (g=0.472). There was a moderate increase in hamstring TMA across both phases of the intervention during PC (+Δ13.3%, g=0.460, p=0.144). Knee TMA increased between post-intensive training and post-maintenance training during PC (+Δ10.2%, g=0.351) and WA (+Δ10.2%, g=0.456).

Prior to the intervention medial/lateral DCCR were directed toward muscles with lateral moment arms during PC and WA. In contrast, following the intensive training phase, medial/lateral DCCR were directed toward muscles with medial moment arms during PC (g=0.596, p=0.046) and WA (g=0.561, p=0.049). Similarly, SM/BF DCCR was laterally directed toward BF prior to training, yet following the intensive training phase SM/BF DCCR was medially directed toward SM during PC (g=0.720, p=0.015) and WA (g=0.609, p=0.045). Following maintenance training SM/BF DCCR returned to a lateral activation strategy during PC (g=0.574,
p=0.018) and WA (g=0.194, p=0.035) and was not significantly different to activation recorded prior to the intervention.

Table 4.3. Mean (SD) total muscle activation (TMA) of the muscles crossing the knee and hip and directed co-contraction (DCCR) of the muscles crossing the knee with flexion/extension and medial/lateral moment arms. Data are presented at baseline, Post-intensive training and Post-maintenance training during both the PC and WA phases of unplanned sidestepping. For DCCR>0, co-contraction is directed toward muscles with flexion and/or medial moment arms. For DCCR<0, co-contraction is directed toward muscles with extension and/or lateral moment arms. For DCCR=0, co-contraction is maximal.

<table>
<thead>
<tr>
<th></th>
<th>Baseline</th>
<th>Post-intensive training (9 wks)</th>
<th>Post-maintenance training (25 wks)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pre-Contact</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gluteal TMA</td>
<td>0.55 (0.27)</td>
<td>0.63 (0.31)</td>
<td>0.48 (0.20)</td>
</tr>
<tr>
<td>Quadriceps TMA</td>
<td>0.30 (0.15)</td>
<td>0.34 (0.10)</td>
<td>0.29 (0.13)</td>
</tr>
<tr>
<td>Hamstrings TMA</td>
<td>0.60 (0.20)</td>
<td>0.59 (0.20)</td>
<td>0.70 (0.20)</td>
</tr>
<tr>
<td>Gastrocnemii TMA</td>
<td>0.33 (0.22)</td>
<td>0.34 (0.20)</td>
<td>0.41 (0.23)</td>
</tr>
<tr>
<td>Knee TMA</td>
<td>1.23 (0.43)</td>
<td>1.27 (0.40)</td>
<td>1.40 (0.33)</td>
</tr>
<tr>
<td>F/E DCCR</td>
<td>0.51 (0.21)</td>
<td>0.47 (0.20)</td>
<td>0.61 (0.24)</td>
</tr>
<tr>
<td>M/L DCCR</td>
<td>0.00 (0.25)</td>
<td>0.15 (0.26)</td>
<td>0.01 (0.21)</td>
</tr>
<tr>
<td>SM/BF DCCR</td>
<td>-0.08 (0.31)</td>
<td>0.16 (0.36)</td>
<td>-0.14 (0.21)</td>
</tr>
<tr>
<td><strong>Weight Acceptance</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gluteal TMA</td>
<td>0.56 (0.26)</td>
<td>0.73 (0.27)</td>
<td>0.61 (0.23)</td>
</tr>
<tr>
<td>Quadriceps TMA</td>
<td>0.80 (0.14)</td>
<td>0.78 (0.14)</td>
<td>0.79 (0.21)</td>
</tr>
<tr>
<td>Hamstrings TMA</td>
<td>0.50 (0.17)</td>
<td>0.43 (0.17)</td>
<td>0.53 (16)</td>
</tr>
<tr>
<td>Gastrocnemii TMA</td>
<td>0.40 (0.18)</td>
<td>0.44 (0.19)</td>
<td>0.50 (0.18)</td>
</tr>
<tr>
<td>Knee TMA</td>
<td>1.70 (0.32)</td>
<td>1.65 (0.40)</td>
<td>1.82 (0.33)</td>
</tr>
<tr>
<td>F/E DCCR</td>
<td>-0.15 (0.18)</td>
<td>-0.18 (0.20)</td>
<td>0.00 (0.18)</td>
</tr>
<tr>
<td>M/L DCCR</td>
<td>-0.08 (0.23)</td>
<td>0.04 (0.22)</td>
<td>0.00 (0.18)</td>
</tr>
<tr>
<td>SM/BF DCCR</td>
<td>-0.11 (0.31)</td>
<td>0.10 (0.36)</td>
<td>-0.15 (0.28)</td>
</tr>
</tbody>
</table>

*Indicates a significant difference from baseline p<0.05
^Indicates a significant difference from post-intensive training p<0.05
Indicates a greater than moderate effect size (g ≥ 0.60) from the baseline
^Indicates a greater than moderate effect size (g ≥ 0.60) from post-intensive training
Indicates a moderate effect size (0.30 ≤ g < 0.6) from the baseline
^Indicates a moderate effect size (0.30 ≤ g < 0.6) from post-intensive training

4.5 DISCUSSION

The overall findings of this study support the use of biomechanically informed training to reduce the biomechanical (i.e., peak joint moments) and neuromuscular (i.e., muscle support) risk factors associated with ACL injury risk among team sport athletes who may be at higher predisposition to injury. The majority of the improved biomechanical constraints elicited in an
intensive 9-week training program were maintained following 16-weeks of maintenance training which comprised of reduced duration but not intensity.

4.5.1 INTENSIVE TRAINING

Nine weeks of intensive training was successful in reducing peak knee extension, valgus, and internal rotation moments among the elite female hockey players within the responder group. Interestingly, responder athletes possessed PKV moments that were 44% higher in magnitude to athletes within the non-responder group prior to the training program, indicating that they may have been “high-risk” at the program commencement (Figure 5.3). Similarly, Myer and colleagues (2007) through logistic regression, identified “high-risk” and “low-risk” athletes in a cohort of 18 high school female athletes and found that high risk athletes reduced their PKV moments by 13% following seven weeks of training, while the low risk and control groups did not demonstrate any meaningful reduction. Taken in combination with previous findings the results from this manuscript suggests that athletes who have high knee loading may be able to reduce these loads through training, however athletes who have relatively low knee loading at baseline will not experience a similar benefit (by magnitude). Identifying athletes who have high PKV moments during dynamic tasks such as sidestepping may therefore be an important factor when assessing the efficacy of injury prevention training programs to avoid data “wash-out” and to help enhance coach/athlete compliance to training. Future research with large sample data should also be directed toward clarifying what are low, moderate or high cut-off values for PKV moments to prospectively identify high and low risk athletes at baseline. In the present study, all athletes who displayed PKV moments >0.80 Nm.kg⁻¹.m⁻¹ responded favourably to the training intervention with the single exception of Participant 12.

Two biomechanical strategies capable of reducing ACL injury risk in sport were assessed within this study, of which; 1) found no statistically significant differences in full body sidestepping kinematics (technique), however, 2) there were significant improvements in gluteal TMA and
medial DCCRs following intensive training. Sidestepping is a complex dynamic movement with a vast kinematic solution space, and while we were able to observe kinetic changes, this did not translate to a measurable kinematic effect. Simply, there may have not been a single unilateral kinematic change by this sample to explain the observed reductions in peak knee moments. This is not unusual or unexpected as simulation research has shown that for the same unplanned sidestepping task, an athlete can choose from 511 kinematic solutions to effectively reduce their PKV moments. As such, athletes may have responded to each of the training pillars differently, however all resulted in reduced or similar levels of knee loading in parallel with elevated musculature support at the hip.

The absence of any change to kinematics may also be explained by the lack of explicit sidestepping technique training. Dempsey et al. (2009) observed a reduction in peak lateral trunk flexion and foot distance from mid-pelvis, accompanied by a 36% reduction in PKV moments following the implementation of specific technique training for 15 minutes, 2 x per week for 6 weeks. Coach to athlete ratio in that study was 1:2, compared with the 1:14 ratio of the present study. However, baseline knee flexion angles, foot placement and trunk lateral flexion angles were comparable to that observed post-technique training by Dempsey et al. (2009), suggesting that the athletes within this study may have displayed low risk techniques at baseline. This may also be due to our sample being elite female field hockey athletes compared with amateur male Australian Football Players of Dempsey et al. (2009).

The observed improvements in gluteal TMA are likely attributed to the strong training focus on hip neuromuscular training within the intervention training program. The gluteal muscles can act to maintain a stable pelvis and prevent excessive hip adduction and internal rotation during single limb support. The observed increase in gluteal TMA would be considered a positive neuromuscular strategy elicited from the intensive training phase. Medially directed DCCRs for all muscles crossing the knee and hamstrings were observed following the intensive training
phase. This strategy supports the knee joint in the frontal plane and can therefore protect the knee from externally applied valgus moments when elevated.

4.5.2 Maintenance Training

During the maintenance training phase, there were no significant changes in peak knee moments among athletes within the responder and non-responder groups. However, there was a moderate effect for a further 32.9% decrease in PKV moments among the athletes initially classified as responders. It should be noted that there was a moderate increase in PKE moments among non-responder athletes. However, it has been established that extension knee moments alone are incapable of rupturing the ACL, meaning their injury risk classification would not have likely changed. These findings support the hypothesis that the initial stimulus from intensive training, among athletes who initially responded to the biomechanically informed training within the first 9-weeks, was sufficient to maintain reductions in the high PKV moments from 9-25 weeks.

Maintenance training, in combination with and in isolation to intensive training, produced no statistically significant changes in kinematics. The increase in gluteal TMA along with the medial M/L DCCR strategy observed during intensive training was retained following maintenance training. However SM/BF DCCR returned to a lateral activation strategy, which may be due to insufficient training volume stimuli. In a retention study, Padua and colleagues found that following 3 months of detraining, a 9 month training group maintained benefits, whereas a 3 month training group did not. This suggests that training stimulus required to elicit safe movement patterns may require more than the traditionally prescribed 2x15 minute sessions p/wk for 6-12 weeks as reported in ACL intervention literature. This is in contrast to the high dose intensive training phase in the present study which saw 4x20 minute sessions for 9 weeks. It is therefore important to ensure there is appropriate stimulus in the intensive training phase before understanding the retention effect of maintenance training.
Participant 12 who experienced an 86% increase in her PKV moments following intensive training, reduced these by 67% following maintenance training and 36% in the program overall. This athlete had sustained an ACL injury three years prior to this intervention, and sustained a graft rupture two years following the implementation of this program. Research has shown female athletes who have undergone ACL reconstruction display elevated peak knee moments accompanied by higher frontal plane knee excursions. Though this athlete had fully recovered from injury and had returned to normal training and competitive games for 18 months post-surgery, the significant outlying response to training for this athlete may be attributed to altered joint biomechanics following ACLR. A larger training volume over a longer period (exposure), as in the case of the combined intervention successfully reducing this athletes PKV moments, may be necessary for athletes who have previously sustained an ACL injury. This may also highlight an additional benefit for ACLR athletes who complete biomechanically informed training for rehabilitation and post-rehabilitation settings. However this is speculation and must be tested among a larger group of previously injured athletes.

4.5.3 LIMITATIONS

There were two notable limitations to this study. The first is the absence of a control group to compare these findings to as our sample was limited to an Olympic female hockey team of which there is only one in Australia. Second was the limited sample size of the present study, although statistical power was achieved (Appendix D). While all athletes completed both phases of training, competing scheduling demands resulted in access to only 17 players for 3D biomechanical testing. Finally, due to retirement, injury and availability over the study timeframe, six players were lost to follow up following the maintenance phase of the intervention training and testing.
4.6 **CONCLUSION**

Biomechanically informed injury prevention training was successful in reducing peak knee moments and subsequent ACL injury risk during an intensive 9-week intervention, which were retained during a 16-week maintenance (reduced session frequency and volume) training phase for an identified responder athlete cohort. While there were no discernible changes to sidestepping technique (i.e. kinematics), improved gluteal muscle activation and medially directed co-contraction strategies were found to complement reductions in peak knee moments following the 9-week *intensive* training phase. To improve the efficacy of training studies, researchers should aim to; 1) screen for “high-risk” athletes and place these athletes into targeted interventions, 2) ensure initial intensive training programs have an appropriate initial stimulus, and lastly 3) implement RCTs with varied dose maintenance training phases to determine optimal training volumes.
4.7 REFERENCES


CHAPTER FIVE

A RELIABLE VIDEO BASED ANTERIOR CRUCIATE LIGAMENT INJURY SCREENING TOOL FOR THE ASSESSMENT OF FEMALE TEAM SPORT ATHLETES

This manuscript was prepared for The American Journal of Sports Medicine.

Conference abstracts pertaining to this manuscript is provided in Appendix E of this thesis.


Weir, G.J., Smailes, N., Alderson, J., Elliott, B.C., Donnelly, C.J. A Two-Dimensional Video Based Screening Tool To Predict Peak Knee Loading and ACL Injury Risk in Female Community Level Athletes. In proceedings of the XXIV Congress of the International Society of Biomechanics, Natal, Brazil, August 4 -9, 2013.

The PhD candidate, Gillian J Weir, accounted for 80% of the intellectual property associated with the final manuscript. Collectively, the remaining authors contributed 20%. The formatting and references of this chapter follow the guidelines for submission to The American Journal of Sports Medicine.
FOREWORD

Study one and study two presented the efficacy of biomechanically informed training in reducing ACL injury risk and incidence, while simultaneously improving athletes’ neuromuscular activation strategies and athletic performance. Study two demonstrated that training was more effective among “responder” athletes who were classified from changes in their peak valgus knee moments. Three-dimensional analysis of peak knee moments however, is not readily available to the community level athlete. Therefore this study aimed to test the suitability of employing two-dimensional video technique analysis to predict an athlete’s peak knee moments during unplanned sidestepping. Two-dimensional measures of both upper and lower body kinematics across multiple planes were predictive of peak knee extension, valgus and internal rotation knee moments. The results from this study provides a medium to screen and identify athletes who are at higher risk of ACL injury with the overarching aim of improving the efficacy of injury prevention training protocols. This is twofold; 1) improving coach intent to implement these programs, and 2) improving the effectiveness of the intervention itself by targeting training toward athletes with specified biomechanical or neuromuscular deficits.
5.1 Abstract

**Background:** Identifying athletes at “high-risk” of anterior cruciate ligament (ACL) injury has been identified as an effective means to improve the specificity and efficacy of injury prevention training. However, clinically relevant methods capable of identifying ‘at-risk’ athletes on a large scale are limited.

**Purpose:** This study aimed to develop a two-dimensional video screening tool capable of identifying the kinematic factors associated with an athlete’s peak three dimensional knee moments during unplanned sidestepping among a heterogeneous group of female team sport athletes.

**Study Design:** Descriptive laboratory study

**Methods:** Two dimensional video based measures of upper and lower body kinematics in the frontal and sagittal planes were simultaneously captured with three-dimensional measures of peak knee moments during unplanned sidestepping for 30 female team sport athletes (15 junior and 15 senior field hockey players). Linear regression models were used to model peak three dimensional knee moments from seven 2D kinematic variables utilising eighty percent of the total sample (n=26). The regression equations were then validated on a randomised subset of the remaining sample (n=6). Intra- and inter- tester reliability and limits of agreement of all 2D kinematic measures were also performed.

**Results:** Movement patterns such as high dynamic knee valgus, low knee flexion angle at foot strike, elevated trunk flexion range of motion (ROM), increased trunk lateral flexion away from the intended direction of travel, large peak hip abduction and knee flexion ROM effectively predicted peak knee extension, valgus and internal rotation moments during unplanned sidestepping. All 2D measures had good to excellent intra- and inter-rater reliability.

**Conclusion:** Two dimensional frontal and sagittal plane video based measurements of an athlete’s full body kinematics during unplanned sidestepping provides a reliable, specific,
sensitive and cost-effective means for screening ‘at-risk’ female team sport athletes of varying competition levels.

**Clinical Relevance:** This research provides a feasible and cost-effective screening tool that can empower coaches, clinicians and researchers to identify high ACL injury risk populations who can then undergo targeted injury prevention training programming.

**Key Terms:** Screening, injury prevention, valgus knee moments, training.

**What is known about the subject:** One half of non-contact ACL injuries occur during sidestepping tasks. Combined knee extension, valgus and internal rotation moments, which are observed during sidestepping tasks have been shown to increase ACL strain in-vivo. In-lab analyses have shown these aforementioned peak knee moments and ACL injury risk are elevated further when sidestepping is performed in unplanned or unanticipated scenarios.

**What this study adds to existing knowledge:** This study translates laboratory based biomechanics research into the development of a repeatable, cost-effective mass ACL injury screening tool. Specifically, two dimensional video data were used to assess an athlete’s ACL injury risk during an unplanned sidestepping testing protocol.
5.2 Introduction

Neuromuscular training has been identified as a cost-effective solution for anterior cruciate ligament (ACL) injury prevention. However, current intervention-based research has reported mixed success in reducing ACL injury rates among community level athletes. These varied results suggest that the underlying factors (i.e., biomechanical and neuromuscular) associated with ACL injuries are not being effectively targeted. Research has shown injury prevention training can be more successful in reducing knee moments (surrogate measure of ACL injury risk) when interventions have high compliance and when they initially target “high-risk” athletes. One avenue identified to improve the effectiveness of injury prevention training protocols is to screen and identify “high-risk” athletes so targeted injury prevention training protocols toward the individuals biomechanical deficits can be applied. More specifically, control of an athlete’s whole body centre of mass via dynamic trunk control, dynamic knee valgus knee postures, knee flexion angle at foot strike and foot placement relative to whole body centre of mass have been identified as key biomechanical factors associated with peak knee moments during sidestepping and landing sport tasks.

While a number of screening tools have been developed for the identification of athletes at risk of ACL injury, not all are cost nor time effective. As such, four considerations have been proposed for the implementation of injury screening tools, particularly among community level training environments. The first is to ensure there is a strong relationship between the measured modifiable biomechanical factors (i.e. techniques and neuromuscular support) within the screening test and peak knee loads or injury risk. Second, in an ACL injury risk context, we must strive toward the development of methods/movements which assess athletes during the injurious task itself (i.e. sidestepping and single leg landing), specifically those which result in high extension, valgus and internal rotation moments, which have been shown to be associated with ACL injury events and high ACL injury risk. Third, these methods must be robust enough to be applied to a wide range of heterogeneous sporting populations (i.e. elite and community...
level). Finally, screening must be implemented alongside an intervention program to document that it is more cost and time effective to train identified “high-risk” athletes than delivering the same program to all athletes. While taking these factors into consideration, for these screening tools to be integrated within field based training environments with relative ease, they must also be simplistic, have low financial/time expense and be user friendly.

Three-dimensional (3D) biomechanical kinematic and kinetic measures are currently used as the gold standard for measurement of an athlete’s SS technique, peak knee moments and relative injury ACL injury risk classification. These methods however are limited to a laboratory settings, which are both cost and time expensive, limiting their access to community level athletic populations where the majority of ACL injuries are known to occur. Two-dimensional (2D) video analysis is a practical and accessible technology (i.e. smart phones) for athletes to record and measure their full body kinematics in multiple planes during the sporting tasks such as sidestepping, which is where non-contact ACL injuries are known to occur. This builds upon the potential for integration into community level sport as smart phone video recording and software applications are widely accessible and cost effective.

The purpose of this study was to develop a reliable 2D, video based screening tool capable of predicting peak knee moments from upper and lower body kinematic variables during unplanned sidestepping. This was assessed among a group of female team sport athletes of different levels of maturation and skill.

### 5.3 Methods

#### 5.3.1 Participants

Fifteen junior (age = 15.1 ± 1.2yr, height = 1.70 ± 0.05m, mass= 55.8 ± 6.7kg) and 15 elite senior (age = 22.1 ± 2.3yr, height = 1.68 ± 0.09m, weight = 66.3 ± 7.0kg) female field hockey players volunteered for this study. Female athletes were chosen for initial development of this screening tool as previous literature has shown this cohort to be at higher risk of ACL injury than their male
counterparts. Additionally, when compared with novice athletes, experienced female athletes display significantly higher peak knee valgus moments during sidestepping tasks. Therefore it was important to understand the characteristics of female athletes of different levels of competition. This study was approved by the human research ethics committee at the University of Western Australia (see Appendix A.2), and informed written consent was obtained from all participants and/or a parent/legal guardian prior to the commencement of the study.

5.3.2 CLINICAL MOVEMENT ASSESSMENT

Participants completed a previously published sidestepping protocol which involved a series of pre-planned (PP) and unplanned (UP) straight line run, cross-over step and sidestep running tasks in a laboratory setting. All tasks were completed with their self-selected preferred limb and their order randomised using a customised software program (Kinematic Measurement System, Optimal Kinematics, Australia). A projector screen was placed 5m in front of a force plate and displayed a 30cm arrow to indicate each of the required running conditions. During PP running tasks, the arrow was projected onto the screen prior to run commencement. For UP running conditions, the arrow was triggered by the athlete running through infra-red timing gates and appeared when participants were approximately 400ms from making contact with the force plate, a time corresponding with contralateral limb toe-off. Software was used to measure and alter the delay between the timing gate trigger and arrow appearance to allow for individual differences in reaction time. For a trial to be considered successful, an approach velocity of the right anterior iliac spine marker, calculated in Vicon® Nexus® software (Oxford Metrics, Oxford, UK) was between 3.5-4.5m/s. Successful change of direction trials also required participants to follow a line marked on the laboratory floor with tape, 45º ±10 º relative to global x-axis of the laboratory, with the contralateral leg during cutting manoeuvres.
5.3.3 Data Capture

The running and change of direction clinical movement assessment was dual captured with 3D motion capture system and 2D video in a laboratory setting to allow for the measurement of ground reaction forces in six degrees of freedom (GRF), which were used to define the weight acceptance (WA) phase of stance and to calculate peak knee extension, valgus and internal rotation knee moments during WA. Participants were affixed with 30 retro-reflective markers to the trunk and lower limbs according to a customised kinematic model. Marker trajectories were recorded using a 12 camera Vicon® MX motion analysis system (Oxford Metrics, Oxford, UK) operating at 250 Hz. Cameras were synchronized with a 1.2m x 1.2m force plate (AMTI, Watertown, MA) recording at 2,000Hz. These data, with a reliable full body customised model fully compliant with International Society of Biomechanics (ISB) standards for the reporting of data, were used to calculate peak knee moments via inverse dynamics procedures in Vicon® Bodybuilder software through the Vicon® Nexus software pipeline (Vicon, Exford Metrics, Oxford, UK).

Two standard video cameras (Sony Handycam, HDR-CX700) recording at 50Hz were used for analysis as it was assumed that these video capture technologies would be accessible to most community level training environments. Cameras were placed in the frontal and sagittal planes to the force plate. A spirit level on the camera tripods was used to ensure cameras were absolutely level in both roll and pitch. Two-dimensional video data were synchronised with 3D using a LED light stimulus placed in the camera field of view which was triggered at foot-strike on the force plate (i.e. when the vertical GRF vector exceeded 10N).

5.3.4 Data Analysis

Peak 3D knee moments and 2D video kinematic data from the UP sidestepping task were analysed at initial foot contact (IC) and during the WA phase of stance. The vertical GRF data were used to define WA and the time base was then divided by a factor of five to time-link to the 2D kinematic data that was recorded at a lesser sampling rate (i.e. 250Hz/50Hz). Knee
moment data were calculated using custom lower limb kinematic and inverse dynamic models in Bodybuilder (Vicon Peak, Oxford Metrics Ltd., UK). Peak knee extension, valgus and internal rotation moments were normalised to body mass (kg) and height (m). Centre of mass was used to calculate pre-contact running velocities and change of direction angles.

Video data were imported into SiliconCoach Pro 7.0 software (SiliconCoach, Dunedin, NZ) for analysis. Trunk and lower limb kinematics identified in previous literature to have an association with ACL injury risk were measured in the frontal and sagittal planes (Table 5.1). These selected variables are a condensed set of kinematics refined from pilot testing (See Appendix D.7).
Table 5.1. Two-dimensional kinematic variable measurement definitions and conventions used in SiliconCoach Pro 7.0 software. ASIS=anterior superior iliac spine, HJC=hip joint centre, KJC=knee joint centre, AJC=ankle joint centre.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Measurement Method</th>
<th>Measurement Convention</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Trunk Lateral Flexion Angle (°)</strong></td>
<td>Line 1: Global vertical Y axis from the midpoint of left and right ASIS.</td>
<td>+ve = toward stance leg</td>
</tr>
<tr>
<td></td>
<td>Line 2: Midpoint of left and right ASIS to clavicle.</td>
<td>-ve = away from stance leg</td>
</tr>
<tr>
<td></td>
<td><strong>Measurement</strong>: Relative angle between Line 1 and Line 2.</td>
<td></td>
</tr>
<tr>
<td><strong>Thigh Abduction Angle (°)</strong></td>
<td>Line 1: Swing limb ASIS through stance limb ASIS.</td>
<td>+ve = adduction</td>
</tr>
<tr>
<td></td>
<td>Line 2: Draw a 90° angle on Line 1 toward stance limb ASIS. Then draw a line over the second defining line. Erase 90° angle.</td>
<td>-ve = abduction</td>
</tr>
<tr>
<td></td>
<td><strong>Measurement</strong>: Relative angle between Line 1 and Line 2.</td>
<td></td>
</tr>
</tbody>
</table>
### Table 5.1. (continued)

#### Frontal Plane

<table>
<thead>
<tr>
<th>Variable</th>
<th>Measurement Method</th>
<th>Measurement Convention</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dynamic Knee Valgus Angle (°)</td>
<td><strong>Line 1</strong>: ASIS to KJC.</td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Line 2</strong>: KJC to AJC.</td>
<td>+ve = 'dynamic' valgus</td>
</tr>
<tr>
<td></td>
<td><em>Measurement</em>: Relative normal angle between Line 1 and Line 2. Subtract from 180°.</td>
<td>-ve = 'dynamic' varus</td>
</tr>
<tr>
<td>Dynamic Medial Knee Shift (m)</td>
<td><strong>Line 1</strong>: Stance limb ASIS to ankle lateral malleolus.</td>
<td>+ve = medial shift</td>
</tr>
<tr>
<td></td>
<td><strong>Line 2</strong>: Draw a 90° angle on Line 1 through KJC. Then draw a line over the second</td>
<td>-ve = lateral shift</td>
</tr>
<tr>
<td></td>
<td>defining line. Erase 90° angle.</td>
<td></td>
</tr>
<tr>
<td></td>
<td><em>Measurement</em>: Perpendicular distance from Line 1, along Line 2 toward KJC.</td>
<td></td>
</tr>
</tbody>
</table>
Table 5.1. (continued)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Measurement Method</th>
<th>Measurement Convention</th>
</tr>
</thead>
<tbody>
<tr>
<td>Foot Placement (m)</td>
<td><strong>Line 1:</strong> Left ASIS to right ASIS.</td>
<td>+ve = stance limb away from midline</td>
</tr>
<tr>
<td></td>
<td><strong>Line 2:</strong> Vertical line from midpoint of Line 1 to ground.</td>
<td>-ve = stance limb crosses midline</td>
</tr>
<tr>
<td></td>
<td><strong>Measurement:</strong> Perpendicular distance from Line 2 to AJC.</td>
<td></td>
</tr>
</tbody>
</table>
### Table 5.1. (continued)

<table>
<thead>
<tr>
<th>Sagittal Plane</th>
<th>Variable</th>
<th>Measurement Method</th>
<th>Measurement convention</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><strong>Trunk Flexion Angle (°)</strong></td>
<td><strong>Line 1:</strong> Global vertical (Y) axis from the HJC. &lt;br&gt;<strong>Line 2:</strong> HJC to acromion marker</td>
<td>+ve = Flexion &lt;br&gt;-ve = Extension</td>
</tr>
<tr>
<td></td>
<td><strong>Knee Flexion Angle (°)</strong></td>
<td><strong>Line 1:</strong> HJC to KJC &lt;br&gt;<strong>Line 2:</strong> KJC to AJC</td>
<td>+ve = Flexion &lt;br&gt;-ve = Hyperextension</td>
</tr>
</tbody>
</table>

All 2D video based kinematic data were measured on two separate occasions by one assessor (Tester 1a and Tester 1b) and once by a second assessor (Tester 2) to test intra- and inter-rater reliability respectively.

5.3.5 Statistical Analysis

Data for all individual UP sidestepping trials for both junior and senior athletes (n=92) were analysed in SPSS (IBM SPSS Statistics 22, SPSS Inc., Chicago, IL) with an alpha set to 0.05 for all statistical tests. All analysis was conducted in collaboration with the UWA School of Mathematics and Statistics. First, a one-way ANOVA was conducted to determine if there were differences in peak knee moments and predictor variables between junior and senior athletes. Following this analysis, eighty per cent of the initial sample (12 participants’ trials from each junior and senior cohort n=72) were used to predict peak knee moments to generate initial regression models. Regression was performed using a linear mixed model to independently predict peak extension, valgus and internal rotation knee moments from a subset of 2D video based kinematic variables. Individual participants were modelled as random factors to account for entering individual trials into the analysis and independent 2D kinematic variables as fixed factors. To assess differences in predictor variables (i.e. 2D kinematics) between female athletes of different levels of competition, athlete level (i.e. junior and senior) were also entered as a fixed factors. Independent variables were sequentially removed from the regression model when the p value was greater than 0.05. Variables were removed manually in order of highest p value until all variables within the model were significant (α = 0.05) predictors of the dependant variable. The regression equations developed in the initial sample (80% total sample) were externally validated on a randomised subsample of 3 junior and 3 senior athletes (trials n=17) by calculating predicted values of peak knee extension (PKE), valgus (PKV) and internal rotation (PKIR) moments from the measured 2D kinematics. These predicted values were then compared with experimentally recorded values using a paired samples t-test and Cohen’s d effect sizes where d<0.30 indicated a small effect, 0.30<d<0.60 indicated a moderate effect and d>0.60
indicated a greater than moderate effect. The *a priori* definition used to qualify the regression equations as an adequate predictors of the measured peak knee moments were: 1) the prediction was not statistically different to measured value and 2) the observed difference between the predicted and measured value were small to moderate in effect size. If the *a priori* criterion were met, linear regression was then performed again on the entire dataset (i.e. 100%, n=92 trials) to generate complete regression model(s) or prediction equation(s). Intra-class correlations (ICC) and limits of agreement (LoA) were used to test inter- and intra-rater reliability of 2D kinematic measures for junior athletes’ individual UP sidestepping trials (n=41). ICC values were interpreted according to the following criteria: poor <0.40, fair 0.40 to 0.60, good 0.60 to 0.75 and excellent >0.75.

5.4 Results

There were no significant differences in PKE, PKV and PKIR moments between groups. Additionally there were no differences in approach velocity and change of direction angle. Senior athletes had significantly higher peak trunk lateral flexion (p=0.025), peak hip abduction (p=0.001) and knee flexion ROM (p=0.027) kinematics when compared with the junior athletes. Senior athletes also displayed lower dynamic knee valgus postures (p<0.001), knee valgus displacement (p<0.001) and foot-pelvis distances (p=0.004) (see Table 5.2).
Table 5.2. Mean (SD) of all dependent and independent variables for junior (n=15) and senior (n=15) athletes.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Junior</th>
<th>Senior</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak knee extension moments (Nm.kg⁻¹.m⁻¹)</td>
<td>2.35 (0.31)</td>
<td>2.29 (0.47)</td>
</tr>
<tr>
<td>Peak knee valgus moments (Nm.kg⁻¹.m⁻¹)</td>
<td>0.56 (0.36)</td>
<td>0.67 (0.41)</td>
</tr>
<tr>
<td>Peak knee internal rotation moments (Nm.kg⁻¹.m⁻¹)</td>
<td>0.10 (0.07)</td>
<td>0.09 (0.09)</td>
</tr>
<tr>
<td>Peak trunk lateral flexion (⁰)</td>
<td>4.35 (5.22)</td>
<td>7.68 (4.82)*</td>
</tr>
<tr>
<td>Peak hip abduction (⁰)</td>
<td>6.42 (6.33)</td>
<td>12.50 (5.92)**</td>
</tr>
<tr>
<td>Dynamic knee valgus (⁰)</td>
<td>25.91 (7.43)</td>
<td>14.93 (8.61)**</td>
</tr>
<tr>
<td>Dynamic medial knee shift (m)</td>
<td>0.10 (0.02)</td>
<td>0.04 (0.02)**</td>
</tr>
<tr>
<td>Knee flexion (IC) (⁰)</td>
<td>24.85 (8.82)</td>
<td>26.43 (5.89)</td>
</tr>
<tr>
<td>Knee flexion RoM (⁰)</td>
<td>24.85 (8.82)</td>
<td>29.52 (5.28)*</td>
</tr>
<tr>
<td>Trunk flexion (IC) (⁰)</td>
<td>3.78 (5.37)</td>
<td>4.58 (4.16)</td>
</tr>
<tr>
<td>Trunk flexion RoM (⁰)</td>
<td>6.61 (5.63)</td>
<td>7.02 (4.17)</td>
</tr>
<tr>
<td>Foot-pelvis distance (IC) (m)</td>
<td>0.32 (0.06)</td>
<td>0.28 (0.04)**</td>
</tr>
<tr>
<td>Approach velocity (m/s)</td>
<td>4.3 (0.3)</td>
<td>4.4 (0.3)</td>
</tr>
<tr>
<td>Change of direction angle (⁰)</td>
<td>24.4 (7.3)</td>
<td>26.5 (9.2)</td>
</tr>
</tbody>
</table>

**Significantly different from junior athletes (p<0.001)
*Significantly different from junior athletes (p<0.05)

Dynamic knee valgus angle and knee flexion ROM predicted and were positively correlated to PKE moments for both junior and senior athletes (Table 5.3).

Table 5.3. Parameter coefficients (β) and standard error (SE) for significant independent predictors of peak knee extension moments.

<table>
<thead>
<tr>
<th>Peak Knee Extension Moments</th>
<th>β</th>
<th>SE</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>1.807</td>
<td>0.178</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Dynamic knee valgus angle</td>
<td>0.010</td>
<td>0.005</td>
<td>0.026</td>
</tr>
<tr>
<td>Knee flexion angle ROM</td>
<td>0.011</td>
<td>0.005</td>
<td>0.020</td>
</tr>
</tbody>
</table>
For both athlete levels, peak trunk lateral flexion, peak hip abduction, knee flexion angle (IC) and
trunk flexion ROM were significant predictors of PKV moments. Peak trunk lateral flexion, peak
hip abduction and trunk flexion ROM were positivity correlated with PKV moments. Increased
knee flexion at foot-strike were negatively correlated with PKV moments (Table 5.4).

Table 5.4. Parameter coefficients (β) and standard error (SE) for significant independent predictors of
peak knee valgus moments.

<table>
<thead>
<tr>
<th>Parameter Coefficients</th>
<th>β</th>
<th>SE</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>0.881</td>
<td>0.177</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Peak trunk lateral flexion angle</td>
<td>0.021</td>
<td>0.007</td>
<td>0.003</td>
</tr>
<tr>
<td>Peak hip abduction angle</td>
<td>0.012</td>
<td>0.006</td>
<td>0.037</td>
</tr>
<tr>
<td>Knee flexion angle (IC)</td>
<td>-0.025</td>
<td>0.006</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Trunk flexion angle ROM</td>
<td>0.015</td>
<td>0.007</td>
<td>0.037</td>
</tr>
</tbody>
</table>

Dynamic knee valgus angle, peak hip abduction angle and knee flexion angle (IC) were significant
predictors of PKIR moments for both athlete levels. Increases in dynamic knee valgus angle were
negatively correlated with PKIR moments. Increases in knee flexion angle (IC) negatively
correlated with PKIR moments for junior athletes, however were positively correlated with PKIR
moments for senior athletes. Increases in peak hip abduction were associated with reductions
in PKIR moments for junior athletes and increases in PKIR moments for senior athletes (Table
5.5).

Table 5.5. Parameter coefficients (β) and standard error (SE) for significant independent predictors of
peak knee internal rotation moments.

<table>
<thead>
<tr>
<th>Parameter Coefficients</th>
<th>β</th>
<th>SE</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>0.191</td>
<td>0.084</td>
<td>1.000</td>
</tr>
<tr>
<td>Dynamic knee valgus</td>
<td>-0.003</td>
<td>0.001</td>
<td>0.002</td>
</tr>
<tr>
<td>Peak hip abduction</td>
<td>-0.007</td>
<td>0.003</td>
<td>0.012</td>
</tr>
<tr>
<td>Knee flexion (IC)</td>
<td>0.002</td>
<td>0.002</td>
<td>0.412</td>
</tr>
<tr>
<td>Athlete level</td>
<td>0.175</td>
<td>0.117</td>
<td>1.000</td>
</tr>
<tr>
<td>Athlete level*peak hip abduction</td>
<td>0.011</td>
<td>0.003</td>
<td>0.003</td>
</tr>
<tr>
<td>Athlete level*knee flexion (IC)</td>
<td>-0.009</td>
<td>0.003</td>
<td>0.007</td>
</tr>
</tbody>
</table>

The parameter coefficients described in Tables 3-5 were used to predict peak knee moments in
the randomised subsample (n=6). As there were no significant differences in peak knee
moments between junior and senior athletes as presented in Table 2, both cohorts were collapsed in to one group for this analysis. There were no significant differences and low to moderate effect size differences in predicted and real PKE, PKV and PKIR moments (Table 5.6).

**Table 5.6.** Mean (SD) experimentally measured and predicted peak knee moments for the randomised subsample (trials n=17).

<table>
<thead>
<tr>
<th>Variable</th>
<th>Measured</th>
<th>Predicted</th>
<th>p</th>
<th>d</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak knee extension moments (Nm.kg⁻¹.m⁻¹)</td>
<td>2.25 (0.36)</td>
<td>2.25 (0.08)</td>
<td>0.676</td>
<td>-0.026</td>
</tr>
<tr>
<td>Peak knee valgus moments (Nm.kg⁻¹.m⁻¹)</td>
<td>0.59 (0.19)</td>
<td>0.52 (0.22)</td>
<td>0.331</td>
<td>-0.354</td>
</tr>
<tr>
<td>Peak knee internal rotation moments (Nm.kg⁻¹.m⁻¹)</td>
<td>0.10 (0.06)</td>
<td>0.11 (0.04)</td>
<td>0.974</td>
<td>0.144</td>
</tr>
</tbody>
</table>

All three prediction equations met the *a priori* definitions of; 1) predicted values of peak knee moments not statistically different to measured values and 2) observed differences between the predicted and measured value were small to moderate in effect size (Table 5.6). Therefore, linear regression was performed again on the entire (i.e. 100%, n=92 trials) dataset to generate complete regression model(s) or prediction equation(s). The regression equations (Eq. 1-4) developed from 100% of the original sample are presented below.

\[
PKE\text{ Moment } = 1.715 + 0.014(\text{dynamic knee valgus angle}) + 0.012(\text{knee flexion angle ROM})
\]  
\[
PKV\text{ Moment } = 0.788 + 0.017(\text{trunk lateral flexion angle}) + 0.017(\text{peak hip abduction angle}) – 0.019(\text{knee flexion angle IC}) + 0.017(\text{trunk flexion angle ROM})
\]

\[
PKIR\text{ Moment}_{\text{junior}} = 0.247 – 0.003(\text{dynamic knee valgus angle}) – 0.005(\text{peak hip abduction angle}) + 0.007(\text{knee flexion angle IC})
\]

\[
PKIR\text{ Moment}_{\text{senior}} = 0.256 – 0.003(\text{dynamic knee valgus angle}) – 0.007(\text{peak hip abduction angle}) + 0.002(\text{knee flexion angle IC})
\]
Intra- and inter-tester reliability of all 2D kinematic variables were good to excellent for all independent variables, with the exception of dynamic medial knee shift (Table 5.7). Intra-class correlations ranged from 0.377 to 0.998 with LoAs for displacement variables ranging from 0.28m to 0.49m and angle variables ranging from 1.2° to 4.9° for intra-tester measurement. Inter-tester measurement produced ICCs ranging from 0.542 to 0.949 and LoAs for displacement variables between 0.10m to 0.27m and angle variables from 7.1° to 26.3°.
Table 5.7. Inter- and Intra-class Correlations (ICC) and 95% Limits of Agreement (LoA) for independent variables for junior female athletes’ individual trials (n=41).

<table>
<thead>
<tr>
<th>Variable</th>
<th>Tester 1a vs Tester 1b</th>
<th>Tester 1a vs Tester 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ICC</td>
<td>Mean Difference</td>
</tr>
<tr>
<td>Peak trunk lateral flexion (°)</td>
<td>0.976**</td>
<td>-0.084</td>
</tr>
<tr>
<td>Peak hip abduction (°)</td>
<td>0.991**</td>
<td>0.075</td>
</tr>
<tr>
<td>Dynamic knee valgus (°)</td>
<td>0.998**</td>
<td>-0.112</td>
</tr>
<tr>
<td>Knee valgus displacement (m)</td>
<td>0.377*</td>
<td>-0.035</td>
</tr>
<tr>
<td>Knee flexion (IC) (°)</td>
<td>0.997**</td>
<td>0.085</td>
</tr>
<tr>
<td>Knee flexion RoM (°)</td>
<td>0.996**</td>
<td>0.112</td>
</tr>
<tr>
<td>Trunk flexion (IC) (°)</td>
<td>0.997**</td>
<td>-0.136</td>
</tr>
<tr>
<td>Trunk flexion RoM (°)</td>
<td>0.936**</td>
<td>-0.154</td>
</tr>
<tr>
<td>Foot-pelvis distance (IC) (m)</td>
<td>0.539*</td>
<td>-0.002</td>
</tr>
</tbody>
</table>

**p<0.001
*p<0.05
5.5 Discussion

Multi-planar, full body video based measures of an athletes’ two dimensional kinematics during UP sidestepping were shown to have good-excellent intra- and inter-rater reliability and capable of predicting peak knee extension, valgus and internal rotation knee moments among a cohort of junior and senior female field hockey players. This, to our knowledge is the first 2D video based screening tool that has incorporated multi-planar assessment of both lower and upper body kinematics. Results were promising, as this research has shown in principle that video based screening tools have the potential to: 1) screen and identify “high-risk” athletes in large scale community level training environments and, 2) place these athletes into targeted interventions to reduce their associated risk and improve the efficacy of intervention based injury prevention research.

Unplanned sidestepping is a non-linear complex dynamic sporting task, and as such, there is rationale for an athletes’ upper and lower body kinematics to be analysed in multiple planes to effectively predict peak knee moments and ACL injury risk during WA 8 37 39. Results from this analysis confirm there is indeed a non-linear interplay between an athlete’s upper and lower body kinematics in one plane (i.e. frontal or sagittal plane) for predicting peak knee moments in another (i.e. sagittal or frontal plane). One example were dynamic knee valgus postures being predictors of peak extension knee moments. To help explain these seeming unintuitive results, it should be stated that dynamic knee valgus postures, measured in the frontal plane in 2D analysis, are in part the result of increased knee flexion, combined with hip abduction and hip internal rotation, which are associated with the neuromuscular control of the hip musculature. It would therefore be expected that poorer hip neuromuscular control, which influences the dynamics of the knee and upper body would be related to, in part, the peak extension moments observed at the knee during the highly dynamic loading occurring during the WA phase of sidestepping. Increases in knee flexion ROM were also positively associated with PKE moments. Although knee flexion at foot strike was not associated with PKE moments, it may be likely that
athletes who displayed less knee flexion at foot strike displayed greater subsequent knee flexion ROM and therefore a probable association with elevated PKE moments. This may also be a result of the nature of measurement in 2D. Results presented in Figure D.5 (See Appendix D.7.2) showed an absolute net differences of 2.9° in knee flexion at foot strike across four running conditions (planned and unplanned straight line running and sidestepping) between 2D and 3D measurements. Therefore ROM values may remove the absolute offset between 2D and 3D measures and serve as a more consistent measurement variable moving forward than absolute knee flexion at initial foot contact.

Both upper and lower body kinematics together were significant predictors of PKV moments. Results showed that increasing lateral trunk flexion toward the stance limb, elevated peak hip abduction and elevated trunk flexion ROM were all associated with elevated PKV moments. These findings directly align with previous research showing upper body motor control and trunk position to be associated with PKV moments 8 19 20, lending further support for the appropriateness of translating laboratory based research into the field. Consistent with video analysis of ACL injury events which have been documented to occur when the knee is near full extension 15, increasing knee flexion angle at initial foot strike (IC) was associated with reduced PKV moments. These results are also supported by cadaveric studies showing that in the presence of increased knee flexion and eccentric quadriceps forces, ACL strain is reduced 41.

While the same 2D kinematic variables (peak hip abduction angle, knee flexion (IC) and dynamic knee valgus) served to predict PKIR moments for junior and senior athletes, they predicted PKIR differently. This may be explained by the observed kinematic differences between the two groups (Table 5.2). Compared with seniors, junior athletes presented with lower peak hip abduction angles (junior = 6.42 ± 6.33, senior = 12.50 ± 5.92, p=0.001), higher dynamic knee valgus (junior = 25.91 ± 7.43°, senior = 14.93 ± 8.61°, p<0.001) and adopted a wider foot placement (junior = 0.32 ± 0.06m, senior = 0.28 ± 0.04, p=0.004). This may also be explained by differences in baseline lower limb strength or neuromuscular coordination, where it would be
expected that the senior group would have greater absolute strength and neuromuscular coordination due to the maturation associated with a full time professional completion and training schedules. Though plausible hypotheses, these observed differences require further research to verify these findings.

All three regression equations were capable of reproducing the measured PKE, PKV and PKIR moments among the randomised external subsample of junior and senior athletes where low to moderate effect sizes and no significant differences were observed. Additionally, the differences in measured vs predicted peak knee moments were no greater than 0.07 Nm.kg^{-1}.m^{-1} which is typically less than changes observed following a training intervention and between previously described high and low risk groups. This, in combination with reliable 2D kinematic measures, suggests that the developed video based injury screening tool has the potential to identify athletes who may be predisposed to elevated ACL injury risk. Peak knee moments (Table 5.2) are similar to that previously been reported in the sidestepping literature. Interestingly and contrary to previous research, peak knee moments did not differ between female athletes of varying competition levels. This may be a result of the interplay between experienced athletes’ technique as described in Table 2 and less experienced and more junior athletes’ neuromuscular characteristics. As the majority of screening tools have been focused around lower limb mechanics during drop jump and single leg landing with mixed findings, using a high risk dynamic task as utilised in testing this 2D screening tool, may improve the sensitivity of the screening process. It is also important to highlight that the proposed injury screening tool, in contrast to what has been previously presented within the literature, assessed athletes’ techniques in multiple planes and assessed both upper and lower body kinematics.

Given the aim of creating a 2D video based injury screening method accessible to community level athletes, the inherent delimitation is that only 2D kinematic measures were assessed. Though 3D kinematic measures are considered a gold standard, the accuracy of 2D vs 3D kinematic measures have been previously described and considered to have moderate to high
correlation. We also have shown that the measures used within the regression models had good to excellent intra- and inter-tester repeatability providing confidence that these measures can be utilised in real-world training environments. Another delimitation is that this tool has only been applied in female team sport populations, therefore future research is recommended to determine if this 2D video based screening tool can be used to assess injury risk among male athletes. A further limitation to the present study was that measurements of muscle activation were not performed in parallel, which if available may have provide more comprehensive injury risk interpretations. However, with time and cost being the focus for the development of this screening tool, we did not feel it appropriate to incorporate these data. Another limitation to this study was the moderate amount of data processing required to be performed by the user to manually identify anatomical landmarks and joint centres necessary for quantifying the 2D kinematic measures. Therefore, in order to minimise time-cost when combined with labour intensive training interventions, future development is recommended in the area of automated computer vision tracking to assist users in the auto-detection and rapid turn-around of the 2D measures in the field (i.e. a turn-key real-time tracking and analysis software application).

Future research must aim to determine thresholds for peak knee moments in classifying a “high-risk” athlete. This must be performed with large prospective injury databases. This is crucial to further refine screening tools that incorporate cause (kinematics) and effect (peak knee moments) in their analysis.

5.6 CONCLUSION

A repeatable and reliable 2D video-based screening tool was found to be successful in identifying movement patterns associated with injurious peak knee moments during unplanned SS among junior and senior level female athletes. Movement patterns such as dynamic knee valgus, low knee flexion angle at foot strike, large trunk flexion ROM, trunk lateral flexion away from the intended direction of travel, large peak hip abduction and large knee flexion ROM effectively predicted PKE, PKV and PKIR moments during unplanned SS. The results from this investigation,
which identify underlying kinematic patterns associated with peak knee moments during sidestepping with 2D video, may improve the potential for large scale mass screening and the implementation of targeted neuromuscular training for community level environments.
5.7 References


6.1 SUMMARY

In 2012, the Australian Women’s hockey team (Hockeyroos) team member Kellie White became one of the 52/100,000 people in Australia to rupture their ACL. The following statement describes the common non-contact mechanism, the extensive rehabilitation protocols and the psychosocial aspects of returning to sport;

“...I was playing in New Zealand, sidestepped quickly and partially tore ligaments in my left knee. I played on and carried the injury for another two years but in 2012, just before the London Olympics, I ruptured my left ACL. It was pretty devastating at the time and a hard slog during the recovery period. I had to tick all the boxes to have any hope of career longevity”.

There is accumulating evidence that ACL injuries can be prevented through targeted neuromuscular training, however, the extent to which research is being effectively translated to practise is unclear. Potential barriers to injury prevention training implementation include a coach’s understanding and ranking of the importance of time dedication toward injury prevention training and athlete attendance, adherence and compliance. The ACL injury prevention framework, including athlete screening, provides the basis for the development of injury prevention interventions aimed at reducing the likelihood of injury. This is achieved through the understanding the biomechanical mechanisms of, and countermeasures to, injury. This research was dedicated toward contributing to stages 3 and 4 of the ACL injury prevention framework proposed by Donnelly et al. (2012), bridging the gap between injury prevention research and practice (Stage 5/6).
The thesis aims were to combine the knowledge gained from injury surveillance (Stage 1) and aetiology (Stage 2) research for the purposeful development of effective ACL injury prevention training and injury screening protocols among elite and community level athletes alike. More specifically, this thesis aimed to assess the effectiveness of a novel and biomechanically informed training injury prevention program on the incidence of lower limb and ACL injuries among a group of elite female field hockey players. To understand the mechanisms underpinning the observed reductions in injury rates, biomechanical (i.e. peak knee moments) and neuromuscular (i.e. technique and muscle activation strategies) measures were appraised over two (intensive and maintenance) phases of training. It has been identified that in order to improve the efficacy of injury prevention training interventions, we must in parallel identify those at “high-risk” of injury prior to commencement of any prevention training program. Currently the only robust method to identify “high-risk” athletes is to measure peak knee moments using costly and labour intensive 3D biomechanical analysis. To address this barrier affecting community level screening implementation, the feasibility and reliability of a 2D video screening tool used to identify “high-risk” athletes during a clinically relevant and injury specific unplanned SS movement task was explored.

The research outlined above was addressed by first describing the ACL injury prevention framework as a whole in the literature review, followed by three interrelated studies to address Stage 3 (countermeasure development and athlete screening) and Stage 4 (training interventions – ideal scenario) of the model. This chapter will summarise the findings of each of these studies with respect to their hypotheses, draw conclusions based on the results and make recommendations for practical implications and future research to contribute toward community level adoption and maintenance of injury prevention protocols (Stage 6).
6.1.1 Chapter Three – Study One

Injury Prevention and Athlete Performance Are Not Mutually Exclusive: A Biomechanically Informed Anterior Cruciate Ligament Injury Prevention Program

The aim of this study was to assess the efficacy of a novel, biomechanically informed injury prevention training program on reducing ACL injury incidence and ACL injury risk among a group of elite female hockey players. A secondary aim was to understand how this training intervention effected their athletic performance. Twenty six elite female hockey players from the national Australian women's field hockey team participated in injury prevention training sessions conducted alongside regular pre- and in-season training for two consecutive seasons. Lower limb and ACL injury incidence, together with athletic performance (i.e. strength, speed and aerobic power), were measured during a control season, and following two intervention seasons. To assess the effectiveness of the program on biomechanical risk factors, peak knee moments were measured during unplanned SS prior to, and following, two training phases within intervention season 1. The first hypothesis, that the training program would reduce biomechanical injury risk factors and in turn ACL injury rates, was supported. While training exposure increased following the control season, both total lower limb injury incidence (control season: 23, intervention season 2: 5.2) and ACL injury incidence (control season: 3, intervention season 2: 0) were reduced (Table 2, Chapter Three). Additionally, following intervention season 1, peak knee valgus and internal rotation moments were reduced. As the principles of the training program were generated from an understanding of WBCoM stability during common change of direction sporting tasks \textsuperscript{11,12}, the effect of the training intervention in combination with the Hockeyroos medical setting on total lower limb injury rates was not unexpected.

While training was specific to ACL injury prevention, selected athletic performance measures were not compromised. In fact, improvements were observed in beep test scores, 40m sprint times and upper body one repetition maximum push and pull lifts. These findings supported the second hypotheses that any changes brought about by injury prevention training would not be
at the detriment of athletic performance. These findings are supported by previous research where plyometric \(^{13,14}\), resistance \(^{15,16}\) and balance \(^{17}\) training were found to improve speed performance. Resistance training has also been directly associated with improvements to strength \(^{18}\), and plyometric training to improvements in aerobic power that has also been found to be related to improvements to running economy \(^{19}\). These findings provide evidence that injury prevention and athletic performance are not mutually exclusive and provide the necessary framework that coaches and sport science staff can embrace to facilitate both.

6.1.2 Chapter Four – Study Two

A 25-Week Biomechanically Informed Two Phase Injury Prevention Training Program: Implications for ACL Injury Risk Among Elite Female Hockey Players

Chapter three demonstrated that biomechanically informed training was successful in reducing total lower limb and ACL injury rates among a group of elite female field hockey players. To understand by what means this intervention influenced the biomechanical mechanisms of injury, Study two aimed to verify the efficacy of training to reduce peak knee moments and improve technique and muscle activation strategies during unplanned SS. While the majority of research only reported these factors immediately prior to, and following, 4-12 week intervention periods, it was considered important to understand the long term retention effects of biomechanically informed training. This was assessed via implementation of a two-phase program whereby nine weeks of intensive training (4 x 20 minute sessions per week) was immediately followed by 16 weeks of maintenance training (3 x 10 minute sessions per week). Peak knee moments, full body kinematics, total muscle activation (TMA) and directed co-contraction ratios (DCCR) were measured during unplanned SS at baseline, following the nine week intensive training phase, and again following 16 weeks of maintenance training.

The first hypothesis that peak knee moments associated with ACL injury risk would be reduced following intensive training was partially supported. There were no reductions in peak knee
extension (PKE), valgus (PKV) and internal rotation (PKIR) moments in the total group of athletes following intensive training. Previous research has shown training to be more effective in “high-risk” populations. Based on these findings a “responder” analysis was performed and five athletes were identified as responders and 11 as non-responders. At baseline, responder athletes displayed 43.8% higher PKV moments than non-responders, suggesting that these athletes may have been “high-risk” prior to program commencement. In support of the first hypothesis, responder athletes significantly reduced peak knee moments in all three planes following the intensive training phase. In contrast, non-responders experienced a 19.8% increase in PKV moments, an 8.8% increase in PKE moments and no change to PKIR moments. These conflicting responses to training are likely a result of ceiling effects of training with Olympic level athletes, where non-responders experienced increases in PKV and PKE moments. However, there were no differences between groups following intensive training, showing that the “high-risk” group were certainly more affected by training. Improvements in gluteal total muscle activation and medially directed co-contraction ratios were observed for all athletes (i.e. both responders and non-responders), however there were no changes to investigated kinematics. A non-uniform change in kinematics was not surprising given the multiple strategies an athlete can use to modify their knee joint loading and injury risk. It is possible that the analysis performed on the investigated kinematic variables was not complex enough to identify combinations of, or synergistic type kinematic solutions explaining the observed knee loading and injury risk findings. The combined neuromuscular and kinetic response to intensive training suggests that injury prevention training was successful in eliciting positive biomechanical changes to reduce an athlete’s injury risk profile.

The second hypothesis that biomechanical improvements to ACL injury risk elicited in the intensive training phase would be preserved following maintenance training was again, partially supported. Improvements in hip neuromuscular control (i.e. elevated gluteal TMA) and medially directed co-contraction ratios were maintained. However, medially directed co-contraction for
the hamstrings muscle group was not retained following *maintenance* training whereby a return to a lateral activation strategy was observed. This finding may be related to insufficient stimuli of specific hamstring exercises that target semitendinosus (i.e. knee flexion/extension exercises over hip flexion/extension exercises) \(^{20}\). The initial stimulus from *intensive* training among athletes, who initially responded to the biomechanically informed training following the first nine weeks, was sufficient to maintain reductions in the high PKV moments from 9-25 weeks. The findings from this study show that biomechanically informed training is effective in reducing peak knee moments, a known biomechanical mechanism for ACL injury in responder or “high-risk” athletes, while also improving desirable muscle activation strategies to support the knee joint. Secondly, these improvements can generally be maintained over a lower volume maintenance phase of training. This study highlights the significance of investigating the effect of training based on an individual’s initial risk classification, and during initial intensive and long-term maintenance training programs.

6.1.3 *Chapter Five – Study Three*

*A RELIABLE VIDEO BASED ANTERIOR CRUCIATE LIGAMENT INJURY SCREENING TOOL FOR THE ASSESSMENT OF FEMALE TEAM SPORT ATHLETES*

Chapter Three and Four describe successful implementation of biomechanically informed and focussed training in an ideal training environment. The findings from Chapter Four highlight the significance of identifying “high-risk” populations before implementing training in order to improve efficacy. This can be achieved in two ways; 1) identify those in need of training to allow the appropriate application of treatment to the population at risk and, 2) train these at-risk athletes for their specific observed deficits \(^{10}\). Measures of an athlete’s technique and peak knee moments during sidestepping have been associated with ACL injury risk and rates. However these measures have previously been restricted to 3D motion analysis in a laboratory setting, which is both cost and computationally expensive. The screening tool developed within this
study utilised 2D measures of an athlete’s upper and lower body kinematics in multiple panes to evaluate their association with peak knee moments during unplanned sidestepping. Our first hypothesis that selected 2D measures of upper and lower body kinematics in frontal and sagittal planes would predict peak knee moments during unplanned SS was supported. Movement patterns including high dynamic knee valgus, low knee flexion angle at foot strike, elevated trunk flexion RoM, trunk lateral flexion away from the intended direction of travel, large peak hip abduction and large knee flexion RoM, effectively predicted peak knee extension, valgus and internal rotation moments during unplanned SS.

In support of the second hypothesis, these 2D kinematic measures were found to have good to excellent intra- and inter-rater reliability and agreement. Previous research has shown 2D kinematic measures to be both repeatable and accurate when compared with 3D measures. Using the prediction equations described in this paper along with previously published data, clinicians, coaches and researchers can make informed judgements about an athlete’s associated risk of ACL injury and tailor interventions to target individual deficiencies.

6.2 CONCLUSIONS
This thesis aimed to contribute to improving the efficacy of injury prevention training programs in reducing ACL injury rates and risk among female team sport athletes. This was approached by utilising the literature contributing through stages 1-4 of the ACL injury prevention framework, with particular focus on implementation strategies as outlined in the IOC current concepts statement for non-contact ACL injuries in female athletes. How these recommendations initially outlined in Table 1.1 in Chapter 1 are described in Table 6.1.
Table 6.1. International Olympic Committee (IOC) identified important factors for a successful prevention program and how these recommendations are addressed in this research.

<table>
<thead>
<tr>
<th>IOC Recommendations</th>
<th>How IOC recommendations are addressed in this thesis</th>
</tr>
</thead>
</table>
| The program should include strength and power exercises, neuromuscular training, plyometric and agility exercises.                           | • Body-weight based balance, plyometric, resistance and technique exercises were prescribed in the training program.  
  • These exercises were progressed in intensity and difficulty every two weeks in the initial training intervention. While intensity and type of exercises were maintained, only duration and frequency were reduced in the maintenance training phase.  
  • A number of injury prevention programs have incorporated combinations of these exercise modalities in anticipation of reducing ACL injury rates with mixed success. Evidence from stages 1 and 2 of the ACL injury prevention framework provide rationale that the biomechanical mechanisms and countermeasures of injury should be the focus of the training program, with exercise modality as the platform. |
| Design as a regular warm-up program increases adherence.                                                                                  | • Intensive training phase sessions were delivered twice a week as warm-up sessions and twice a week, as an extension of weights sessions.  
  • Maintenance training phase sessions were delivered three times a week during warm-ups.  
  • Attendance and compliance were 81.1±25.0% and 88.2±19.7% respectively, with attendance only missed due to injury, as advised by team medical staff. |
| Focus should be on performance of the hip-knee-foot line and “kissing knees” should be avoided (excessive valgus strain).                  | • Not only did this intervention focus on technique recommendations to improve dynamic knee valgus postures, it specifically targeted hip neuromuscular control through a variety of exercises and was successful in elevating gluteal total muscle activation.  
  • In addition to targeting dynamic knee valgus, this intervention utilised research from stage 3 of the ACL injury prevention framework and identified another three important biomechanical factors to focus on within ACL injury prevention programs. These were; increasing knee flexion at foot strike, improving the dynamic control of the trunk and upper body, and increasing the strength of the gastrocnemius muscle group. |
| Maintenance and compliance of prevention programs before, during and after the sports participation season are essential to minimise injuries. | • Maintenance training implemented following the initial intensive intervention was found to: 1) maintain initial biomechanical benefits of intensive training and 2) reduce total lower limb and ACL injuries over a two year period. |
| The drop vertical jump test should be used to identify players at risk.                                                                     | • Previous research has shown discrepancies in knee loading between drop jump landing and sidestepping tasks, where sidestepping has been shown to have five times higher PKV moments.  
  • As such, study three implemented an unplanned sidestepping clinical movement assessment using 2D video to enhance the feasibility of use in community level sporting sessions. |
### IOC Recommendations

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<tr>
<th>IOC Recommendations</th>
<th>How IOC recommendations are addressed in this thesis</th>
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| The program must be well received by coaches and players to be successful.          | - Anecdotally, since the training program’s implementation in 2013, Hockeyroos strength and conditioning and medical staff have continued to use this training approach independently, beyond the commitment of this research.  
- “I started (the ACL injury prevention program) about 12 months after the ACL rupture when I was just beginning to come back into competition. I lacked confidence in my knee’s ability to cope in those high pressure situations. There’s been a massive improvement in my core stability and gluteal strength. My knee is as strong as it’s ever going to be and I’m much more confident running on to the field” – Kellie White (Hockeyroos athlete) |
| Evaluation of success or failure of a prevention program requires large numbers of athletes and injuries. | - This research only investigated this injury prevention training program among one elite team which is a limitation of the present study. However research guided by findings from this thesis is presented among a community level training environment with a control group (see Appendix C.4). |
1.7.1 Future Research

Based on the findings from this research, the following recommendations are made for future research:

- The sample sizes documented in Chapters 3 and 4 of this thesis comprised elite athletes from one team and are relatively small. As such future research should expand on the findings within these chapters using larger populations. It would be expedient to use the methods outlined on a pre-identified “high-risk” population to provide a more definitive profile of the effect of biomechanically focussed ACL injury prevention program.

- The positive findings from Chapters 3 and 4 are a product of strong empirical background to injury prevention training program design and implementation; equally as important is coach and athlete engagement to the program. As this study was implemented in an ideal training scenario, future research should evaluate implementation strategies for real-world community level training environments. More specifically, studies should examine the effect of combined training and coach/athlete education of injury prevention training.

- The training intervention described in Chapters 3 and 4 should be implemented as a randomised control trial with “high” and “low” risk treatment groups identified.

- Randomised control trials should also investigate the effect of varied dose maintenance training phases to determine optimal training volumes for long term effects on injury risk profiles.

- Large prospective databases should aim to identify injury risk stratifications for peak knee moments to facilitate classification of high and low risk athletes.

- The methods from Chapter 5 should first be applied in male athletes of different levels of maturation and skill to determine if the same predictors exist for male athletic populations. Secondly, the prediction algorithms from this study should be validated in
an independent separate sample of heterogeneous female athletes from different sporting codes (i.e., netball, basketball, soccer etc.)

- The efficacy of the screening tool presented in Chapter 5 should be validated in a prospective study utilising a large sample of athletes.

- Finally, the screening tool presented in Chapter 5 should be used in parallel to the implementation of a training program described in Chapters 3 and 4, to differentiate between “high” and “low” risk athletes prior to the commencement of training. It should also determine if training is more successful in those athletes identified as “high-risk” and also if their risk classification changes following training.

1.7.2 Significance of this Research

Anterior cruciate ligament injuries are traumatic and debilitating to the athlete, their team, their long term health related quality of life and the health care system as a whole. One of the prevention strategies for non-contact ACL injuries is targeted training to improve an athlete’s technique to reduce externally applied moments to the knee and improve desirable muscle activation strategies. This thesis addressed the efficacy of injury prevention training via two approaches; 1) biomechanically informed and focussed training during a short term intensive training phase and following long term implementation (25 weeks and two years) and, 2) screening for “high-risk” athletes so training can be applied to athletes at risk, and to target individual deficiencies. This research provides a template for an injury prevention training paradigm that focusses on four biomechanically informed goals; 1) increase knee flexion angle at foot strike, 2) improve the dynamic control the trunk and upper body, 3) strengthen the hip external rotators to prevent athletes from attaining “dynamic knee valgus” postures and, 4) increase strength of the gastrocnemius muscle group. In combination with a 2D video based screening tool, this approach enables researchers and coaches to tailor programs to suit their environment, sport and age group.
6.3 REFERENCES


APPENDICES

APPENDIX A - UNIVERSITY OF WESTERN AUSTRALIA HUMAN ETHICS APPROVAL

APPENDIX A 1 – ETHICS APPROVAL STUDY ONE AND TWO

Our Ref: RA/4/1/5713

Mr Cyril Donnelly
Sport Science, Exercise & Health (School of)
MEDP: M408

Dear Mr Donnelly

HUMAN RESEARCH ETHICS APPROVAL - THE UNIVERSITY OF WESTERN AUSTRALIA

Trunk and hip neuromuscular control during side-stepping and landing: implications for knee loading and ACL injury risk

Student(s): Gilian Wett - PhD - 2026473

Ethics approval for the above project has been granted in accordance with the requirements of the National Statement on Ethical Conduct in Human Research (National Statement) and the policies and procedures of The University of Western Australia. Please note that the period of ethics approval for this project is five (5) years from the date of this notification. However, ethics approval is conditional upon the submission of satisfactory progress reports by the designated renewal date. Therefore until approval has been granted from 31 December 2012 to 31 December 2013.

You are reminded of the following requirements:

1. The application and all supporting documentation form the basis of the ethics approval and you must not depart from the research protocol that has been approved.
2. The Human Research Ethics Office must be approached for approval in advance for any requested amendments to the approved research protocol.
3. The Chief Investigator is required to report immediately to the Human Research Ethics Office any adverse or unexpected event or any other event that may impact on the ethics approval for the project.
4. The Chief Investigator must inform the Human Research Ethics Office as soon as practicable if a research project is discontinued before the expected date of completion, providing reasons.

Any conditions of ethics approval that have been imposed are listed below:

Special Condition:
None specified

The University of Western Australia is bound by the National Statement to monitor the progress of all approved projects until completion to assure continued compliance with ethical standards and requirements. The Human Research Ethics Office will forward a request for a Progress Report approximately 60 days before the due date. A further reminder will be forwarded approximately 30 days before the due date.

If your progress report is not received by the due date for renewal of ethics approval, your ethics approval will expire, requiring that all research activities involving human participants cease immediately.

If you have any queries please contact the HREO at hreo.research@uwa.edu.au

Please ensure that you quote the file reference – RA/4/1/5713 – and the associated project title in all future correspondence.

Yours sincerely

[Signature]

Pete Johnston
Manager, Human Research Ethics
APPENDIX A 2 – ETHICS APPROVAL STUDY THREE

Our Ref: RA.4/1/5333

30 April 2012

Mr Cyril Donnelly
Sport Science, Exercise & Health (School of)
MBDP: M408

Dear Mr Donnelly

HUMAN RESEARCH ETHICS APPROVAL - THE UNIVERSITY OF WESTERN AUSTRALIA

Body weight based neuromuscular training to increase the dynamic functioning of the trunk and hip during sidestepping: implication of ACL injury risk

Student(s): Natalie Smale

Ethics approval for the above project has been granted in accordance with the requirements of the National Statement on Ethical Conduct in Human Research (National Statement) and the policies and procedures of The University of Western Australia. Please note that the period of ethics approval for this project is five (5) years from the date of this notification. However, ethics approval is conditional upon the submission of satisfactory progress reports by the designated renewal date. Therefore until approval has been granted from 30 April 2012 to 01 May 2017.

You are reminded of the following requirements:

1. The application and all supporting documentation form the basis of the ethics approval and you must not depart from the research protocol that has been approved.
2. The Human Research Ethics Office must be approached for approval in advance for any requested amendments to the approved research protocol.
3. The Chief Investigator is required to report immediately to the Human Research Ethics Office any adverse or unexpected events or any other event that may impact on the ethics approval for the project.
4. The Chief Investigator must inform the Human Research Ethics Office as soon as practicable if a research project is discontinued before the expected data of completion, providing reasons.

Any conditions of ethics approval that have been imposed are listed below:

Special Conditions

None specified

The University of Western Australia is bound by the National Statement to monitor the progress of all approved projects until completion to ensure continued compliance with ethical standards and requirements.

The Human Research Ethics Office will forward a request for a Progress Report approximately 60 days before the due date. A further reminder will be forwarded approximately 30 days before the due date.

If your progress report is not received by the due date for renewal of ethics approval, your ethics approval will expire, requiring that all research activities involving human participants cease immediately.

If you have any queries please do not hesitate to contact the Human Research Ethics Office (HREO) at http://research@uwa.edu.au or on (08) 6488 3703.

Please ensure that you quote the file reference – RA.4/1/5333 – and the associated project title in all future correspondence.

Yours sincerely,

[Signature]

[Name]
Manager, Human Research Ethics

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APPENDIX B – PARTICIPANT FORMS

APPENDIX B 1 – STUDY ONE AND TWO PARTICIPANT INFORMATION SHEET

- Body Weight Based Neuromuscular Training to Increase the Dynamic Functioning of the Trunk and Hip During Sidestepping: Implications for ACL Injury Risk -

Participant Information Sheet

BACKGROUND AND PURPOSE

This study is attempting to determine if body weight neuromuscular training can be used to modify an athlete's trunk and hip control when conducting sporting manoeuvres such as side stepping and single leg landing. The primary outcome of this research is to determine if postural changes brought about from such a training intervention can reduce an athlete's knee loading and subsequent risk of anterior cruciate ligament (ACL) injury.

ACL injuries are one of the most severe knee injuries an athlete can sustain. Short term consequences will see 20% of athletes not being able to return to play following a reconstruction, while long term consequences will result in 23-30% of athletes developing knee osteoarthritis within 10 years of sustaining an ACL injury. Previous research has also shown that when compared with males, females are 4-6 times more likely to sustain an ACL injury which some researchers attribute to functional deficits in muscle strength and neuromuscular control during sporting manoeuvres. By establishing the link between targeted trunk and hip neuromuscular control training and its effect on knee loading, we hope to develop training protocols to reduce ACL injury risk amongst team sport athletes.

This investigation consists of a training developed in conjunction with and supervised by, Hockey Australia's medical, coaching and training staff. As a general guide, these sessions will involve plyometric (jumping and ball skills), balance and strength training exercises with a large focus on body control and posture (technique) during change of direction and landing tasks. These exercises will be integrated into your current training sessions.

You will be asked to attend two biomechanical analysis sessions at the UWA Sports Biomechanics laboratory, the first in week one (pre-test) and the second at the end of the training intervention (post-test). At these sessions we will record both 3D Vicon motion capture data and 2D high speed video. During biomechanical testing, you will be asked to complete a well-established sidestepping and single-leg landing lab protocol that has been developed over a 15 year period at UWA (see below for further information). During the mid-point of the intervention period, we will also check on the effectiveness of the training using 2D video analysis. General feedback on your side stepping and single leg landing technique will again be provided following this session.
The measurement of your 3D kinematics (joint angles) and kinetics (joint forces) before and after the training intervention will allow the research team and the strength and conditioning staff to determine if the training has effectively reduced your risk of ACL injury. Findings from this study will also help the wider community in aiding the development of screening tools to identify individuals at a high risk of ACL injury.

PROCEDURES
After you have read the information sheet and signed a consent form you will be asked to participate in a training intervention focused on increasing your hip and trunk neuromuscular control during dynamic sporting tasks (e.g. sidestepping). You will also be asked to participate in two dual capture 2D video and 3D Vicon motion capture biomechanical analysis sessions and one 2D video analysis and technique feedback session scheduled at the approximate mid-point of the training intervention.

Biomechanical Screening
Biomechanical screening will occur in weeks 1 (pre-test) and 8-12 (post-test) of the training intervention using a state of the art Vicon 3D motion capture system and 2D high speed video. This involves attaching 40 retro-reflective markers using double sided non-allergenic tape to your trunk, pelvis and lower limbs. The movement of these markers (their trajectories) will be captured using twelve cameras recording information at 100 frames a second. Video analysis will be performed with two high speed video cameras sampling at 50Hz, placed front and side on to the movement. A force plate, located in the lab runway will also record ground reaction forces (2000 samples a second) during the sidestepping, cross over and landing tasks. Together, the marker and ground reaction force information will allow us to calculate the forces at your knee.

Once fitted with the UWA full body marker set, participants will undertake the UWA sidestep and single leg landing protocol involving a series of planned and unplanned change of direction and landing tasks. For the UWA sidestep procedure, you will be asked to complete a random series of pre-planned and unplanned straight-run, crossover-cut and sidestep running tasks, with you preferred leg landing on a force plate located in the middle of the laboratory volume. This involves you running into the lab at approximately 12-15 km/h for 15 m, and performing each task as directed by arrows projected onto a screen in front of you. For the UWA single-leg landing procedure, you will be asked to run in the laboratory at 12-15 km/h and instructed to jump for maximum height with your preferred jumping leg and then land on the force plate. You will also be asked to perform three single-leg squats on your preferred leg. Biomechanical testing will be used to measure peak 3D knee joint loading, knee flexion angle, upper centre of mass position relative to the stance foot and trunk lateral flexion.

To minimise participant fatigue during the testing period, players will be restricted to a maximum of 50 running trials during testing and will be given at least 30-60 seconds of rest between each trial. Any risk of physical injury during the testing is no higher than what would be encountered in a typical training session.

2D Video Analysis Feedback
2D video cameras and biomechanical software (SiliconCoach) will be used to analyse and provide feedback on your sidestepping and single-leg landing technique during the Biomechanical Screening pre-test, Biomechanical Screening post-test and during a specific session at the approximate mid-point of the training intervention phase.

Body Weight Training Intervention
The body weight neuromuscular training intervention will be included as part of your standard training sessions with Hockey Australia strength and conditioning staff. The focus of this training is to increase your trunk and hip strength and dynamic control during side-
stepping and single leg landing. The genres of training used in each session will include strength, balance and plyometric with a continual focus on technique. All exercises will become progressively more difficult every two weeks, with the last two weeks of training intended to be a maintenance phase.

RISKS
During the training intervention you may experience some muscle soreness 1 to 2 days following testing (delayed onset muscle soreness). However, if you perform stretching and a warm up/cold down before and following testing, the delayed onset muscle soreness will be no more than what you would expect during normal training. It should also be noted that there are no known long-term negative effects from being exposed to this type of testing.

The sidestepping and jumping manoeuvres performed in the training intervention and during the biomechanics testing have been related to knee injuries in sport. However, the speed at which you will be asked to perform these manoeuvres is a medium jog (12-15km/hr), which is considered to place you at very little risk to injury. We have used these testing protocols on over 4000 people in past 15 years without a single incidence of injury.

CONFIDENTIALITY
In lab you will be recorded with standard 2D video along with all of the measurements described above. This will be undertaken for the researcher to identify successful completions of the sporting manoeuvres highlighted above. In an effort to maintain your anonymity, your data will be de-identified using a generic code. Once data collection is completed all trials will either be stored on computer located in a secure room on the University Campus, accessible only by authorised personnel. Computers will also be password protected.

BENEFITS
There is evidence to suggest that body weight based trunk and hip neuromuscular control is associated with risk of ACL injury. If the results from this study show that increasing strength and dynamic control of the hip and trunk is successful in reducing knee loading and ACL injury risk during sporting manoeuvres, physiotherapists, athletic therapists and coaches will be able to identify high risk athletes and implement a low cost, training intervention in the wider community. Even though previous experimental intervention programs of other research groups have not been shown to reduce injury rates, they have been shown to decrease dangerous knee loading post training. If successful, the results from this study will have significant benefit for individual athlete’s (decreased risk of injury) and society (cost of ACL reconstruction and rehabilitation).

PARTICIPANT RIGHTS
1. If you have any questions concerning the research please ask the researcher at any time.
2. Participation in this research is voluntary and you are free to withdraw from the study at any time and for any reason, without penalty or prejudice from Hockey Australia or the University of Western Australia. You do not have to give any justification for your decision and your records will be destroyed unless otherwise agreed by you.

Further information regarding this study may be obtained from the co-ordinating researcher Dr Cyril J Donnelly, MSc, PhD at 6488 3919 or 04 2486 4580.

Approval to conduct this research has been provided by The University of Western Australia, in accordance with its ethics review and approval procedures. Any person considering participation in this research project, or agreeing to participate, may raise any questions or issues with the researchers at any time. In addition, any person not satisfied with the response of researchers may raise ethics issues or concerns, and may make any complaints about this research project by contacting the Human Research Ethics Office at The University of Western Australia on (08) 6488 3703 or by emailing to hreo-research@uwa.edu.au

All research participants are entitled to retain a copy of any Participant Information Form and/or Participant Consent Form relating to this research project.
APPENDIX B 2 – STUDY ONE AND TWO PARTICIPANT CONSENT FORM

- Body Weight Based Neuromuscular Training to Increase the Dynamic Functioning of the Trunk and Hip During Sidestepping: Implications for ACL Injury Risk -

Participant Consent Form

I ___________________________ have read the information provided and any questions I have asked have been answered to my satisfaction. I agree to participate in this activity, realising that I may withdraw at any time without reason and without prejudice.

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

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

Participant Signature ___________________________ Date ___________________________

Approval to conduct this research has been provided by The University of Western Australia, in accordance with its ethics review and approval procedures. Any person considering participation in this research project, or agreeing to participate, may raise any questions or issues with the researchers at any time.

In addition, any person not satisfied with the response of researchers may raise ethics issues or concerns, and may make any complaints about this research project by contacting the Human Research Ethics Office at The University of Western Australia on (08) 6488 3703 or by emailing to hreo-research@uwa.edu.au.

All research participants are entitled to retain a copy of any Participant Information Form and/or Participant Consent Form relating to this research project.
APPENDIX B 3 – STUDY ONE AND TWO PARTICIPANT PHOTOGRAPHIC CONSENT FORM

- Body Weight Based Neuromuscular Training to Increase the Dynamic Functioning of the Trunk and Hip During Sidestepping: Implications for ACL Injury Risk -

Participant Photographic Consent Form

I ______________________ give permission for use of images and video that may be identifiable of myself for teaching and research purposes. I also understand that by granting permission to these images they may be used in the continual development and implementation of similar ACL injury prevention training protocols in the future.

________________________________________  __________________________
Participant Signature                        Date

Approval to conduct this research has been provided by The University of Western Australia, in accordance with its ethics review and approval procedures. Any person considering participation in this research project, or agreeing to participate, may raise any questions or issues with the researchers at any time.

In addition, any person not satisfied with the response of researchers may raise ethics issues or concerns, and may make any complaints about this research project by contacting the Human Research Ethics Office at The University of Western Australia on (98) 3498 3703 or by emailing to hreo-research@uwa.edu.au

All research participants are entitled to retain a copy of any Participant Information Form and/or Participant Consent Form relating to this research project.
A Two Dimensional Video Analysis to Predict Peak Knee Loading During Sidestepping in Female Athletes

--- Subject Information Sheet ---

BACKGROUND AND PURPOSE
This study is being conducted by the University of Western Australia. We are attempting to determine if a 2D clinically relevant screening tool that has recently been developed at the School of Sport Science, Exercise and Health is effective in predicting ACL injury risk and subsequent rates in an athletic cohort. With this information, we will be able to further develop this screening tool in order to translate it into community-level sporting environments to enable coaches, medical staff, and sports trainers to identify “high” risk athletes and intervene with relevant training protocols.

Over half of the ACL injuries in sport occur during non-contact situations, typically during sidestepping and landing tasks, which are often associated with high external knee joint loads. Recent simulation studies have highlighted the importance of the dynamic stability of the trunk and hip in these manoeuvres to reduce an athlete’s risk of injury. Currently, we assume athletes who display high knee internal rotation and valgus moments during these movements to be associated with high risk of ACL injury as cadaveric literature has shown that these loading patterns elevate ACL strain. However, this has not been reported in a prospective athletic cohort. Also, the contribution of the trunk and hip as a causal link to these dangerous loads is not yet understood. This study aims to determine if ACL injured male West Australian Football League (WAF) players and female state netball and hockey players display high knee loading and if this arises from poor or abnormal neuromuscular control of the hip and trunk.

This investigation consists of a 2D video analysis screening protocol. The 2D video analysis screening tool will require athletes to complete the UWA sidestepping protocol consisting of a series of planned and unplanned straight-line and side-stepping tasks. Two 2D high-speed video cameras will set up to capture motion in the frontal and sagittal planes. Following the screening, participants will be issued with a report on their results. Findings from this study will help the greater community as the development of screening tools to identify high ACL injury risk athletes and the ability to prescribe personalized programs to reduce their risk is indeed possible.

PROCEDURES
After you have read the information sheet and signed a consent form, you will be asked to participate in the 2D biomechanical video analysis screening. You will also be asked to enable the School of Sport Science, Exercise and Health to access your medical information should you sustain an injury.

2D Biomechanical Analysis Video Screening
All testing procedures will be performed at the UWA biomechanics laboratory. Following a self-selected warm-up, you will be placed through the UWA side-step protocol where you will conduct a
APPENDIX B 5 – STUDY THREE PARTICIPANT CONSENT FORM

A Two Dimensional Video Analysis to Predict Peak Knee Loading During Sidestepping in Female Athletes

--- Consent Form ---

I have read the information provided and any questions I have asked have been answered to my satisfaction. I agree to participate in this activity, realising that I may withdraw at any time without reason and without prejudice.

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

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

Participant Signature ___________________________ Date ____________

Approval to conduct this research has been provided by The University of Western Australia, in accordance with its ethics review and approval procedures. Any person considering participation in this research project, or agreeing to participate, may raise any questions or issues with the researcher at any time. In addition, any person not satisfied with the response of researchers may raise ethics issues or concerns, and may make any complaints about this research project by contacting the Human Research Ethics Office at The University of Western Australia on (08) 6458 3781 or by emailing hreo-research@uwa.edu.au.

All research participants are entitled to retain a copy of any Participant Information Form and/or Participant Consent Form relating to this research project.
A Two Dimensional Video Analysis to Predict Peak Knee Loading During Sidestepping in Female Athletes

--- Consent Form ---

I __________________________ have read the information provided and any questions I have asked have been answered to my satisfaction. I agree for my child to participate in this activity, realising that they may withdraw at any time without reason and without prejudice.

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

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

______________________________
Legal Guardian Name

______________________________
Relationship to Participant

______________________________
Legal Guardian Signature

______________________________
Date

Approval to conduct this research has been provided by The University of Western Australia, in accordance with its ethics review and approval procedures. Any person considering participation in this research project, or agreeing to participate, may raise any questions or issues with the researchers at any time.

In addition, any person not satisfied with the response of researchers may raise ethics issues or concerns, and may make any complaints about this research project by contacting the Human Research Ethics Office at The University of Western Australia on (08) 6488 3703 or by emailing to hreo-research@uwa.edu.au.

All research participants are entitled to retain a copy of any Participant Information Form and/or Participant Consent Form relating to this research project.
Joint dynamics of rear- and fore-foot unplanned sidestepping

Cyril J. Donnelly a,*, Chamnan Chinnasee b,c,1, Gillian Weir a, Siriporn Sasimontonkul b, Jacqueline Alderson a

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ARTICLE INFO
Article history:
Received 15 September 2015
Received in revised form 25 May 2016
Accepted 16 June 2016
Available online XXX

Keyword(s):
Rehabilitation
Foot strike
Kinetics
Power

ABSTRACT
Objectives: Compare the lower-limb mechanics and anterior cruciate ligament (ACL) injury risk of athletes using a habitual rear-foot (RF) and fore-foot (FF) fall pattern during unplanned sidestepping (UnSS).

Methods: Nineteen elite female field hockey players attended one biomechanical motion capture testing session, which consisted of a random series of pre-planned and unplanned sidestepping sport tasks. Following data collection, participants were classified as possessing a habitual RF or FF fall pattern during UnSS. Hip, knee and ankle joint angles, moments, instantaneous powers and net joint work were calculated during weight acceptance. Between group differences were evaluated using independent sample t-tests (α = 0.05).

Results: Athletes using a habitual RF fall pattern during UnSS absorbed significantly more work and power through their knee joint (p < 0.001), which was coupled with significantly elevated externally applied peak sagittal plane peak ankle moments (p < 0.05) as well as peak flexion and abduction knee moments (p < 0.005). Athletes using a habitual FF fall pattern during UnSS absorbed more work through their ankle joint (p < 0.001).

Conclusions: A RF fall pattern during UnSS places a large mechanical demand on the knee joint, which is associated with elevated ACL injury risk. Conversely, a FF fat pattern placed a large mechanical demand on the ankle joint. Modifying an athlete’s foot fall pattern during UnSS may be viable technique recommendation when returning from knee or ankle injury.

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1. Introduction

Single-leg landing or unplanned sidestepping (UnSS) have been identified as the dynamic movements where the vast majority of non-contact anterior cruciate ligament (ACL) injuries occur in sport. The general mechanical etiology of an ACL injury is when externally applied knee loads are elevated (e.g. peak anterior translation forces and combined knee moments) and muscle support is low. Simulation research has shown for an ACL injury event to occur during sidestepping, both abduction and externally applied flexion knee moments need to be present. Research by Hewett et al. has also shown peak valgus knee moments are predictive of ACL injury incidence in sport with 73% specificity and 78% sensitivity.

To develop effective countermeasures to reduce non-contact ACL injury risk in sport, much biomechanics research has focused on understanding the complex mechanical relationship between athletes’ movement and knee load patterns during single-leg landing and unplanned sidestepping. During planned sidestepping, relationships between an athlete’s foot position relative to midline, knee valgus angle (posture), hip mechanics, arm position and ‘toe landing’ position have been related to peak abduction knee moments and ACL injury risk. From a comparatively small pool of UnSS research, Donnelly et al. showed that an athlete’s upper-body trunk mechanics were critical kinematic variables related to peak abduction knee moments. In the same study, ankle dors/plantarflexion kinematics were also shown to be related to an athlete’s peak abduction knee moments. As a validated foot-contact model was not used during the simulation process, conclusions relating to an athlete’s ankle kinematics and

subsequent ACL injury risk during UnSS were not made, leaving this relationship to be verified with further research.

A growing body of running literature has shown that the distribution of mechanical power and work between an athlete's ankle and knee is a function of their foot fall pattern (i.e. ankle kinematics) during the first half of stance.\textsuperscript{14,15} Research has also shown that runners using a forefoot fall pattern (i.e., ankle plantarflexion) reported significantly lower peak abduction moments relative to runners using a rearfoot fall pattern (i.e., neutral or ankle dorsiflexion).\textsuperscript{16,17} With limited ex-vivo biomechanics research investigating the relationship between foot fall patterns and lower limb mechanics during UnSS, it is unknown an athlete's foot fall pattern during UnSS influences an athlete's lower limb mechanics and injury risk in sport.

The purpose of this study was to compare the lower-limb mechanics (i.e., hip, knee and ankle joint) of athletes who display habitual forefoot or rearfoot fall patterns during UnSS. We hypothesize differences in knee and ankle mechanics (i.e., joint kinetics - joint power and joint work) between athletes using a habitual rearfoot (UnSS-RF) vs. forefoot (UnSS-FF) fall pattern during the weight acceptance (WA) phase of UnSS. We further hypothesize that athletes using a habitual UnSS-RF fall pattern will display elevated peak abduction knee moments and ACL injury risk when compared with athletes possessing habitual UnSS-FF fall patterns.

### 2. Methods

Nineteen elite female field hockey players participated in this study (22.2 ± 2.9 yrs, 1.7 ± 0.1 m, 62.9 ± 7.1 kg). This sample was representative of all athletes listed on the Australian the Female Field Hockey team roster who were deemed fit, healthy and injury free by the team's medical staff (i.e., team physiotherapist or team doctor) prior to testing. The reason an elite female population was chosen for this investigation is because previous literature has shown this cohort is at risk of ACL injury when compared with males\textsuperscript{18} and less experienced players of the same sex.\textsuperscript{18} When comparing the total number of NCAAC soccer related ACL injuries between women and men from 1994 to 1998, women were shown to have injury rates 2.8 times higher than their male counterparts.\textsuperscript{17} When compared to novice athletes, experienced females display significantly elevated peak valgus knee moments (p < 0.01) during sidestep cutting sporting tasks (0.4 ± 0.5 vs. 0.9 ± 0.6Nm/kg + BW) respectively.\textsuperscript{10} All participants provided their informed written consent prior to data collections. Ethics approval was obtained from the Human Research Ethics Office at the University of Western Australia (UWA) (RA/4(1)/15713).

All participants attended a single motion capture testing session. During this testing session athletes were instructed to wear their normal training attire, which consisted of a sports bra, singlet, form fitted shorts and their team shoes. The shoes each athlete wore for testing were all the ASICS women's gel Kayano 21 (Kogan, Australia Pty Ltd.). All participants completed the previously published UWA sidestepping protocol, which consisted of a random series of pre-planned and unplanned straight run, crossover and change of direction (i.e., sidestepping) sporting tasks using their self-selected preferred leg.\textsuperscript{15,20} Participants completed five successful trials of each sporting task before testing was complete. Three-dimensional full-body kinematics were recorded using a 12-camera Vicon MX system (Oxford Metrics, Oxford, UK) recording at 250 Hz, synchronised with a 1.2 m × 1.2 m force plate (AMTI, Watertown, MA) sampling at 2000 Hz. Kinematic and ground reaction force data were both low pass filtered with a zero-lag fourth order Butterworth filter at 14 Hz, which was determined following residual analysis and visual inspection.\textsuperscript{12,22} These data, with functional hip joint centres and knee joint axes\textsuperscript{23} and a custom lower body kinematic model (BodyBuilder (Vicon Peak, Oxford Metrics Ltd., UK), were used to calculate lower limb kinematics and kinetics via inverse dynamics from an established biomechanical model with established repeatability.\textsuperscript{24} A full description of the experimental procedures and kinematic and kinetic modelling approaches have been described previously.\textsuperscript{15,20}

Following data collection, participants were initially classified as possessing a natural habitual rear-foot (RF) or 2) habitual forefoot (FF) fall pattern during UnSS from their motion capture data (Fig. 1). Borrowing from the running literature, a RF fall pattern was defined as when the rear of the foot segment made initial contact with the ground at 0% of stance and a FF fall pattern when the front of the foot made initial contact with the ground at 0% of stance.\textsuperscript{25} The vertical ground reaction force vector was used to define 0% and 100% of stance, which was when the vector was greater than and less than 10N, respectively.

Following the initial classification of each athlete's foot fall pattern, their ankle plantar/dorsiflexion angles were calculated for each individual UnSS trial. Participants were removed if they did not consistently use the same foot fall pattern for all five of the UnSS trials collected in lab. This left nine (47%) participants (1.7 ± 0.1 m, 63.9 ± 6.4 kg) classified as possessing a habitual UnSS-RF fall pattern and seven (37%) participants (1.7 ± 0.1 m, 62.9 ± 7.6 kg) classified as possessing a UnSS-FF fall pattern (see Table 1 and Fig. 2). The approach velocity of the participants within the UnSS-RF (4.3 ± 0.5 ms\textsuperscript{-1}) and UnSS-FF (4.3 ± 0.2 ms\textsuperscript{-1}) were compared using an independent sample t-tests and were not significantly different (p = 0.81) from each other.

Mean hip, knee and ankle joint angles, moments, instantaneous power and net joint work were calculated from five UnSS trials during the weight acceptance phase of stance. Kinematic estimates

<table>
<thead>
<tr>
<th>Joint kinematics for habitual UnSS-RF and UnSS-FF at initial foot contact (0% stance) and range of motion (ROM) through WA.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kinematic variable</td>
</tr>
<tr>
<td>---------------------</td>
</tr>
<tr>
<td>Angle at 0% stance (°)</td>
</tr>
<tr>
<td>Ankle plantarflexion</td>
</tr>
<tr>
<td>Ankle plantarflexion</td>
</tr>
<tr>
<td>Ankle inversion/extension</td>
</tr>
<tr>
<td>Knee flexion/extension</td>
</tr>
<tr>
<td>Hip flexion/extension</td>
</tr>
<tr>
<td>Rom through WA (°)</td>
</tr>
<tr>
<td>Ankle plantarflexion</td>
</tr>
<tr>
<td>Ankle inversion/extension</td>
</tr>
<tr>
<td>Knee</td>
</tr>
<tr>
<td>Hip</td>
</tr>
</tbody>
</table>

Note: Positive values indicate knee flexion, hip flexion, ankle dorsiflexion, ankle adduction and ankle inversion. Bold and italicized significance was set to an α = 0.05.


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included joint angles at initial foot contact (0% stance) and range of motion (RoM) through WA. Joint mechanics included peak externally applied flexion moments and peak knee abduction moments, peak instantaneous joint power and net joint work during WA. Instantaneous joint power was calculated from joint angular velocities multiplied by net joint moments for each trial \( (P_i = M_i + a_i) \). Negative mechanical joint work was calculated by integrating the negative portion of the joint power curves with respect to stance time (equation (1)):

\[
(W_{\text{jgss}} = \int_0^{\text{stance}} P_j \, dt)
\]

where \( J \) represents the joint (ankle, knee or hip), \( P \) the joint power, \( \text{and} t \) and \( \text{d}t \) represent the start and end time of the integration respectively. Negative joint work values represent energy absorption by the muscle-tendon unit. It should be noted that net joint work at the hip, knee and ankle joint were negative throughout WA. Joint moments (Nm), power (W) and net-work (J) were normalised to body mass (kg). Group differences were evaluated using independent sample t-tests accounting for unequal samples in SPSS statistical software (\( \alpha = 0.05 \)) (IBM, Chicago, IL, USA).

3. Results

A number of significant lower-limb kinematic and mechanical differences were observed between athletes using habitual UnSSS-RF and UnSSS-FF fall patterns. Athletes using an UnSSS-RF fall pattern were dorsiflexed at initial foot contact compared with athletes using an UnSSS-FF fall pattern who were plantarflexed \( (p < 0.001) \). Following initial foot contact, ankle joint dorsiflexion RoM was significantly greater \( (p < 0.001) \) among athletes using an UnSSS-FF fall vs. UnSSS-RF fall pattern (Table 1; Fig 2A).

Peak extension (plantar-flexion) ankle moments were significantly greater among athletes using a habitual UnSSS-RF fall pattern compared with athletes using a habitual UnSSS-RF pattern \( (1.7 \pm 0.3 \text{ vs. } 0.7 \pm 0.3 \text{ Nm kg}^{-1} ; p = 0.001; \text{power } (1 - \beta) = 1.00) \). Peak non-sagittal plane (adduction and inversion) moments were significantly lower among athletes using a habitual UnSSS-RF-RF pattern \( (0.02 \pm 0.03 \text{ Nm kg}^{-1} \text{ vs. } 0.04 \pm 0.09 \text{ Nm kg}^{-1} ; p = 0.001; \text{power } (1 - \beta) = 0.83) \) and abduction \((1.1 \pm 0.5 \text{ Nm kg}^{-1} \text{ vs. } 0.5 \pm 0.4 \text{ Nm kg}^{-1} ; p = 0.001; \text{power } (1 - \beta) = 0.95) \) knee moments when compared with athletes using a habitual UnSSS-RF fall pattern (Fig 2B).

Negative peak instantaneous ankle joint power was significantly elevated among athletes using a habitual UnSSS-FF fall pattern compared with athletes using a habitual UnSSS-RF fall pattern \((-15.3 \pm 4.4 \text{ vs. } -5.8 \pm 1.8 \text{ W kg}^{-1} ; p < 0.001; \text{power } (1 - \beta) = 1.00) \). Conversely, negative peak instantaneous knee joint power was significantly elevated among athletes using a habitual UnSSS-RF-RF fall pattern compared with athletes using a habitual UnSSS-FF fall pattern \((-68.8 \pm 18.5 \text{ W kg}^{-1} \text{ vs. } -32.0 \pm 7.5 \text{ W kg}^{-1} ; p < 0.001; \text{power } (1 - \beta) = 1.00) \). Negative net hip joint work during WA was significantly elevated among athletes using a habitual UnSSS-FF fall pattern compared with athletes using a habitual UnSSS-RF fall pattern \( (0.5 \pm 0.2 \text{ vs. } 0.2 \pm 0.1 \text{ kg m}^{-1} ; p = 0.001; \text{power } (1 - \beta) = 0.93) \). Though not significant, athletes using a habitual UnSSS-RF fall pattern possessed elevated negative net ankle joint work when compared with athletes using a habitual UnSSS-RF fall pattern \( (0.3 \pm 0.3 \text{ vs. } 0.2 \pm 0.2 \text{ kg m}^{-1} ; p = 0.001; \text{power } (1 - \beta) = 0.94) \).
Fig. 2. Reaction of lower-limb kinematics at initial foot contact (A), as well as lower-limb peak moments (B), peak instantaneous joint power (C) and net joint work (D) during the weight acceptance (first 10% of stance) phase of forefoot (UnSS-RF) and shank (UnSS-FF) unloaded single-footing. Solid and dotted lines represent statistically significant kinematic, peak joint moment, peak instantaneous joint power or net joint work difference of a given joint and/or joint anatomical degree of freedom (p < 0.05).
4. Discussion

The relationship between an athlete's foot fall pattern, lower-limb mechanics and injury risk has been researched extensively within the running literature.\textsuperscript{14-16} Though recommended by Donnelly et al.\textsuperscript{13} as a focus for future ACL injury prevention research, the relative merits of modifying and athlete's foot fall pattern to mitigate ACL injury risk during running has yet to be investigated. Supporting our research hypotheses, the mechanical demands placed on the knee and ankle, as well as an athlete's ACL injury risk classification, differed substantially between athletes who used habitual UnSSS-RF and UnSSS-RF fall techniques. Athletes using a habitual UnSSS-RF fall pattern absorbed more power at the ankle joint, which was coupled with reduced peak abduction knee moments and non-sagittal plane peak ankle moments. Athletes adopting a habitual UnSSS-RF absorbed more energy and power through their knee joint, which was coupled with elevated non-sagittal plane peak ankle moments as well as elevated peak abduction knee moments, externally applied flexion knee moments and ACL injury risk.

Results presented in this study are supported by the running literature, which has shown that runners with a habitual RF fall pattern place increased mechanical demand on the knee joint, in both the flexion/extension and abduction/adduction degrees of freedom, whereas runners with a habitual FF fall pattern place more demand on the ankle joint in the dorsiflex/plantarflexion degree of freedom.\textsuperscript{14,15,23} Results also align with the change of direction literature, where Kristiansund et al.\textsuperscript{16} showed 'toe landing' postures (i.e., surrogate measure of foot fall postures), among other upper and lower body kinematic variables, were predictive of peak abduction knee moments and ACL injury risk during planned sidestepping ($R^2 = 0.62, p < 0.001$).

The results in this study do not directly align with UnSSS data presented by Cortes et al.,\textsuperscript{24} who reported that athletes with an enforced FF fall patterns displayed greater peak internal adduction knee moments at initial foot contact (OS stance). It is possible these differing results are associated with the type of foot fall patterns being compared (enforced vs. habitual). However, it is more probable that these differing results are because Cortes et al.\textsuperscript{24} conducted their analyses, and formulated conclusions from joint loading data calculated at initial foot contact, rather than when peak joint loading was observed within the weight acceptance phase of stance. Interestingly, when Cortes et al.\textsuperscript{24} analysed their data between 0% and 50% of stance, where non-contact ACL injury likely occurs,\textsuperscript{2,5} no statistical differences in peak knee joint loading were reported. As shown by results presented in this investigation and supported by previous literature,\textsuperscript{14,15,23} the distribution of power and work through the ankle and knee are elevated depending on whether a FF fall and RF fall pattern is employed, which is the probable reason peak abduction knee moments and ACL injury risk was almost three times greater among athletes using a UnSSS-RF fall pattern vs. a UnSSS-RF fall pattern.

Though not the primary purpose of this manuscript, results showed that athletes who adopted a UnSSS-RF pattern possessed lower non-sagittal plane ankle moments when compared to athletes who used a UnSSS-RF pattern. We do appreciate that the magnitude of these moments are relatively small, and the single segment foot model used may not be appropriate to measure non-sagittal plane ankle moments during high velocity sporting tasks. However, these results should add some thought to clinicians or coaches before making recommendation associated the modification of an athlete's foot fall pattern in sport, particularly if they are healthy and uninjured. Future studies, with a more detailed foot model, are recommended in order to better contextualize the influence an athlete's footfall pattern has on the peak non-sagittal plane moments applied to the ankle joint during unplanned sidestepping sporting tasks.

With all research studies, there are some limitations that should be noted. First, the test population was a group of elite team sport athletes. Future research is recommended before these results are extrapolated to homogenous athletic populations. Second, we do not know if the observed footfall patterns are due to the surface the athletes were changing direction on during testing or if they are truly habitual UnSSS foot fall patterns. Again, future research is recommended.

When results are considered in a sport rehabilitation context, technique recommendations associated with an athlete's foot fall pattern during UnSSS may have interesting implications associated with best practice ankle and knee injury-pre injury management. As the mechanical demand placed on the ankle and knee joint is dependent on an athlete's foot fall pattern during running\textsuperscript{14,23} and UnSSS, recommending a FF or RF fall pattern during these tasks may be effective technique recommendations for redistributing loading away from specified muscle-tendon, ligament and/or cartilage tissues during the maturation process. Re-training an athlete's foot fall pattern during running and UnSSS may also be effective technique modifications for reducing an athlete's risk of re-injury when the rehabilitation process is complete. An assessment of an athlete's foot fall pattern during running and UnSSS may also become essential components within clinicians return to play guidelines among team sport athletes. It is acknowledged that changing an athlete's foot fall pattern during a sporting tasks does not guarantee that they will replicate the lower-limb mechanics of a habitual foot fall pattern.\textsuperscript{14} However, with future research, the potential for sport scientists and clinicians to recommend changing foot fall patterns during running and UnSSS, as an effective lower limb (i.e., ankle and knee) injury/re-injury prescription(s) is apparent.

5. Conclusion(s)

Negative net energy and peak power absorption at the knee were greater during habitual UnSSS-RF compared with habitual UnSSS-FF. Conversely, peak power absorption at the ankle was greater during habitual UnSSS-FF vs. UnSSS-RF. Individuals using a habitual UnSSS-RF pattern possessed elevated peak externally applied non-sagittal plane peak ankle moments as well as peak knee flexion, abduction moments and ACL injury risk when compared with individuals using a habitual UnSSS-FF pattern. Conversely, individuals using a habitual UnSSS-FF pattern were characterized as having elevated peak ankle flexion moments when compared with those using a habitual UnSSS-RF. With further research, recommendations surrounding the modification of foot fall patterns during unplanned sidestepping when returning from knee and/or ankle injury may be a viable technique recommendation for mitigating risk of re-injury during the rehabilitation process and after returning to game play.

6. Practical implications

- A habitual rear-foot fall pattern during unplanned sidestepping places increased mechanical demand on the knee joint and may place an athlete at elevated risk of ACL injury/re-injury.
- A habitual rear-foot fall pattern during unplanned sidestepping is coupled with elevated peak externally applied non-sagittal plane peak ankle moments.
- A habitual fore-foot fall pattern during unplanned sidestepping places increased mechanical demand on the ankle joint in the sagittal plane.
- Re-training an athlete's foot fall pattern during running and unplanned sidestepping may be an effective technique
modifications for redistributing loading away from specified musculo-tendon, ligament and/or cartilage joint tissues during the rehabilitation process.

- An athlete's football pattern during unplanned sidestepping has minimal influence on their hip joint mechanics.

Financial statement

There were no sources of external financial support nor grant funding for the presented works. None of the named authors have any known conflicts of interest.

Acknowledgements

There were no external sources of financial assistance nor grant funding associated with the design, implementation and analysis of this project. We thank Kate Starre, Jen Cooke, Carmel Goodman for their continued support and the Australian women's field hockey team for their participation in this study.

References

Injury prevention and athletic performance are not mutually exclusive: An anterior cruciate ligament injury prevention training program

Background: Significant research has been dedicated to injury prevention training programs with limited success in reducing ACL injury rates. A contributing factor to unsuccessful injury prevention programs are low athlete attendance, compliance and/or engagement. Though lower limb injury rates are high among elite level athletes, injury prevention programs are generally considered to be low priority as coaches have a misguided perception that there is an inverse relationship between prophylactic training and athletic performance. Recent literature has identified the dynamic strength and control of the hip and trunk during dynamic sporting tasks is of paramount importance for reducing an athlete’s peak knee loading and injury risk in sport. The purpose of this study was to show that a biomechanically-informed ACL injury prevention training protocol is effective in reducing ACL injury rates, while simultaneously having no negative effect on athletic performance.

Methods: The Australian national women’s hockey team participated in 25-weeks of biomechanically-informed injury prevention training (Weeks 1-9 Intensive Training: 4x20 minute sessions, Weeks 9-25 Maintenance Training: 3x10 minute sessions) implemented adjunct to their 2012-2013 regular season training schedule. Irrespective of the training genre (plyometric, balance and resistance), the overriding goal (www.youtube.com/bodyfitworkouts) was to improve the control of the trunk and hip during dynamic sporting tasks. Lower limb injury data during from the 2011-2012 (pre-intervention) and 2012-2013 (training intervention period) were collected. Prior to and following the intensive training phase (weeks 1-9), each participant’s athletic performance (i.e., speed/agility, aerobic power, strength) were recorded as well as coach rated attendance, compliance and athlete engagement.

Results: Pre-intervention there were 0.53 knee injuries per player, and 0.07 non-contact ACL injuries per player. During the training intervention season, there were 0.77 knee injuries per player, and 0.00 non-contact ACL injuries per player. There were no changes in one-repetition maximum (1RM) bench press, bench pull and back squat scores following the training intervention. There was significant improvements in 10m sprint times (↓1.7%, p=0.023) and aerobic power beep test scores (↑2.2%, p=0.022). Attendance and compliance were 81.1±25.0% and 88.2±19.7% respectively, with attendance only missed due to injury. Athlete engagement was high with 89.2±11.5% commitment, 89.9±11.2% motivation and 91.9±9.9% perseverance.

Discussion: Biomechanically-informed injury prevention training is successful in reducing non-contact ACL injury rates, while also improving and/or maintaining athletic performance. These results provide valuable information to coaches and medical staff interested in implementing effective injury prevention training protocols in time-poor competitive season schedules without sacrificing athletic performance.
APPENDIX C 3 - STUDY ONE ACCEPTED CONFERENCE ABSTRACT


Injury
SS-0078

SIMULATION AND PROPHYLACTIC RESEARCH: INTERESTING BEDFELLOWS
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Introduction and Objectives: Modern biomechanics can be dated back to the late 1800’s, with the invention of stop-action photography by Eadweard Muybridge [1], which was developed to describe animal motion that could not be observed with the human eye. Later, with the development of the force platform [2], and the application of the Newton-Euler equations of motion, the ability to calculate the forces that cause human motion became possible. With the invention of the programmable computer in the 1960’s and the evolution of the silicon processor, our ability to create dynamic simulations has become an apparent reality. Now, over 100 years later, following significant scientific and technological advancements, simulation based research has firmly established its place within the field of biomechanics. The purpose of this manuscript will be to present an applied example of how simulation based research has been used to inform the development of an effective knee injury prevention training protocol.

With the use of the open-source musculoskeletal modelling framework OpenSim, our group has been using simulation based experiments to better understand how specific movements and/or muscle forces during a movement are related to an athlete’s lower limb injury risk in sport. Using the residual reduction algorithm, we were able to optimize an athlete’s technique to reduce their risk of knee injury during unplanned sidestepping tasks. Through simulation, we showed a causal relationship exists between an athlete’s upper body mechanics, knee loading and injury risk during dynamic sporting tasks [3]. We then used computed muscle control to measure and characterize the muscle forces an athlete uses during single-leg landing tasks. Findings from this research showed that the gastrocnemius muscles are used significantly more than the hamstring muscles to stiffen and support the knee during the impact phase of single-leg landing [4]. From these simulation findings and relevant prophylactic research, we have developed and implemented a novel prophylactic training intervention designed to reduce and athlete’s risk of knee injury in sport.

Methods: The Australian national field hockey team participated in a novel nine-week body-weight based training intervention. The intended focus of the intervention was to A) improve gluteal muscle strength, increasing an athlete’s capacity from attaining ‘dynamic-valgus’ knee postures, which have been shown to predict anterior cruciate ligament (ACL) injuries in sport [5]. From our group’s simulation findings, added foci were to B) improve the dynamic control of the upper body and C) improve the strength of the gastrocnemius muscles. During training, athletes’ performed a range of strength, plyometric and balance exercise that continually targeted on or all of the intervention’s intended foci. Prior to and following the training intervention, full-body kinematics, lower body kinetics and lower limb muscle activation were collected for 16 athletes during the UWA sidestepping protocol. All experimental methods have been described previously [6, 7].
Results: Following training, athlete’s identified as ‘high-risk’ from their knee moments during unplanned sidestepping (n = 5) significantly reduced their peak valgus knee moments by 28% (p = 0.024), becoming consistent with valgus knee moments observed pre- post training from the ‘low-risk’ group (n = 11). All athletes (n = 16) were better able to utilize their hip versus their knee to generate their support moment during sidestepping, redistributing the relative contribution of their support moment from their knee to hip (Cohen’s d = 0.56). For all athletes (n = 13), total gluteal muscle activation significantly increased by 27% (p = 0.006), while co-contraction of the hamstring muscle group were re-directed from the biceps femoris to the semitendinosus (Δ226%, p < 0.001). It is likely an athlete’s capacity to prevent hip internal rotation, which is associated with the ‘dynamic-valgus’ posture would be improved. Increases in medial hamstring muscle activation would help athlete’s support their knee against valgus knee moments, which is a surrogate for ACL injury risk [3, 5, 6]. We are currently analysing further motion capture data from this population to determine if these positive training effects have been preserved following 16-weeks of maintenance training.

![Figure 1](image1.png)

**Figure 1:** Depiction of UWA sidestepping protocol.

Conclusion: Simulation research can be used to help inform the development of effective lower limb injury prevention training protocols. The efficacy of a novel hip, trunk and gastrocnemius focused training intervention has been verified among elite level female field hockey players.


Disclosure of Interest: None Declared
Targeting associated mechanisms of anterior cruciate ligament injury in female community-level athletes

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ABSTRACT
This study aims to determine if biomechanically informed injury prevention training can reduce associated factors of anterior cruciate ligament injury risk among a general female athletic population. Female community-level team sport athletes, split into intervention ($n = 8$) and comparison groups ($n = 10$), completed a sidestepping movement assessment prior to and following a 9-week training period, in which kinetic, kinematic and neuromuscular data were collected. The intervention group completed a biomechanically informed training protocol, consisting of plyometric, resistance and balance exercises, adjacent to normal training, for 15–20 min twice a week. Following the 9-week intervention, total activation of the muscles crossing the knee ($n = 7$) decreased for both the training ($\Delta - 15.02\%, d = 0.45$) and comparison ($\Delta - 9.68\%, d = 0.47$) groups. This decrease was accompanied by elevated peak knee valgus ($\Delta + 27.78\%, d = -0.36$) and internal rotation moments ($\Delta + 37.50\%, d = -0.56$) in the comparison group, suggesting that female community athletes are at an increased risk of injury after a season of play. Peak knee valgus and internal rotation knee moments among athletes who participated in training intervention did not change over the intervention period. Results suggest participation in a biomechanically informed training intervention may mitigate the apparent deleterious effects of community-level sport participation.

Introduction
An anterior cruciate ligament (ACL) injury is among the most severe injury an athlete can sustain in sport, with incidence and associated health costs continuing to rise each and every year (Janssen, Orchard, Driscoll, & van Mechelen, 2012). Female athletes have a higher incidence of non-contact ACL injury when compared to males participating in similar sports (Renstrom et al., 2008). The detrimental effect to the athlete is considerable, with approximately 70% of surgically treated athletes retiring from competition within three years (Øiestad, Engebretsen, Storheim, & Risberg, 2009). Due to the short- and long-term
health consequences of an ACL injury, considerable research efforts have been devoted to preventative measures (Gagnier, Morgenstern, & Chess, 2012). Two general biomechanical approaches to reducing ACL injury risk are commonly identified; (1) modifying an athlete's movement patterns/technique to reduce the magnitude of external forces applied to the knee joint, a mechanical risk factor of ACL injury (Dempsey, Lloyd, Elliott, Steele, & Munro, 2009; Pappas et al., 2014) and, (2) improving the coordinated activation of the supporting musculature around the knee when peak joint loading is elevated (Besier, Lloyd, Cochrane, & Ackland, 2001; Postma & West, 2013).

It is often the goal of ACL intervention research to explore the effectiveness of neuromuscular training in reducing ACL injury rates, with many studies assessing the relative merits of different exercise modalities (e.g. balance, resistance and plyometric) (Sugimoto, Myer, McKeon, & Hewett, 2012). Despite the attention devoted to neuromuscular training, published interventions are only effective in preventing 51% of ACL injuries in athletic populations (Gagnier et al., 2012). The mechanisms by which these type of interventions work is still unclear (Donnelly, Elliott, Ackland, et al., 2012), and it is possible that unsuccessful interventions do not sufficiently address the mechanical aetiology of ACL injury. That is, the exercises undertaken within these training interventions are not effectively targeting biomechanical mechanisms associated with increased risk of sustaining an ACL injury.

An ACL will rupture when the load applied to the ligament is greater than it can withstand (Lloyd, 2001). Consequently, researchers may need to critically re-evaluate the goals of the intervention, to ensure that mechanisms hypothesised to load the ACL are taken into account. The primary function of the ACL is to limit anterior translation of the tibia relative to the femur, as well as limit internal rotation and valgus moments at the knee (Markolf et al., 1995). In vitro and in vivo evidence suggests that ACL strain is greatest during the first 20–30% of stance (weight acceptance), when the knee is flexed between 0° and 30°, and valgus and internal rotation moments are applied (Cerulli, Benoit, Lamontagne, Caraffa, & Liti, 2003). Recent research has highlighted a number of biomechanical movement patterns associated with injurious knee loading, which will be discussed below.

Robinson, Donnelly, Vanreunterghem and Pataky (2015) reported evidence that knee flexion angle at impact of an unplanned sidestep (UnSS) predicts the combined magnitude of peak knee valgus and internal rotation moments during weight acceptance (WA). This finding is in agreement with previous research which has observed reduced ground reaction forces when landing with greater knee flexion (Podraza & White, 2010), highlighting the importance of knee flexion posture when assessing ACL injury risk during movement tasks. Donnelly, Lloyd, Elliott and Reinbolt (2012) identified that small changes in weight bearing whole-body centre of mass (CoM) can reduce peak knee valgus moments by over 40%. The trunk is the heaviest body segment and the largest contributor to an individual's whole body CoM calculation. Control of this segment over all others during dynamic sporting tasks is paramount in the context of lower limb and ACL injury prevention. Trunk orientation has previously been associated with risk of sustaining an ACL injury (Dempsey et al., 2007; Hewett, Torg, & Boden, 2009). Implications from these studies suggest that dynamic control of the trunk during sporting movements is an important biomechanical factor for mitigating an athlete's ACL injury risk.

Recent research has shown elevated gastrocnemius force during the impact phase of landing, increases joint compressive forces, which is hypothesised to protect the ACL from injury (Morgan, Donnelly, & Reinbolt, 2014). This evidence conflicts with previous
research suggesting that when activated the gastrocnemius increases ACL strain or acts as an antagonist to the function of the ACL (Fleming et al., 2001). However, ACL strain values attributable to gastrocnemius activation were only present at low knee flexion angles (5° and 15°) in a non-weight bearing task (Fleming et al., 2001). The findings from Morgan et al. (2014) were observed during the WA phase of single-leg landing tasks, which is similar to movement situations where non-contact ACL injuries are observed (Olsen, Myklebust, Engebretsen, & Bahr, 2004). Research by Morgan et al. (2014) suggests the gastrocnemius is an important muscle group needed for joint compression and should not be overlooked in the development of ACL injury prevention training protocols.

‘Dynamic valgus’ knee posture, defined as the position of the distal femur towards and the distal tibia away from the midline of the body, is predictive of future ACL injury in female athletes (Hewett et al., 2005). Internal rotation of the hip when the knee is flexed moves the knee closer towards an individual’s midline and towards a ‘dynamic valgus’ posture, highlighting the importance of hip external rotator muscles. More recently Khayambashi, Ghodossi, Straub and Powers (2015) reported that isometric hip external rotation strength predicted non-contact ACL injuries in a sample of mixed gender athletes. These findings are evidence of a link between hip external rotator muscles and ACL injury risk.

Applied loads and movement patterns with scientific evidence of their association with ACL injury risk (i.e. knee flexion dynamics, dynamic trunk control, gastrocnemius muscle forces and hip external rotator strength) should be considered when implementing an ACL training intervention. Weir, Cantwell, Alderson, Elliot and Donnelly (2014a, 2014b) implemented a novel nine-week ACL training intervention in an elite athlete cohort comprising the Australian women’s hockey team. Participants trained for 20 min four times a week over the nine-week period. The training intervention was designed with a biomechanical focus, specifically aimed to reduce associated risk factors of ACL injury. A combination of plyometric, resistance and balance exercises were included, with exercises progressing in intensity (Weir et al., 2014a). The included exercises were required to target at least one of the following injury mechanisms: knee flexion kinematics (e.g. broad jumps), trunk control (e.g. skater hops), gastrocnemius muscle strength (e.g. calf raises) and hip external rotator strength (e.g. clam shells) (Weir et al., 2014a). The intervention was successful in reducing peak knee valgus moments (Δ −29%, p = 0.003) in previously identified ‘high risk’ (n = 4) athletes during UnSS (Weir et al., 2014b).

Research by Weir et al. (2014a, 2014b) established the efficacy of a biomechanically informed injury prevention programme among elite athletes in an ideal (Donnelly, Elliott, Ackland, et al., 2012) training environment (low athlete to trainer ratio and 100% athlete compliance). However, with the goal of reducing ACL injury rates in female athletes, there is a need to verify its efficacy among a more general female sporting population. A confounding factor worth consideration when working with a general athlete population, is the observed increase in risk of sustaining a non-contact ACL injury during a regular season of sport in male athletes (Donnelly et al., 2014; Donnelly et al., 2012). It is unknown whether a similar phenomenon occurs within female community-level athletes over a season of sport, and this will be investigated in the current study.

The primary purpose of the current study is to determine if biomechanically informed ACL injury prevention training (Weir et al., 2014a, 2014b) was effective in reducing biomechanical factors associated with ACL injury, among a general athlete population. A secondary aim of this research is to explore potential changes in ACL injury risk indicators
among female community-level athletes during a regular season of sport. Based on changes seen among male Australian Football athletes (Donnelly et al., 2014; Donnelly, Elliott, Doyle, et al., 2012), we hypothesise that athletes not participating in the training intervention will exhibit biomechanical changes over a sporting season which are unfavourable to ACL injury risk. Secondly, we hypothesise that the training intervention will counter the changes in injury risk over a sporting season. Specifically, we expect that athletes participating in the training intervention will maintain or decrease their ACL injury risk over the nine-week intervention period.

Methods

Participants

Twenty-five female community level athletes were recruited from Western Australian community sporting clubs, to participate in a nine-week controlled clinical trial training intervention during a season of team-based sport participation. A priori power analysis indicated a total sample size of 20 was required (power of 0.8, $\alpha < 0.05$, effect size of 0.78, from G*Power v3.1, Düsseldorf, Germany) (Dempsey et al., 2009). With an estimated attrition rate of 10% (Stevenson, Hamer, Finch, Elliot, & Kresnow, 2000) a total sample size of 22 was deemed sufficient for this study. Subsequently, 25 participants were recruited from community sports (field hockey, netball, basketball and soccer) that involved dynamic movement tasks such as sidestepping and single-leg landing. Participants were excluded from the study if they presented with a lower limb injury, or less than two years had passed from full recovery of a major lower limb injury. The human ethics research committee from the University of Western Australia approved this study, and written informed consent was obtained from all participants.

A large attrition rate of 42.9% was observed in the training group pre-test ($n = 14$) to post-test ($n = 8$) compared with the comparison group pre-test ($n = 11$) to post-test ($n = 10$) attrition rate of 9%. The training group’s high attrition rate was attributed to acute injuries unrelated to the implemented training programme, previously undiagnosed overuse injuries and one athlete who was unable to attend the post-testing session.

Eight athletes (21.1 ± 5.7 years, 1.70 ± 0.06 m, 67.5 ± 3.6 kg) completed the biomechanically informed training intervention (Weir et al., 2014a) adjunct to their normal in-season training (training group), and participated in both biomechanical testing sessions. The comparison group comprised ten athletes (19.9 ± 3.2 years, 1.69 ± 0.07 m, 63.4 ± 10.2 kg) completing their normal in-season training between testing sessions.

Data collection

Prior to and following the intervention, all 18 athletes completed a sidestepping functional movement assessment, consisting of single-leg squats, single-leg drop jumps, counter movement jumps and a series of planned and unplanned straight line running and change of direction tasks (Besier et al., 2001; Donnelly, Elliott, Doyle, et al., 2012). Pre-testing was conducted during the first few weeks of the training season; one to four weeks before the first competitive game. Post-testing was conducted in the three weeks immediately following the last training intervention session; six to eight weeks after the first competitive game.
During testing, a three-dimensional motion analysis system recorded each athlete. Upper and lower body kinetics and kinematics were collected using a 12 camera Vicon* MX and 10 camera Vicon* T40 (Oxford Metrics, Oxford, UK) system operating at 250 Hz, which was synchronised with an AMTI force plate, recording at 2,000 Hz (Advanced Mechanical Technology Inc., Watertown, USA).

The activation of nine muscles was recorded with a telemetry surface electromyography (EMG) system at 1,500 Hz (TeleMyo 2400 G2, Noraxon, Scottsdale, USA). Pairs of surface electrodes were placed over the muscle bellies of the gluteus maximus, gluteus medius, rectus femoris, vastus lateralis, vastus medialis, bicep femoris, semimembranosus, lateral gastrocnemius and medial gastrocnemius (Perotto, 2011a, 2011b, 2011c). Due to telemetry issues, surface EMG data were obtained from six participants in the intervention group and nine from the comparison group.

**Data analysis**

Reliable full body models were used to calculate knee joint, trunk and hip kinematics and knee joint kinetics via inverse dynamics procedures during UnSS in BodyBuilder* software using the Nexus* software pipeline (Vicon*, Oxford Metrics, Oxford, UK) (Besier, Sturnies, Alderson, & Lloyd, 2003; Donnelly, Elliott, Doyle, et al., 2012). A custom model utilising triad cluster markers and a calibrated anatomical systems technique (Cappozzo, Catani, Della Croce, & Leonardini, 1995) with functional hip and knee joint centres was employed (Besier et al., 2003). Following the SENIAM surface EMG processing recommendations (Stegeman & Hermens, 1999), DC offsets were removed, then band-pass filtered between 30 and 500 Hz with a zero-lag, fourth order Butterworth digital filter. The signal was then full-wave rectified and linearly enveloped using a low pass with a zero-lag, fourth order Butterworth at 6 Hz. Muscle activation was normalised to the maximal activation observed for each muscle during either the functional or sidestepping trials and expressed as 0–100% maximal voluntary contraction (Donnelly et al., 2014). Muscle activation was normalised to maximal activation recorded during all of the functional and sidestepping trials, to better represent each participant’s true maximum activation.

Kinetic, kinematic and muscle activation data were analysed during the WA phase of UnSS as defined by Dempsey et al. (2007). Kinetic variables included external peak knee valgus, internal rotation and flexion moments normalised to height and bodyweight (Ht * BW), and expressed in scientific notation ×10⁻¹. As per Donnelly et al. (2014) mean total muscle activation (TMA) of the gluteal, quadriceps, hamstrings and gastrocnemius groups were calculated, as well as for all muscles crossing the knee. Directed co-contraction ratios (DCCR) were calculated between muscle groups crossing the knee with flexion/extension (F/E) and medial/lateral (M/L) moment arms (Donnelly et al., 2014). Semimembranosus/bicep femoris muscles (SM/BF) DCCR was also calculated. The DCCRs were calculated as follows (Heiden, Lloyd, & Ackland, 2009):

If flexion/medial mean EMG > extension/lateral mean EMG:

\[ \text{DCCR} = 1 - \frac{\text{extension/lateral mean EMG}}{\text{flexion/medial mean EMG}} \]

Else

\[ \text{DCCR} = \frac{\text{extension/lateral mean EMG}}{\text{flexion/medial mean EMG}} - 1 \]
Training Intervention

The training intervention was biomechanically informed (Weir et al., 2014a,b), and targeted proposed mechanisms of ACL injury (i.e. knee flexion dynamics, dynamic trunk control, gastrocnemius muscle strength and hip external rotator muscle strength). Exercises relied on body weight and consisted of resistance, plyometric and balance exercises. Exercises targeted muscles of the trunk and lower limb and progressed in complexity and intensity over the nine-week period. Examples of exercises and progressions included: (1) static squats, single-leg squats, jumping squats, broad jumps, (2) single-leg hops, diagonal single-leg hops, single-leg 90° turns, (3) standing single-leg balances progressing to dynamic movements with the arms and legs lifted. The intervention was incorporated into the athlete’s regular training as a warm up, for 15–20 min twice a week and was facilitated by the research team. A recommended high coach to athlete ratio of 1:8 was implemented (Chappell & Limpisvasti, 2008). Training sessions were time-based for the first four weeks, to account for differences in fitness levels and encourage maximum participation. In the remaining weeks, a repetition-based approach was used to control training intensity level. Athlete attendance and compliance (Jackson, Dimmock, Taylor, & Hagger, 2012) were recorded at every training session by the researchers implementing the training intervention. Compliance was rated on a five-point scale and expressed as a percentage.

Statistical analysis

A two-way mixed-model ANOVA was used to identify any significant ($\alpha = 0.05$) main or interaction effects (group $\times$ time) of each dependent variable between training intervention and comparison groups, pre to post-testing. When interaction effects (group $\times$ time) were observed protected Sidak $t$-tests were performed as post hoc analyses ($\alpha < 0.05$). Despite an initial recruitment sample of $n = 25$, a higher than expected attrition rate (Stevenson et al., 2000) resulted in 18 participants completing the study. The final sample size risked the analysis being slightly underpowered, and as such additional analysis using Cohen's $d$ tests were performed to determine effect sizes ($d \geq 0.60$: moderate/large effect size), in an attempt to indicate the practical significance of a finding, independent of the sample size (Ellis & Steyn, 2003).

Results

No significant main effects were observed for any of the analysed variables. Significant interaction effects (group $\times$ time) were observed during UnSS for trunk flexion RoM ($F = 7.044$, $p = 0.05$) and knee flexion at foot strike ($F = 6.34$, $p = 0.05$). Protected post hoc Sidak $t$-tests found no significant pre to post-test within group differences in trunk flexion RoM or knee flexion at foot strike ($p \geq 0.05$), for either the intervention or comparison group. Due to the higher than expected attrition rate (Stevenson et al., 2000), effect sizes were reported to indicate the practical significance of kinetic, kinematic or neuromuscular changes pre to post-testing. Percentage change and effect sizes were reported for within-group comparisons.

Significant interaction effects were not found in peak knee moment variables. However, moderate to large effect sizes for changes in peak knee moments were observed. Peak knee flexion moments increased ($\Delta + 13\%$, $d = -0.77$) in the training group, with minimal increases in peak knee valgus and internal rotation moments (Table 1). Moderate increases
Table 1. Mean (standard deviation) normalised kinetics (Ht * BW) and electromyography (DCCD and TMA) during the WA phase of UnSS.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Comparison group (n = 10)</th>
<th>Training group (n = 8)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pre-test</td>
<td>Post-test</td>
</tr>
<tr>
<td><strong>Kinetics (Ht * BW)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peak knee extension moment</td>
<td>2.13 ± 0.37</td>
<td>2.10 ± 0.33</td>
</tr>
<tr>
<td>Peak knee valgus moment</td>
<td>0.36 ± 0.25</td>
<td>0.46 ± 0.46*</td>
</tr>
<tr>
<td>Peak knee internal rotation moment</td>
<td>0.08 ± 0.05</td>
<td>0.11 ± 0.04*</td>
</tr>
<tr>
<td><strong>Kinematics</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trunk flexion ROM (°)</td>
<td>9.19 ± 7.9</td>
<td>10.57 ± 6.13</td>
</tr>
<tr>
<td>Peak lateral trunk flexion (°)</td>
<td>14.74 ± 3.09</td>
<td>12.82 ± 3.69*</td>
</tr>
<tr>
<td>Peak hip abduction (°)</td>
<td>11.94 ± 7.60</td>
<td>10.61 ± 7.17</td>
</tr>
<tr>
<td>Mean knee flexion (°)</td>
<td>37.94 ± 4.48</td>
<td>35.26 ± 5.14*</td>
</tr>
<tr>
<td>Knee flexion ROM (°)</td>
<td>36.27 ± 9.40</td>
<td>37.45 ± 8.75</td>
</tr>
<tr>
<td>Knee flexion at foot strike (°)</td>
<td>2162 ± 5.4</td>
<td>19.00 ± 5.90*</td>
</tr>
<tr>
<td>Peak knee abduction (°)</td>
<td>3.45 ± 3.90</td>
<td>3.22 ± 4.41</td>
</tr>
<tr>
<td>Foot to CoM (cm)</td>
<td>28.16 ± 2.76</td>
<td>25.15 ± 4.24*</td>
</tr>
<tr>
<td><strong>DCCD</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F/E</td>
<td>−0.13 ± 0.33</td>
<td>−0.22 ± 0.29</td>
</tr>
<tr>
<td>M/L</td>
<td>0.05 ± 0.14</td>
<td>−0.15 ± 0.09*</td>
</tr>
<tr>
<td>SM/BF</td>
<td>−0.07 ± 0.36</td>
<td>−0.05 ± 0.32</td>
</tr>
<tr>
<td><strong>TMA</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gluteal</td>
<td>0.68 ± 0.17</td>
<td>0.64 ± 0.17</td>
</tr>
<tr>
<td>Quadriceps</td>
<td>0.89 ± 0.26</td>
<td>0.85 ± 0.31</td>
</tr>
<tr>
<td>Hamstrings</td>
<td>0.47 ± 0.24</td>
<td>0.27 ± 0.17*</td>
</tr>
<tr>
<td>Gastrocnemius</td>
<td>0.50 ± 0.16</td>
<td>0.46 ± 0.16</td>
</tr>
<tr>
<td>Knee</td>
<td>1.86 ± 0.31</td>
<td>1.68 ± 0.46*</td>
</tr>
</tbody>
</table>

All kinetic data are presented in scientific notation x 10⁻¹.  
*Indicates a greater than moderate effect size pre-test to post-test (d ≥ 0.60).  
Indicates a moderate effect size pre-test to post-test (0.30 ≤ d < 0.60).
in both peak knee valgus ($\Delta +28\%, d = -0.36$) and internal rotation moments ($\Delta +38\%, d = -0.56$) were observed in the comparison group.

Both the training ($\Delta -15\%, d = 0.45$) and comparison groups ($\Delta -10\%, d = 0.47$) reported decreases in mean TMA of muscles crossing the knee following the nine-week intervention period. Mean gastrocnemius TMA moderately decreased in both the training ($\Delta -35\%, d = 0.74$) and comparison ($-8\%, d = 0.29$) groups. Mean hamstring TMA also moderately decreased in both the training ($\Delta -17\%, d = 0.44$) and the comparison group ($\Delta -21\%, d = 0.55$). Following the intervention, the SM/BF DCCR of the training group was laterally redirected (BF) ($d = 0.67$), a result not observed in the comparison group. Both the training ($d = 0.74$) and comparison group’s ($d = 0.96$) M/L DCCR were redirected laterally.

Following the intervention, the training group exhibited a 4.5° decrease in hip abduction ($\Delta -31\%, d = 0.70$), a 5.2° increase in knee flexion at foot strike ($\Delta +33\%, d = -0.59$) and a 2.6° decrease in trunk flexion range of motion (RoM) ($\Delta -29\%, d = 0.97$). These postural changes were not observed in the comparison group (Table 1). Both the training and comparison groups reported small to moderate effect sizes in peak lateral trunk flexion, adopting a more upright trunk position post-test ($\Delta -16\%, d = 0.4$ and $\Delta -13\%, d = 0.57$, respectively). The comparison group reduced lateral foot placement by 3 cm ($\Delta -11\%, d = 0.84$).

The training group attendance to, and compliance with, the intervention programme was 71 ± 14 and 77 ± 7%, respectively.

**Discussion and implications**

Aligning with previous literature, both groups reported increases in select peak knee moments (Table 1) during UnSS following a sporting season (Donnelly et al., 2014; Donnelly, Elliott, Doyle, et al., 2012). The training group showed a large effect size for increases in peak externally applied knee flexion moments, alongside minimal changes in peak knee valgus and internal rotation moments. However, sagittal plane knee moments alone are unlikely to rupture the ACL (McLean, Huang, Su, & van den Bogert, 2004) and this change was accompanied by an increase in knee flexion at foot strike. Therefore, this change is unlikely to increase an athlete’s risk of ACL injury. Moderate increases were observed in both peak knee valgus and internal rotation moments in the comparison group, with minimal increases in peak knee flexion moments. Both peak knee valgus and internal rotation moments are believed to be related to ACL injury risk (Besier et al., 2001). These results suggest that the biomechanically informed training employed in this study may have maintained an athlete’s relative risk of ACL injury pre to post-testing. Whereas, the comparison group’s risk of ACL injury appears to have increased following participation in a season of community-level sport. When adjusted for variable normalisation approaches, all peak knee moment measurements (Table 1) fall within the range of previously reported values (Brown, Brughelli, & Hume, 2014).

Pre to post-testing, both groups reported decreases in the mean TMA of muscles crossing the knee. When accounting for kinetic changes, reduced muscle activation suggests that the level of support against injurious knee moments was also reduced (Donnelly et al., 2014). These observed reductions were primarily attributable to decreases in mean gastrocnemius and mean hamstring TMA. Reduced hamstring and gastrocnemius activation, relative to quadriceps activation, suggests a decrease in compressive forces at the knee—which is thought to reduce joint stability and potentially increase ACL strain (Morgan et al., 2014;
Withrow, Huston, Wojtys, & Ashton-Miller, 2008). When changes in muscle activation and knee loading are considered together, it is apparent that participants in this study were at increased risk of ACL injury following a season of sport, with the comparison group observing a greater change in injury risk. This finding is in agreement with previous research which reported increases in ACL injury risk in male community-level athletes over a sporting season (Donnelly et al., 2014; Donnelly, Elliott, Doyle, et al., 2012).

Following the intervention, the SM/BF DCCR of the training group were laterally redirected (BF), a result not observed in the comparison group. It has been previously reported that when the knee is flexed both the SM and BF have large moment arms capable of supporting the knee against internal/external rotation moments (Buford, Ivey, Nakamura, Patterson, & Nguyen, 2001). It is reasonable to suggest that both SM and BF are capable of producing internal/external rotation moment during UnSS, as the knee is typically flexed during WA (Fox, Bonacci, McLean, Spittle, & Saunders, 2014). As the knee flexes, there is an increase in the mechanical advantage of external rotator muscles over internal rotator muscles (Buford et al., 2001). The training group's knee flexion at foot contact increased from pre to post-testing, suggesting they had a greater mechanical ability to counter internal rotation moments after the intervention.

The observed changes in DCCR between the SM/BF may be an effective neuromuscular adaptation to support the knee against internal rotation moments and associated risk of ACL injury. These results may also explain why increases in peak internal rotation moments were not observed in the training group. It is important to note that this explanation would not have been considered without the combined analysis of kinetics and muscle activation. The comparison group's SM/BF DCCR remained unchanged, suggesting their muscular support against internal rotation moments also remained unchanged. With increases seen in internal rotation moments, it is likely that an unchanged SM/BF DCCR fails to provide the extra support required at the knee. This suggests the comparison group was at increased risk of ACL injury during post-testing. While there is evidence for a relationship between changes in SM/BF DCCR and internal rotation moments, it should be noted that the sample size for kinetic data (eight training and ten comparison) differs from neuromuscular data (six training and nine comparison). It is therefore recommended that this relationship be investigated in future research.

Following the intervention, both groups M/I DCCR were redirected laterally, which is thought to be an ineffective neuromuscular strategy to support against valgus knee moments (Donnelly et al., 2014). Though not an ideal neuromuscular adaptation, it may be inappropriate to make definitive injury risk statements based on these changes, as not all the muscles with medial (e.g. gracilis) and lateral (e.g. tensor fasciae latae) moments arms crossing the knee were included in the M/I DCCR estimates. Future research, recording activation from all muscles with medial and lateral moment arms crossing the knee, is therefore recommended to verify these neuromuscular adaptations and associated injury risk statements.

Positive kinematic changes were observed in the training group, with increased knee flexion at foot contact, which is hypothesised to be protective against ACL injury risk (Markolf et al., 1995). Both groups demonstrated a decrease in lateral trunk flexion which is associated with reduced peak knee valgus moments during sidestepping (Dempsey et al., 2007; Donnelly, Lloyd, et al., 2012). The reduction in trunk flexion RoM observed within the training group was too small (2.6°) to be clinically meaningful. The comparison group reduced lateral foot placement by 3 cm, which is associated with reduced peak knee
valgus moments (Dempsey et al., 2009). There are over 500 possible kinematic solutions to decreasing ACL injury risk, with a single change always being accompanied by change in at least one other variable (Donnelly, Lloyd, et al., 2012); making kinematic changes a less definitive injury risk indicator when compared to known kinetic risk factors.

There are a number of limitations to this study. This study used a controlled clinical trial research design, where ideally a randomised controlled trial would be implemented. However, controlled clinical trials are more practical when implementing an intervention among a general athlete population. A high training group attrition rate and telemetry equipment issues for our EMG recordings reduced the study’s final sample size, which limited our ability to interpret the findings, even though practical significance was found. Lastly, training attendance and compliance were significantly lower than those recorded when the intervention was implemented amongst elite athletes (Weir et al., 2014a), with both being a well-documented challenge in community-level sport research (Donnelly, Elliott, Doyle, et al., 2012). It is important for future research to identify strategies to improve and/or circumvent low athlete attendance and compliance.

Conclusion
Over a season of community-level sport, increases in peak knee valgus and internal rotation moments, alongside decreases in total muscle activation were observed, theoretically serving to increase an athlete's risk of ACL injury during UnSS tasks. Participating in a biomechanically informed ACL training intervention, which maintains peak knee valgus and internal rotation moments, and improves BF/ML. DCCR may assist in mitigating the potentially deleterious effects of community-level sport participation.

Acknowledgements
The authors would like to acknowledge the assistance of Associate Professor Jonas Rubenson for his valuable discussions and Josh 'Coach' Armstrong for his assistance in designing the biomechanically informed training intervention. We thank Suzanne Tvertos and the University of Western Australia Hockey Club for their time and participation.

Disclosure statement
No potential conflict of interest was reported by the authors.

Funding
No external funding was sourced for this manuscript

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References


THE EFFECT OF BIOMECHANICALLY FOCUSED INJURY PREVENTION TRAINING ON REDUCING ANTERIOR CRUCIATE LIGAMENT INJURY RISK AMONG FEMALE COMMUNITY LEVEL ATHLETES

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This study investigated changes in biomechanical risk factors following a 9-week body-weight based training intervention focused on the dynamic control of the hip/trunk. Peak knee moments and lower limb muscle activation of female community level athletes (n=18), split into intervention (n=8) and comparison (n=10) groups, were measured during unplanned sidestepping pre/post training. Following the 9-week intervention, total muscle activation of the muscles crossing the knee decreased, which was accompanied by elevated peak knee valgus and internal rotation moments among the comparison group. Increases in peak knee valgus and internal rotation moments were not observed among the training intervention group. In the context of ACL injury risk, these findings suggest that participation in biomechanically focused training may mitigate the potentially deleterious effects of regular community level sport participation.

KEYWORDS: Knee, intervention, sidestepping, injury prevention

INTRODUCTION: A review of anterior cruciate ligament (ACL) injury training literature has revealed that most published studies were not successful in decreasing non-contact ACL injury rates (Donnelly et al., 2012). Reinforcing the view that there is a need to develop more focused and biomechanically verified prevention training programmes if we are to effectively reduce an athlete’s risk of ACL injury in sport (Hewett et al., 1999). Previous biomechanical research has shown that hip and trunk dynamics during sidestepping and landing tasks are related to an athlete’s risk of sustaining an ACL injury (Donnelly et al., 2012a). This has provided a rationale to shift the focus of ACL injury prevention training from the knee towards the hip and trunk (Donnelly, 2014). Weir and colleagues (2014) recently trialed a novel biomechanically focused injury prevention training protocol with the primary goal of improving the strength of trunk and lower body musculature. A combination of plyometric, resistance and balance training exercises were used in the intervention whilst emphasising correct task specific technique. The intervention was successful in reducing peak knee valgus moments (Δ-29%, p = 0.013) and ACL injury risk among ‘high risk’ athletes during unplanned sidestepping (UnSS), and the entire training group displayed positive neuromuscular adaptations including increased gluteal total muscle activation (Δ+10%, p = 0.006). While this research established the efficacy of a biomechanically focused injury prevention programme among elite level athletes within an ideal (Donnelly et al., 2012) training environment and with 100% athlete compliance, there is a need for future research to verify its efficacy among community level athlete’s where the highest rates of ACL injury are observed (Gianotti et al., 2009).

The purpose of this study was to determine if biomechanically focused (Weir et al., 2014) ACL injury prevention training was effective in increasing lower limb muscle activation and reducing peak knee moments and the associated risk of ACL injury during the weight acceptance (WA) phase of UnSS among female community level athletes.
METHODS: Eighteen female community level athletes participated in a nine-week controlled clinical trial training intervention during a season of play. Community sports included those involving dynamic tasks such as sidestepping, single leg landing and pivoting such as field hockey, netball, basketball and soccer. Eight athletes (21.1±5.7 yrs, 1.70±0.06 m, 67.5±3.6 kg) were selected to participate in a biomechanically focused training intervention (Weir et al., 2014) adjunct to their normal in-season training (training group) and 10 athletes (19.9±3.2 yrs, 1.69±0.07 m, 63.4±10.2 kg) completed their normal in-season training (comparison group). Prior to (pre-test) and following the training intervention (post-test), all eighteen athletes completed biomechanical testing. Pre-testing was conducted during pre-season training, one to four weeks before the first competitive game. Post-testing was conducted six to eight weeks after the first competitive game. During testing a 3D motion analysis system was used to record each athlete completing a previously published sidestepping protocol (Besier et al., 2001; Donnelly et al., 2012), consisting of a series of planned and unplanned straight line running and change of direction tasks. Upper and lower body kinematics were collected using a 12 camera Vicon® MX (Oxford Metrics, Oxford, UK) system operating at 250 Hz, which was synchronized with an AMTI force plate, recording at 2,000 Hz (Advanced Mechanical Technology Inc., Watertown, MA). The activation of nine muscles was recorded with a telemetry surface electromyography (sEMG) system at 1,500 Hz (TeleMyo 2400 G2, Noraxon, Scottsdale, Arizona). Pairs of electrodes were placed over the muscle bellies of the gluteus maximus, gluteus medius, rectus femoris, vastus lateralis, vastus medialis, bicep femoris, semimembranosus, lateral gastrocnemius and medial gastrocnemius (Delagi et al., 1982). Due to telemetry problems during data collection, pre to post sEMG data was obtained from six participants in the intervention group and nine from the comparison group. Reliable lower limb kinematic and kinetic models were used to calculate knee joint kinematics and kinetics via inverse dynamics procedures during UnSS in BodyBuilder® software using the Nexus® software pipeline (Vicon®, Oxford Metrics, Oxford, UK) (Besier et al., 2003; Donnelly et al., 2012). Following the SENIAM sEMG processing recommendations (Stegeman et al., 1999), DC offsets were removed, then band-pass filtered between 30 and 500 Hz with a zero-lag. 4th order Butterworth digital filter, full-wave rectified, then linearly enveloped using a low pass with a zero-lag, 4th order Butterworth at 6 Hz. Muscle activation was normalised to the maximal activation observed for each muscle during either dynamometry, functional and sidestepping trials and expressed as 0 – 100% maximal voluntary contraction. Knee kinetic and muscle activation data were analysed during the WA phase of UnSS as defined by Dempsey et al., (2007). Kinetic variables included peak knee valgus, internal rotation and extension moments normalised to height and bodyweight (Ht*BW). As per Donnelly et al., (2014a), mean total muscle activation (TMA) of the gluteal, quadriceps, hamstrings and gastrocnemius groups were calculated, as well as for all muscles crossing the knee. Directed co-contraction ratios (DCCR) were calculated between muscle groups crossing the knee with flexion/extension (F/E) moment arms and medial/lateral (M/L) moment arms (Donnelly et al., 2014a). Semimembranosus/bicep femoris muscles (SM/BF) DCCR were also calculated. A one-tailed repeated measures mixed-model ANOVA was performed to identify any significant (α = 0.05) main effects and/or interactions of each dependent variable between training intervention and comparison groups, pre to post biomechanical testing. Protected t-tests were performed as post hoc analyses (α < 0.05). Cohen’s d tests were performed to determine effect sizes (d ≥ 0.60: moderate/large effect size).

RESULTS and DISCUSSION: Surprisingly, though aligning with previous literature, both groups reported increases in UnSS peak knee moments following a playing season (Cochrane et al., 2010; Donnelly et al., 2012) (Table 1). Interestingly, the training group showed significant increases in peak knee extension moments (Δ +13%, p = 0.041), with negligible changes in frontal and transverse plane knee moments. For the comparison group, moderate increases in both peak knee valgus (Δ +27%, d = -0.36) and internal rotation moments (Δ +38%, d = -0.56) were observed, with negligible increases in sagittal plane knee moments. With it known that sagittal plane moments alone are unlikely to rupture the ACL (McLean et al., 2004), our training results suggest that adjunct biomechanically focused training maintained an athlete’s relative risk of ACL injury pre to post testing, a finding not observed among athletes in the comparison group. Pre to post biomechanical testing, both the training (Δ -15%, d = 0.45) and comparison groups (Δ -10%, d = 0.47) reported decreases in TMA of all muscles crossing the knee. These observed reductions were primarily due to reductions in gastrocnemius TMA, which was -52% (d = 0.74) in the training group and -10% (d = 0.29) in the comparison group, as well as reductions in hamstring
TMA, which was -18% ($d = 0.44$) and -22% ($d = 0.55$) respectively. In the context of ACL injury risk in sport, these observed changes would be considered negative neuromuscular adaptations (Donnelly et al., 2014a; Morgan et al., 2014). When these changes in muscle activation and knee loading are considered together, it is apparent that participants in this study were at increased risk of ACL injury following a season of play, with the comparison group observing a greater change in injury risk.

Following the intervention, the SM/BF DCCR of the biomechanically focused training group were laterally redirected (BF) ($d = 0.67$), a result not observed in the comparison group. It has been reported previously that when the knee is flexed, as observed during the WA of UnSS, both the SM and BF have large moment arms capable of generating internal/external rotation moments about the knee (Buford et al., 2001). These observed changes in DCCR between the SM/BF may be an effective neuromuscular adaption to help support the knee against internal rotation moments and risk of ACL injury. These results may also, in part, explain why increases in peak internal rotation knee moments were not observed for the biomechanically focused training group.

Following the intervention, both the biomechanically focused training group’s ($d = 0.74$) and comparison group’s ($p = 0.001$) M/L DCCR were redirected laterally, which is thought to be an ineffective neuromuscular strategy to support against valgus knee moments (Donnelly et al., 2014a); the loading patterns known to elevate ACL injury risk. Though not an ideal neuromuscular adaptation, it may be inappropriate to make definitive injury risk statements based on these muscle activation changes as not all the muscles with medial (i.e. gracilis) and lateral (i.e. tensor fasciae latae) moments arms crossing the knee were included in the M/L DCCR estimates. Future research is therefore recommended to verify these neuromuscular adaptations and associated injury risk statements.

Table 1. Mean (standard deviation) normalized kinetics (Ht*BW) and electromyography (DCCR and TMA) during the WA phase of UnSS.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Comparison Group (n = 10)</th>
<th>Training Group (n = 8)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pre-test</td>
<td>Post-test</td>
</tr>
<tr>
<td>Kinetics</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peak Knee Extension Moment</td>
<td>2.13 ± 0.37$^d$</td>
<td>2.10 ± 0.33</td>
</tr>
<tr>
<td>Peak Knee Valgus Moment</td>
<td>0.36 ± 0.25</td>
<td>0.46 ± 0.46</td>
</tr>
<tr>
<td>Peak Knee Internal Rotation Moment</td>
<td>0.08 ± 0.05</td>
<td>0.11 ± 0.04</td>
</tr>
<tr>
<td>DCCR</td>
<td></td>
<td></td>
</tr>
<tr>
<td>F/E</td>
<td>-0.13 ± 0.33$^d$</td>
<td>-0.22 ± 0.29</td>
</tr>
<tr>
<td>M/L</td>
<td>0.05 ± 0.14</td>
<td>-0.15 ± 0.09$^a$</td>
</tr>
<tr>
<td>SM/BF</td>
<td>0.07 ± 0.36</td>
<td>-0.05 ± 0.32</td>
</tr>
<tr>
<td>TMA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gluteal</td>
<td>0.68 ± 0.17d</td>
<td>0.64 ± 0.17</td>
</tr>
<tr>
<td>Quadriceps</td>
<td>0.89 ± 0.26</td>
<td>0.85 ± 0.31</td>
</tr>
<tr>
<td>Hamstrings</td>
<td>0.47 ± 0.24</td>
<td>0.37 ± 0.12</td>
</tr>
<tr>
<td>Gastrocnemius</td>
<td>0.50 ± 0.16$^d$</td>
<td>0.46 ± 0.16$^d$</td>
</tr>
<tr>
<td>Knee</td>
<td>1.85 ± 0.31</td>
<td>1.68 ± 0.46</td>
</tr>
</tbody>
</table>

All kinetic data are presented in scientific notation x10$^d$

$^d$ Indicates a significant difference pre-test to post-test ($p < 0.05$)

$^a$ Indicates a greater than moderate effect size pre-test to post-test ($d ≥ 0.60$)

$^b$ Indicates a significant difference between training and comparison groups ($p < 0.05$)

$^c$ Indicates a greater than moderate effect size between training and comparison groups ($d ≥ 0.60$)

CONCLUSION: Increases in peak knee valgus and internal rotation moments, alongside decreases in knee TMA may leave those participating in a typical sporting season at elevated risk of ACL injury. However, participating in a biomechanically focused ACL training intervention that maintains peak knee valgus and internal rotation moments, and improves BF/ML DCCR may mitigate potential deleterious effects of regular community level sport participation.

REFERENCES:
Appendix C6 – Study Two Accepted Conference Abstract


Changes in Muscle Activation following Hip and Trunk Neuromuscular Training in Elite Female Hockey Players: Implications for ACL Injury Risk

Gillian Weir, Dawn Cantwell, Jacqueline Alderson, Bruce Elliott and Cyril Donnelly
University of Western Australia

Anterior cruciate ligament (ACL) injury risk and the biomechanical risk factors that contribute to ACL strain are influenced among others by the hip and knee kinematic strategies an athlete adopts during dynamic change of direction sporting tasks. Hip and trunk neuromuscular training can be used to improve the dynamic control of the trunk/hip as well as support the knee from external loading, subsequently reducing ACL injury risk during sporting tasks. This study investigated the effects of a body weight based hip and trunk focused training intervention on the functioning of specific muscles crossing the hip and knee joints during unplanned side-stepping tasks. Thirteen national level female hockey players took part in an eight week multifactorial, body weight based hip and trunk focused training intervention. Pre to post training, changes in muscle activation were assessed using a repeated measures ANOVA (α = 0.05). Following the training intervention, gluteal muscle activation (grouped maximus and medius) improved during the weight acceptance phase of unplanned side-stepping tasks (p=0.006). As the gluteal muscle group functions to externally rotate the hip, this neuromuscular adaptation has the potential to prevent an athlete from attaining ‘dynamic knee valgus postures’, which have been shown to be associated with ACL injury rates. Following training there was also an increase in medial directed hamstrings activation during both the pre-contact (p=0.024) and weight acceptance (p=0.012). This is an effective neuromuscular strategy to support the knee against valgus knee moments; a surrogate measure of ACL injury risk. A moderate effect size (d = 0.56) was present for an increase in hip extension moment, with no change observed in the overall support moment. This, in combination with the increased gluteal activation suggests that following hip and trunk focused body-weight based training, athletes better utilize their hip musculature to generate their support moment, which may result in improvements in the biomechanical risk factors associated with ACL injury.
HIP AND TRUNK NEUROMUSCULAR TRAINING TO REDUCE RISK OF ACL INJURY IN SPORT: RESPONDERS AND NON-RESPONDERS IN ELITE FEMALE TEAM SPORT ATHLETES

Weir, G.J., Cantwell, D., Alderson, J.A., Elliott, B.C., Donnelly, C.J.

University of Western Australia

Introduction

The aim of this study was to determine if body-weight based (BWB) neuromuscular training targeting the hip and trunk is effective in altering the activation of the muscles crossing the hip and knee, reducing peak knee joint loading and anterior cruciate ligament (ACL) injury risk among elite female field hockey players. A secondary objective was to determine if all athletes within this cohort responded in a similar manner to training, or when clustered into sub-groups based on response to training (i.e. reductions in peak knee loading) displayed unique biomechanical and/or neuromuscular adaptations that could explain these differences.

Methods

Sixteen elite female hockey players participated in eight weeks of BWB neuromuscular training, targeting the hip and trunk. Hip, knee and ankle moments, support moment and the activation of nine lower limb muscles were calculated during weight acceptance of unplanned sidestepping prior to, and following training. Athletes were then classified as ‘responders’ (n=4) and ‘non-responders’ (n=12). Total muscle activation (TMA) of all lower limb muscles and individual muscle groups (gluteal, quadriceps, hamstrings and gastrocnemii) were calculated. A split-plot ANOVA was used to assess changes in lower limb kinetics (α=0.05) and Cohen’s d for muscle activation changes following training.

Results

As a group (n=16), no differences in lower limb kinetics were observed. Responders displayed reductions in peak knee valgus (-28%; p=0.003) and extension (-10%; p=0.005) moments following training, and interestingly displayed higher peak knee valgus moments relative to non-responders prior to training. No change in support moment existed pre to post training for both groups, however an increase in peak hip extension moments (+18%; p=0.046) were observed in responders. A large effect was observed for increased TMA-gluteal for responders (+29%; d=1.4).

Discussion
Following hip and trunk focused BWB neuromuscular training, responder athletes better utilized their hip musculature to generate their support moment. This is thought to be related to the reduced peak extension and valgus moments observed at the knee, therefore effectively reducing ACL injury risk (Donnelly et al., 2012; Markolf et al., 1995). The analysis of responding athletes is important for improvement of the effectiveness of injury prevention protocols (Myer et al., 2007).

References


Contact

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APPENDIX C 8 – STUDY TWO ACCEPTED CONFERENCE ABSTRACT


CHANGES IN SUPPORT MOMENT AND MUSCLE ACTIVATION FOLLOWING HIP AND TRUNK NEUROMUSCULAR TRAINING: THE HIP AND ACL INJURY RISK

Gillian Weir, Dawn Cantwell, Jacqueline Alderson, Bruce Elliott and Cyril J Donnelly
University of Western Australia

This study investigated lower limb muscular activation strategies following an 8-week body-weight based training intervention focused on the dynamic control of the hip/trunk. Muscle activation, support moment and frontal plane knee moments of elite female hockey players (n=13) were measured during unplanned sidestepping pre/post training. Post-training, gluteal muscle activation increased (+10%;p=0.006). There was no change in support moment or frontal plane knee moments however, the contribution of hip extension to total support moment increased (+10%;d=0.56) following training. Hip/trunk neuromuscular training is effective in improving hip neuromuscular activation, allowing athletes to more effectively utilise their hip to generate their support moment, which may prevent dangerous ‘dynamic valgus’ knee postures during sidestepping sporting tasks.

KEYWORDS: GLUTEAL, UNPLANNED SIDESTEPPING, INTERVENTION.

INTRODUCTION: Anterior cruciate ligament (ACL) injuries are arguably the most debilitating knee injury an athlete can sustain in sport. Females are placed at 4-5 times higher risk of sustaining an ACL injury in sport relative to their male counterparts (Myer, Ford, Heidt, Colosimo, McLean & Succop, 2005). Over half of these injuries occur during non-contact sidestepping tasks, meaning that these injuries can be prevented (Cochrane, Lloyd, Besier, Elliott, Doyle & Ackland, 2010). In-vivo (Besier, Lloyd, Cochrane, & Ackland, 2001; Markolf, Burchfield, Shapiro, Shepard, Finerman, & Slaeterbeck, 1995) and in-silico (Donnelly, Lloyd, Elliott, & Reinbolt, 2012b; McLean, Huang, & van den Bogert, 2008) research show that the ACL is at greatest risk of injury during the weight acceptance (WA) phase of stance, when the knee is in an extended posture, and valgus and internal rotation moments, combined with anterior drawer are applied to the knee. There are two biomechanical approaches that can be utilised to reduce an athlete’s risk of ACL injury in sport. The first is to modify an athlete’s technique in an effort to reduce the external forces applied to the knee during the task (Chaudhari, Hearn, & Andriacchi, 2005; Dempsey, Lloyd, Elliott, Steele, & Munro, 2009; Donnelly et al., 2012b). The second is to improve the coordinated co-activation and force generation of muscles about the knee and hip to support the knee when loading is elevated (Besier, Lloyd, Ackland, & Cochrane, 2001; Lloyd, Buchanan, & Besier, 2005). Improved neuromuscular control of joints proximal to the knee like the hip have been suggested as an effective neuromuscular strategy to reduce ACL injury risk as these muscles can function to prevent the hip from moving into a ‘dynamic valgus knee posture’ which has been associated with ACL injury rates in female athletes (Besier, Lloyd, & Ackland, 2003; McLean, Huang, & van den Bogert, 2005; McLean, Huang, & van den Bogert, 2008). Simulation research has shown an athlete’s technique, more specifically their upper body motor control can influence the aforementioned knee joint loading patterns during sidestepping (Donnelly et al., 2012b). From this, there is rationale to elevate the activation and/or strength of the trunk/hip musculature, in
particular the gluteal muscle group (external hip rotators), when attempting to reduce an athlete's risk of ACL injury in sport. The purpose of this study was to implement an 8-week body-weight based multifactorial training intervention focused on improving the dynamic strength and control of the trunk and hip musculature so to: 1) assess neuromuscular changes following training and 2) determine the effect of these neuromuscular strategies on biomechanical risk factors associated with ACL injury.

METHODS: The Australian national women's hockey team participated in an 8-week body-weight based training intervention focused on improving the dynamic control of the trunk and hip during dynamic sporting tasks. This multifactorial intervention encompassed plyometric, balance and strength body-weight based exercises (www.youtube.com/bodyfitworkouts) and was implemented alongside their regular in-season training schedule. Thirteen athletes (22.2±2.9yrs, 1.67±0.1m, 66.3±6.7kg) participated in biomechanical testing prior to, and following the intervention. During biomechanical testing, athletes were asked to perform a series of planned and unplanned straight line and change of direction running tasks (Figure 1) (Besier et al., 2001; Dempsey et al., 2009; Donnelly, Elliott, Doyle, Finch, Dempsey, Lloyd, 2012a).

Figure 1. Transverse and frontal view of the sidestep sport manoeuvres conducted during biomechanical testing. Mid pelvis position (x, y) coordinates 50 frames prior to heel contact (A), at heel contact (B) (A-B defines the pre-contact phase), contralateral leg heel contact (C) and ipsilateral leg mid swing (D) were used to define vectors AB and CD. The cosine of the dot product between vectors AB and CD represents a participants CoD angle during sidestepping. Adapted from (Donnelly et al., 2012a).

Hip (sagittal plane), knee (sagittal and frontal plane) and ankle (sagittal plane) moments, stance limb support moment and the activation of nine muscles of the lower limb were calculated during the weight acceptance (WA) phase of unplanned sidestepping (UnSS) prior to, and following training. Muscle activation was measured with surface electromyography (sEMG) using a 1500Hz Noraxon Telemetry system (TeleMyo 2400 G2, Noraxon, Scottsdale, Arizona). 3D marker trajectories were collected using a 12 camera Vicon MX system (Oxford Metrics, Oxford, UK) at 250Hz. This was synchronized with a 1.2m x 1.2m force plate (AMTI, Watertown, MA) recording at 2,000Hz. Customised software in MatLab (Matlab 7.8, The Math Works, Inc., Natick, Massachusetts, USA) was used to process sEMG data, as per Donnelly et al (2011). Maximum functional excitation of each muscle (n=9) recorded during any of the dynamic trials was used to normalize each muscle’s sEMG signal to 100% activation. Total muscle activation (TMA) of all lower limb muscles and individual muscle groups (gluteal, quadriceps, hamstrings and gastrocnemii) were calculated. Pre to post training, changes in muscle activation, support moment and frontal plane knee moments during the pre-contact (PC) and weight acceptance (WA) phases of stance of unplanned sidestepping were assessed using effect sizes (Cohen’s d) and a repeated measures ANOVA in SPSS 17.0.1 (SPSS Inc, IBM Headquaters, Chicago, Illinois) (α = 0.05).

RESULTS AND DISCUSSION: Following training there was no significant changes in TMA during PC and WA of unplanned side-stepping tasks. However, TMA of the gluteal (grouped maximus and medius) improved by 10% during WA (p=0.006, power=0.864). No statistically significant
changes in support moment were observed, however a moderate effect size (d = 0.56) was present, showing a 10% increase in hip extension towards the total support moment (Figure 2). There were no changes in frontal plane knee moments following training (p=0.73, d<0.01). There was no change in frontal plane knee loading following training (p=0.73, d<0.01). This may be due to the small sample in this study, however values were lower than that reported in the literature (Robinson, Donnelly, Tsao, & Vanrenterghem, 2013). These findings in combination suggest athletes better utilize their hip musculature to generate their support moment, which may result in improvements in the biomechanical risk factors associated with ACL injury. This can be concluded in two parts, firstly; the complex line of action of the ACL requires combined knee loading in all three planes to maximize ligament strain, therefore redistributing the support moment to the hip musculature may effectively reduce ACL injury risk by decreasing loading at the knee. Secondly, as the gluteal muscle group functions to externally rotate the hip, the elevated neuromuscular response following training signifies an increase in eccentric control of hip internal rotation, which would function to prevent the valgus collapse or ‘buckling’ at the knee, which has been associated with elevated frontal plane knee moments, ACL injury risk and ACL injury rates (Besier et al., 2001; Hewett et al., 2005; McLean et al., 2005).

**CONCLUSION:** Following an 8-week multifactorial body-weight based hip and trunk neuromuscular training intervention, increased gluteal total muscle activation and an elevated contribution of hip extension moment to the total support moment during the weight acceptance phase of unplanned sidestepping was observed. This is a positive neuromuscular strategy that may reduce risk of ACL injury via redistribution of forces to the hip, control of the upper body and prevention of dynamic knee valgus postures. Supporting previous simulation research (Donnelly et al., 2012), training protocols focused on the dynamic control of the trunk and hip are recommended to reduce an athlete’s peak knee loading and ACL injury risk in sport.

**ACKNOWLEDGEMENTS:** We would like to thank Hockey Australia and the Hockeyroos for their involvement and participation in this research and Josh ‘Coach’ Armstrong with the development of the training intervention.

**REFERENCES:**


APPENDIX C 9 – STUDY THREE ACCEPTED CONFERENCE ABSTRACT

Weir, G.J., Smailes, N., Alderson, J., Elliott, B.C., Donnelly, C.J. A Two-Dimensional Video Based Screening Tool To Predict Peak Knee Loading and ACL Injury Risk in Female Community Level Athletes. In proceedings of the XXIV Congress of the International Society of Biomechanics, Natal, Brazil, August 4 -9, 2013.

A TWO-DIMENSIONAL VIDEO BASED SCREENING TOOL TO PREDICT PEAK KNEE LOADING AND ACL INJURY RISK IN FEMALE COMMUNITY LEVEL ATHLETES

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2UWA Sports Performance and Research Centre (SPARC)
University of Western Australia

SUMMARY
Anterior cruciate ligament (ACL) injuries are traumatic and disabling, with over half occurring during non-contact sidestepping situations. In-vivo and in-silico research show that the ACL is at greatest risk of injury during the weight acceptance (WA) phase of stance, when the knee is in an extended posture, and valgus and internal rotation moments, combined with anterior drawer are applied to the knee. Simulation research has shown an athlete’s technique, more specifically their upper body motor control can influence the aforementioned knee joint loading patterns during sidestepping [5]. Clinically relevant methods capable of identifying community level athletes at increased risk of injury on a large scale are limited. The purpose of this study was to develop a reliable two-dimensional (2D) video analysis tool to predict peak knee loading during change of direction tasks in young female athletes. Significant correlations were found between a number of full body kinematics and three-dimensional (3D) knee peak loading variables. Results suggested that poor control of the trunk, reduced knee flexion angle at impact and increased dynamic medial knee collapse (frontal plane) during sidestepping result in higher peak extension and valgus knee moments. These findings are important as it is combined external joint loading that predisposes the ACL to the greatest risk of injury. We are currently analysing data from a cohort of junior male athletes to determine the robustness of this 2D screening tool for use in mass screening of community level athletes.

INTRODUCTION
Over half of anterior cruciate ligament (ACL) injuries occur during dynamic sporting tasks such as sidestepping [1-4]. These sporting tasks are common amongst team sports such as football, where approximately 236 million people participate around the world [7]. Recovery from ACL rupture is an expensive costing Australian and American healthcare approximately $3.5 million AUD and billion USD each year respectively. Cost to the injured athlete is also high with approximately 70% retiring from competition only three years post-surgery [8]. If accompanied by a meniscus injury, these athletes are also at significantly greater risk of developing knee osteoarthritis within 10-15 years [8]. Previous research has identifyed causal links between an athlete’s trunk and hip neuromuscular control and peak valgus and internal rotation knee loading during dynamic sporting tasks [5]. The ability to identify these kinematic-kinetic relationships with the use of two dimensional (2D) video analyses is limited. As such we are restricted in our abilities to conduct mass screening of community level athletes to identify athletes at increased risk of an ACL injury. The aim of this study was to develop a reliable 2D video based screening tool that could be used identify the kinematic factors associated with an athlete’s peak knee loading and ACL injury risk during unplanned sidestepping.

METHODS
Fifteen junior female hockey players (14-17 years) were asked to perform a series of planned and unplanned straight line and change of direction running tasks (Figure 1) [1,6]. 1D marker trajectories were collected using a 12 camera Vicon MX system (Oxford Metrics, Oxford, UK) at 250Hz. This was synchronized with a 1.2m x 1.2m force plate (AMTI, Watertown, MA) recording at 2000Hz and frontal and sagittal plane 2D high speed video cameras at 50 Hz. Full body kinematics and kinetics were analyzed during weight acceptance (WA) [1-3].

Figure 1. Transverse view of the sidestepp sport manoeuvre conducted during biomechanical testing. Mid pelvis position (x, y) coordinates 50 frames prior to heel contact (A), at heel contact (B), contralateral leg heel contact (C) and ipsilateral leg mid swing (D) were used to define vectors AB and CD. The cosine of the dot product between vectors AB and CD
represents a participant's CoD angle during sidestepping. Adapted from [6].

2D kinematic measures including knee flexion range of motion (ROM), knee flexion at foot strike, peak valgus knee angle, peak dynamic medial knee collapse, trunk lateral flexion, trunk flexion at footstrike, trunk flexion ROM, mid-pelvis to foot displacement and peak thigh abduction were analyzed with Silicon Coach software. Peak valgus, extension and internal rotation knee joint moments were calculated via inverse dynamics in BodyBuilder (Vicon, Oxford Metrics, Oxford, UK). 2D kinematic variables measured during unplanned sidestepping (UPSS) and straight line run trials were placed into a backward stepwise regression (p<0.05) to identify 2D kinematic variables that predict the above peak knee loading during UPSS. Intraclass correlations (ICC) and limits of agreement (LoA) were used to test inter- and intra-rater reliability of all nine 2D kinematic measures.

RESULTS AND DISCUSSION

Knee flexion range of motion (ROM) (p<0.01), peak dynamic medial knee collapse (p<0.01) and peak trunk lateral flexion (p<0.02) were good predictors of peak extension knee moments, explaining 43.8% of the variability. Knee flexion at impact (p<0.01), trunk flexion ROM (p=0.028) and peak mid-pelvis to foot displacement (foot placement) (p<0.01) proved to be good predictors of peak valgus knee moments, explaining 55.7% of the variability (Table 1). Interestingly, frontal plane kinematic variables were found to explain variability in peak extension knee moments, whereas sagittal plane kinematic variables explained variability in peak valgus knee moments.

Inter-tester reliability of knee flexion, trunk lateral flexion and trunk flexion were moderate to high (p<0.001; ICC=0.68-0.8; LoA=1.6-8.3°), as were mid-pelvis to foot displacement and dynamic medial knee collapse (p<0.01; ICC=0.78-0.99; LoA=0.02-0.35). Intra-tester reliability of knee flexion, trunk lateral flexion and trunk flexion were moderate to high (p<0.001; ICC=0.65-0.76; LoA=4.2-5.3°). Mid-pelvis to foot displacement and dynamic medial knee collapse also had moderate-high intra-tester reliability (p<0.001; ICC=0.68-0.84; LoA=0.04-0.35).

These results show that there is interplay between an athlete's kinematics in one plane when predicting peak knee loading in another. These findings are consistent with previous simulation research that has shown that kinematic changes in all three planes of motion reduce an athlete's peak knee loading during UPSS [5]. Results also support the rationale that an athlete's upper body kinematics influence their peak knee loading and ACL injury risk during dynamic sporting tasks like unplanned sidestepping.

The reliability of these 2D kinematic measures ensures this tool can be used effectively across laboratories and over time. The next step in this research, which is currently in progress, is to test a group of male team sport athletes to determine the robustness of this clinical screening tool.

Once this tool has been refined it will enable the mass screening of community-level athletes. By identifying 'high risk' athletes we can implement sport-specific training protocols to target the individual musculoskeletal factors predisposing an athlete to increased injury risk in sport. This will help in the effective translation of prophylactic training protocols focused on reducing an athlete's risk of ACL injury in sport.

CONCLUSIONS

A repeatable and reliable 2D video-based screening tool was found to be successful in identifying high-risk movement patterns during unplanned sidestepping in female athletes. Movement patterns such as wide foot placement, low knee flexion angle, large trunk flexion ROM, trunk lateral flexion away from the intended direction of travel and dynamic medial knee collapse effectively predicted peak extension and valgus knee loading during sidestepping.

REFERENCES


<table>
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<tr>
<th>Peak Extension Moment</th>
<th>Peak Valgus/Moment</th>
<th>Total Model</th>
<th>2D Kinematics</th>
<th>β</th>
<th>p</th>
<th>Total Model</th>
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<td>Adjusted R²= 0.434</td>
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<td>Knee Flexion ROM</td>
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<td>Knee Flexion ROM</td>
<td>.205</td>
<td>.005*</td>
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<td>Dynamic Medial Knee Shift Peak</td>
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<td>.000*</td>
<td>Dynamic Medial Knee Shift Peak</td>
<td>.182</td>
<td>.058*</td>
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<tr>
<td>Adjusted</td>
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<td>Adjusted</td>
<td>.507</td>
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* indicates significance at the 0.05 level. When variables were not significant, they were removed from regressions, meaning correlations of significant variables have been adjusted.
**APPENDIX C 10 — STUDY THREE ACCEPTED CONFERENCE ABSTRACT**


**DO FIELD HOCKEY PLAYERS REQUIRE A SPORT-SPECIFIC BIOMECHANICAL ASSESSMENT TO CLASSIFY THEIR ANTERIOR CRUCIATE LIGAMENT INJURY RISK?**

Marc Smith, Gillian Weir, Cyril J. Donnelly, Jacqueline Alderson

Sport Science and Exercise Health, University of Western Australia, Perth, Western Australia

The lower limb biomechanics of 13 elite female hockey players were compared between 1) a generic, and 2) a hockey-specific (i.e., flexed trunk and hockey stick present) ACL injury risk movement assessment. Our aim was to determine if an athlete's ACL injury risk classification differed as a function of their movement assessment. An increase in trunk, hip and knee flexion was observed during the hockey-specific movement assessment. No significant differences in key ACL injury risk factors (i.e., peak three dimensional knee moments) were observed. These results show that imposing hockey-specific requirements during a lab based movement assessment did not change an athlete's ACL injury risk classification when compared to a generic movement assessment.

**KEY WORDS:** postural constraints, ACL injury risk, movement assessment

**INTRODUCTION:** A rupture to the anterior cruciate ligament (ACL) is considered to be one of the most debilitating knee injuries an athlete can sustain in sport (Donnelly et al., 2012a). As motion capture technologies, musculoskeletal models and non-linear analyses evolve, we now have the ability to move from static/quasi-static, to dynamic sport-specific movement assessments of an athlete’s ACL injury classification in sport. In-vivo/in-lab research (Markolf et al., 1995; Besier et al., 2001b) and in-silico research (McLean et al., 2004; Donnelly et al., 2012b) have shown that a combination of peak extension, valgus, and internal rotation moments at the knee is associated with elevated ACL forces and injury risk in sport. Evidence also suggests a causal relationship between peak knee joint moments and an athlete's upper body postures during change of direction sporting tasks (Dempsey et al., 2007; Donnelly et al., 2012b).

Chaudhari et al. (2005) directly tested the influence of constraining an athlete's upper extremity movement in an attempt to replicate different sport-specific demands during planned sidestepping movements. Constraining the arms elevated peak knee valgus moments by 60% when compared with a baseline sidestep with no postural constraints (Chaudhari et al., 2005). In landing tasks, Dempsey et al. (2012) also reported a relationship between whole body kinematics and knee moments, showing peak knee valgus moments increased when the upper-body was perturbed laterally during a single-leg landing task. These findings have direct implications for field hockey athletes, given the upper body constraints brought about through the use of a hockey stick during gameplay. The downstream impact of this sport-specific postural constraint on an athlete’s injury risk in sport is currently unknown. Field hockey athletes may possibly be at greater risk of ACL injury, as the constrained upper body postures could generate a higher mechanical demand on their knee joint versus running with an unconstrained posture. Despite the distinct postural differences that a field hockey athlete adopts during
gameplay, athletes are currently assessed using a well-published and accepted generic movement assessment (upright posture) when measuring an athlete’s ACL injury risk in sport. This generic movement assessment has previously been used to measure field hockey athletes, as well as a wide variety of team sport athletes from an array of sporting codes (McLean et al., 2005; Donnelly et al., 2012a; Weir et al., 2014). The purpose of this study was to determine if an athlete’s peak three dimensional (3D) knee moments and ACL injury risk classification changed when a generic movement assessment (GMA) or a revised hockey-specific movement assessment (HSMA) is used. We hypothesised that during a lab based HSMA, the flexed trunk postures associated with carrying a hockey stick will be accompanied by elevated peak valgus, internal rotation and extension knee moments when compared to the GMA (upright posture).

METHODS: Thirteen elite female hockey players (24.0 ± 3.0 yrs; 1.7 ± 0.7 m; 64.0 ± 6.9 kg) completed the GMA and HSMA in a block counterbalanced design. A random series of planned and unplanned change of direction (CoD) running tasks were completed in each assessment. The HSMA differed from the well-published GMA with the inclusion of a hockey-stick held low to the running surface, encouraging an increased flexed posture during each running task (Figure 1). 3D motion capture was used to record each sidestepping task, in accordance with previously published movement assessments (Besier et al., 2001b; Dempsey et al., 2009; Donnelly et al., 2012a). Kinematics and kinetics were recorded using a 22-camera Vicon MX/T40 system at 250Hz (Oxford Metrics, Oxford, UK) and force plate data at 2,000Hz (AMTI, Watertown, MA). Established kinetics (normalised to body weight (BW) and height (HT)) and kinematics variables associated with ACL injury risk (see Table 1) were analysed during the weight acceptance (WA) phase of three unplanned sidestepping tasks (Dempsey et al., 2007). A successful unplanned sidestep during testing was categorized as when the approach velocities fell between 4.5 m·s⁻¹ and 5.5 m·s⁻¹ and the sidestep CoD angle followed a 45º line marked on the running surface. Pre-contact velocities and mean change of direction (CoD) angles were collected to measure consistency between the GMA and HSMA. Peak extension, internal rotation and valgus knee moments were used to determine an athlete’s risk of ACL injury (Donnelly et al., 2012a). Paired sampled t-tests

<table>
<thead>
<tr>
<th>Kinematics (°)</th>
<th>Kinetics (%BW x HT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak trunk lateral flexion angle</td>
<td>Peak knee valgus moment</td>
</tr>
<tr>
<td>Mean trunk flexion angle</td>
<td>Peak knee internal rotation moment</td>
</tr>
<tr>
<td>Peak hip flexion angle</td>
<td>Peak knee extension moment</td>
</tr>
<tr>
<td>Peak hip abduction angle</td>
<td>Peak hip extension moment</td>
</tr>
<tr>
<td>Peak hip internal rotation angle</td>
<td>Peak ankle plantar flexion moment</td>
</tr>
<tr>
<td>Peak knee flexion angle</td>
<td></td>
</tr>
<tr>
<td>Knee flexion angle at foot-strike</td>
<td></td>
</tr>
</tbody>
</table>

Table 1: Discrete dependent variables measured during WA

Figure 1: Frontal and sagittal views of the GMA and HSMA posture while completing a sidestepping running task.
on pre-contact velocities and CoD angles were calculated to assess differences in means between the HSMA and GMA.

RESULTS: No differences in approach velocities and CoD angles were observed between the HSMA and GMA. Mean trunk flexion in the HSMA was 15° higher than the GMA (F=33.04, p<0.001, d=1.62). This trend continued throughout the lower limb with the hip and knee (F=27.84, p<0.001, d=1.07) displaying significantly higher levels of peak flexion during WA in the HSMA compared with the GMA condition (see Table 2). Consistent with these findings, the HSMA was associated with increased peak hip extension moments relative to the GMA (F=10.04, p<0.01, d=0.79). Interestingly, this trend was not observed at the knee where no differences in peak extension moments were observed between the GMA and HSMA, despite the greater levels of knee flexion recorded at the knee for the HSMA. Importantly, in the context of ACL injury risk, there were no observed differences in peak valgus or internal rotation knee moments between the GMA and HSMA (Table 2).

Table 2: Mean peak ACL injury risk variables measured during the GMA and HSMA. Angles were measured in (°) and moments measured in (%BW x HT).

<table>
<thead>
<tr>
<th>ACL Injury Risk Variables</th>
<th>Generic Mean (SD)</th>
<th>Hockey-Specific Mean (SD)</th>
<th>Effect Size</th>
<th>Observed Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trunk</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean Trunk Flexion Angle</td>
<td>20.7 (6.60)</td>
<td>35.7 (11.9)**</td>
<td>1.62a</td>
<td>0.99</td>
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<td>Lateral Flexion Angle</td>
<td>19.0 (6.20)</td>
<td>18.5 (6.00)</td>
<td>0.08d</td>
<td>0.07</td>
</tr>
<tr>
<td>Hip</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flexion Angle</td>
<td>57.9 (7.30)</td>
<td>62.4 (8.20)**</td>
<td>0.59b</td>
<td>1.00</td>
</tr>
<tr>
<td>Abduction Angle</td>
<td>16.9 (7.70)</td>
<td>19.8 (6.50)</td>
<td>0.4c</td>
<td>0.50</td>
</tr>
<tr>
<td>Internal Rotation Angle</td>
<td>0.6 (7.50)</td>
<td>0.4 (7.30)</td>
<td>0.03d</td>
<td>0.05</td>
</tr>
<tr>
<td>Extension Moment</td>
<td>0.155 (0.030)</td>
<td>0.183 (0.040)*</td>
<td>0.79b</td>
<td>0.83</td>
</tr>
<tr>
<td>Knee</td>
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<tr>
<td>Flexion Angle</td>
<td>52.4 (5.50)</td>
<td>56.0 (3.30)**</td>
<td>1.07a</td>
<td>1.00</td>
</tr>
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<td>Flexion at Foot-Strike Angle</td>
<td>18.9 (5.90)</td>
<td>21.2 (4.60)</td>
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<td>Extension Moment</td>
<td>0.234 (0.040)</td>
<td>0.222 (0.040)</td>
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<td>Valgus Moment</td>
<td>0.030 (0.020)</td>
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<td>Internal Rotation Moment</td>
<td>0.018 (0.010)</td>
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<td>Ankle</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Plantar Flexion Moment</td>
<td>0.061 (0.02)</td>
<td>0.060 (0.02)</td>
<td>0.09d</td>
<td>0.08</td>
</tr>
</tbody>
</table>

*Significant at p<0.05 **Significant at p<0.001
aLarge effect size d≥0.8  bMedium effect size = 0.5
Small effect size d = 0.2  dMinimal effect size ≤0.2

DISCUSSION: Contrary to our hypothesis, peak 3D knee joint moments were not influenced by the incorporation of a hockey stick during an ACL injury risk clinical movement assessment. Relative to the GMA, increases in trunk, hip and knee flexion angles during the HSMA were attributed to the imposition of a hockey stick and instructions to keep the stick low to the ground during testing. Similar peak knee moments during the HSMA may be explained by the adopted flexed posture, which effectively lowered the participant’s whole body CoM during the sidestepping movement. With a lower CoM, an athlete would likely increase the dynamic control of their whole body CoM as described by Winter (1987). Increased dynamic control of the CoM is beneficial from a lower limb and more specifically an ACL injury risk perspective, as seen in previous studies (Dempsey et al., 2007; Donnelly et al., 2012b). We know perturbations of the upper-body caused by postural constraints in the frontal plane, increase moments at the knee (Chaudhari et al., 2005; Dempsey et al., 2012). However, in the current study, postural constraints only influenced sagittal plane kinematics as no significant differences in trunk lateral flexion were observed. Consequently, the flexed posture adopted in the HSMA did not appear to influence the non-sagittal joint moments at the knee, suggesting their ACL injury risk did not differ between the GMA and HSMA.
Increased hip extension moments during the HSMA are required to support the trunk while maintaining a flexed hip posture in order to prevent the CoM from falling to the ground. Previous research has found that decreased hip musculature strength, endurance and activation, predisposes athletes to various knee joint injuries (Kernozek et al., 2008). Given that field hockey athletes must maintain increased levels of trunk flexion throughout an entire game, there is a possibility that the hip extension musculature, responsible for controlling trunk and hip extension, may be predisposed to fatigue (due to constant isometric and eccentric loading). Fatigue of the hip extension musculature over a game may reduce dynamic control of the knee during sidestep movements, placing athletes at risk of knee joint injuries. To further examine the role hip musculature plays while in hockey-specific postures, investigation into neuromuscular control and muscle activation during fatigued and unfatigued states is recommended.

CONCLUSION: An athlete’s peak 3D knee moments during change of direction tasks were not different when their movement was assessed using the GMA when compared to the HSMA, despite displaying elevated trunk, hip and knee flexion angles during the HSMA. In an unfatigued testing environment, a GMA and HSMA will produce similar ACL injury risk classification recommendations.

Acknowledgements: The authors would like to thank Hockey Australia, specifically Adam Commens, Kate Starre, Jen Cooke, Dr Carmel Goodman and the Australian Women’s Hockey Team for their participation in the study.

REFERENCES:


FOOT STRIKE POSTURE AND LOWER-LIMB DYNAMICS DURING SIDESTEPPING AMONG ELITE FEMALE ATHLETES: IMPLICATIONS FOR ACL INJURY RISK

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Faculty of Sports Science, Kasetsart University, Nakompathom, Thailand2
School of Sport Science, Exercise and Health, The University of Western Australia, Perth, Australia3

The purpose of this study was to compare the lower-limb dynamics between fore-foot (FF) and rear-foot (RF) strike patterns during unplanned sidestepping. Three-dimensional (3D) motion capture data were collected from 16 elite female hockey players. Ankle, knee, and hip angle at initial foot contact (IC), range of motion (ROM), peak moment, and negative peak net joint power during weight acceptance phase were compared between athletes using natural RF and FF strike techniques. Results showed ankle and hip angle at IC, ankle ROM, peak ankle and knee extension moments, peak knee valgus moments, and ankle and knee negative peak net power between RF and FF strike patterns were significantly different (α < 0.05). These findings show foot strike technique during unplanned sidestepping can affect athlete lower-limb dynamics, where RF strike athletes may be at higher risk of ACL injury.

KEY WORDS: rear-foot, fore-foot, knee loading

INTRODUCTION: Non-contact sidestepping is a common movement pattern among team sport athletes, where over one-half of non-contact ACL injuries occur (Cochrane et al., 2007; Shimokochi and Shultz, 2008; Griffin et al., 2006). Peak knee valgus moments in combination with extension moments have been shown to elevate ACL strain more than either loading pattern in isolation (Markolf et al., 1995). Laboratory analysis of sidestepping have shown that peak valgus knee moments are significantly elevated when compared with straight line running and more than double than that performed during unplanned versus planned sidestepping scenarios (Besier et al., 2001). Female athletes have a higher rate of ACL injuries relative to their male counterparts (Arendt et al., 1999; Ireland, 1999) and interestingly, more experienced female athletes may be at greater risk of injury (Sigward and Powers, 2006).

There is large amount of research investigating the influence of technique and injury risk during dynamic sporting tasks. Simulation research has highlighted the importance of appropriate upper body dynamics towards peak knee valgus moments and ACL injury risk during unplanned sidestepping (Donnelly et al., 2012). Foot placement close to the sideline and an upright torso during cutting has been reported to reduce peak knee valgus moments (Jamison et al., 2012; Dempsey et al., 2009). A greater and rapid initial hip flexion, internal rotation, and larger initial knee valgus angle has also been shown to produce elevated peak knee valgus loading (McLean et al., 2005; Kipp et al., 2011). Finally, Kristianslund et al. (2012) in a study of cutting technique, reported that narrow cuts with low knee valgus angle and toe landing may decrease knee valgus moments. Though fore-foot landing a popular and common coaching technique recommendation that has been shown to redistribute lower limb loading during running (Stearne et al., 2014), the influence of foot strike posture on an athlete’s ACL injury risk during unplanned sidestepping has yet to be investigated. The purpose of this study was to compare differences in lower-limb dynamics and ACL injury risk variables among athletes who adopt a natural fore-foot and rear-foot strike technique during unplanned sidestepping.
METHODS: Sixteen elite female hockey players participated in this study (22.2±2.9 yrs, 1.69±0.08 m, 62.88±7.13 kg). A 12 camera Vicon MX system (Oxford Metrics, Oxford, UK) capturing at 250 Hz was synchronised with a 1.2 m x 1.2 m force plate (AMTI, Watertown, MA) recording at 2,000 Hz. Each participant performed a series of planned and unplanned straight line and change of direction running tasks as per a previously published sidestepping protocol (Besier et al., 2001; Dempsey et al., 2009; Donnelly et al., 2012). Five successful unplanned side step cutting tasks were used for further analysis. Based on their natural foot strike patterns, participants were classified into: 1) habitual rear-foot (RF) or 2) habitual forefoot (FF) strike groups. A RF strike sidestepping technique was characterised using the orientation of 3D ground reaction force trace as per figure 1A, whereas FF strike sidestepping technique was characterised as per figure 1B. Trials were removed from analysis where no clear RF or FF strike pattern could be identified resulting in 9 participants classified as RF and 7 in the FF groups. Kinematic and ground reaction force data were low pass filtered with a zero-lag fourth order Butterworth filter at 14 Hz with residual analysis conducted to determine the appropriate cut-off frequency. Hip, knee and ankle joint angles, moments, and net power were calculated during the weight acceptance (WA) phase of unplanned sidestepping in accordance with the phase definition approach to the greatest risk of ACL injury (Dempsey et al., 2009). Joint moments and negative joint net power were normalised to body mass. Between group differences were evaluated using independent sample t-tests (α < 0.05) accounting for unequal samples in SPSS statistical software (Chicago, IL, USA).

RESULTS AND DISCUSSION: A number of significant differences in lower-limb kinematics and kinetics were observed between habitual RF and habitual FF strike athletes (Table 1). Joint Kinematics: Unsurprisingly, the RF strike group were dorsi-flexed at IC (7.1±8.5°) compared with the plantar-flexed posture of the FF strike (-16.0±6.5°). At IC, on average the hip was also 10° more flexed in the RF group when compared with the FF-fall group (p=0.01). Ankle joint flexion ROM following initial foot contact for the FF strikers (35.6±7.9°) was 42% higher (p=0.001) than the RF strikers (20.5±1.8°).

Table 1: Summary RF v FF lower-limb variables during sidestepping (mean±SD)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Rear-Foot N=9</th>
<th>Fore-Foot N=7</th>
<th>t</th>
<th>p</th>
<th>95% CI diff</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint angle at IC (°)</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>- Ankle</td>
<td>7.1±8.5</td>
<td>-16.0±6.5</td>
<td>5.94</td>
<td>&lt;0.001</td>
<td>14.7 to 31.4</td>
</tr>
<tr>
<td>- Knee</td>
<td>18.2±6.3</td>
<td>18.2±6.8</td>
<td>0.18</td>
<td>0.908</td>
<td>-7.0 to 7.1</td>
</tr>
<tr>
<td>- Hip</td>
<td>58.7±6.8</td>
<td>48.8±6.3</td>
<td>2.98</td>
<td>0.009</td>
<td>2.8 to 17.1</td>
</tr>
<tr>
<td>ROM at WA phase (°)</td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>- Ankle</td>
<td>20.5±1.8</td>
<td>35.6±7.9</td>
<td>-5.58</td>
<td>&lt;0.001</td>
<td>-20.9 to -9.3</td>
</tr>
<tr>
<td>- Knee</td>
<td>37.5±8.1</td>
<td>33.3±4.8</td>
<td>1.48</td>
<td>0.100</td>
<td>-1.9 to 10.3</td>
</tr>
<tr>
<td>- Hip</td>
<td>10.7±4.8</td>
<td>7.2±3.1</td>
<td>1.65</td>
<td>0.121</td>
<td>-1.0 to 8.0</td>
</tr>
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<td></td>
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<tr>
<td>- Ankle</td>
<td>0.7±0.3</td>
<td>1.7±0.3</td>
<td>-6.66</td>
<td>&lt;0.001</td>
<td>-1.3 to -0.7</td>
</tr>
<tr>
<td>- Knee</td>
<td>4.5±0.6</td>
<td>3.6±0.5</td>
<td>3.38</td>
<td>0.004</td>
<td>0.3 to 1.5</td>
</tr>
<tr>
<td>- Hip</td>
<td>2.4±0.0</td>
<td>2.8±1.2</td>
<td>-0.84</td>
<td>0.411</td>
<td>-1.4 to 0.6</td>
</tr>
<tr>
<td>Peak knee valgus moment (Nm/kg)</td>
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<td>Negative net peak joint power (Watt/kg)</td>
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<td></td>
</tr>
<tr>
<td>- Ankle</td>
<td>-5.8±1.8</td>
<td>-15.3±4.4</td>
<td>5.99</td>
<td>&lt;0.001</td>
<td>6.1 to 12.9</td>
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<td>- Knee</td>
<td>-48.8±18.5</td>
<td>-32.0±7.5</td>
<td>-4.9</td>
<td>&lt;0.001</td>
<td>-52.8 to -20.7</td>
</tr>
<tr>
<td>- Hip</td>
<td>-16.3±9.6</td>
<td>-13.8±13.7</td>
<td>-0.43</td>
<td>0.673</td>
<td>-14.9 to 9.9</td>
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</tbody>
</table>
Joint Moments: Peak extension (plantar-flexion) ankle moments were significantly (143%) higher in the FF strikers compared with the RF group (0.7±0.3 vs 1.7±0.3 Nm/kg respectively; p<0.001). In contrast, RF strikers peak knee extension moments were 22% higher than the FF striking group (4.5±0.6 vs 3.6±0.5 Nm/kg respectively; p=0.004). Similar to the finding reported by Kristianslund et al. (2012), peak knee valgus moments in the RF strike group (1.4±0.5 Nm/kg) were significantly elevated (64%) relative to the FF strikers (0.5±0.4 Nm/kg) (p=0.001), supporting previous recommendations of the adoption of a toelanding technique as one strategy to facilitate lower peak knee valgus moments. Joint Power: FF strike negative net peak ankle joint power (absorption) was 62% higher than the RF group (-15.3±4.4 vs -5.8±1.8 Watt/kg respectively; p<0.001). Conversely, negative net peak knee joint power was 53% greater among the RF group (-68.8±18.5 Watt/kg) when compared with the FF group (-32.0±7.5 Watt/kg) (p<0.001), a finding consistent with the results of similar studies examining foot strike kinematics and kinetics during straight-line running (Stearne et al., 2014; Kulmala et al., 2013).

Figure 1: Foot-strike posture during unplanned sidestepping A) Rear-foot strike and B) forefoot strike.

CONCLUSION: Foot-strike posture during unplanned-sidestepping is an important consideration for an athlete’s lower limb dynamics during unplanned sidestepping. Athletes with a habitual RF strike technique absorbed greater power through the knee joint, flexed more at the hip at IC which was accompanied by elevated peak valgus knee moments, measures contributing to an increased ACL injury risk in this group compared with athletes who adopt a FF strike posture.

REFERENCES:


Acknowledgement
We would like to thank Australian female hockey team for participation and Higher Education Commission, Ministry of Education, Thailand for funding this research.
The influence of digital filter type, amplitude normalisation method,
and co-contraction algorithm on clinically relevant surface
electromyography data during clinical movement assessments

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Article info
Article history:
Received 3 December 2015
Received in revised form 16 September 2016
Accepted 10 October 2016

Abstract
There is a large and growing body of surface electromyography (sEMG) research using laboratory-specific
signal processing procedures (i.e., digital filter type and amplitude normalisation protocols) and data
analysis methods (i.e., co-contraction algorithms) to acquire practically meaningful information from
these data. As a result, the ability to compare sEMG results between studies is often challenging.
The aim of this study was to determine the influence of digital filter type, amplitude normalisation method,
and co-contraction algorithm on the practical clinical interpretation of sEMG data. Sixteen female athletes were recruited. During data collection, sEMG data were recorded from nine lower limb muscles while completing a series of calibration and clinical movement assessments (running and sidestepping). Three analyses were conducted: (1) signal processing with two different digital filter types (Butterworth or critically damped), (2) three amplitude normalisation methods, and (3) three co-contraction ratio algorithms. Results showed the choice of digital filter did not influence the clinical interpretation of sEMG; however, choice of amplitude normalisation method and co-contraction algorithm did influence the clinical interpretation of the running and sidestepping task. Care is recommended when choosing amplitude normalisation method and co-contraction algorithms if researchers are interested in comparing sEMG data between studies.

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1. Introduction
Muscle activity is commonly recorded through the use of surface
electromyography (sEMG). It has been widely used in research and
clinical practice to assess the recruitment, coordination, and
relative activation of skeletal muscle during static, quasi-static,
and dynamic movements (Basmajian and De Luca, 1985; Winter,
2009). Before sEMG can be used to obtain meaningful
information about muscle recruitment and activation, the signal
is first filtered (Basmajian and De Luca, 1985; Winter, 2009) and
then normalised to a reference value (i.e., maximal or maximal
submaximal) (Kuo, 2006). The signal processing of sEMG data generally requires the removal of
direct current offsets, bandpass filtering (De Luca et al., 2010; Drake and Calaghan, 2009), full wave rectification (Merletti and Di Tomio, 1998; Stegeman and Hermens, 1999), and low-pass fil-
tering (Merletti and Di Tomio, 1999; Stegeman and Hermens, 1999) to generate a linear envelope that characterises muscle activity at the interface of the sEMG electrode. Normalisation of
sEMG linear envelopes against a maximal reference value allows
for intra-muscle comparisons (BaI and Scarr, 2011), and improves
the repeatability of within and between-subject comparisons (BaI
and Scarr, 2011; Burden, 2010). Normalised sEMG is also useful for
calculating metrics, such as co-contraction ratios of agonist and
antagonist muscle groups crossing a joint (Berier et al., 2003a; Heides et al., 2008; Hamstra-Wright et al., 2006) and mean total
muscle activation (Donnelly et al., 2015). Clinical decisions associ-
ated with musculoskeletal disease progression, and an individual’s
risk of injury can be made using these sEMG dependent variables
alongside relevant joint mechanics information (Sexton et al., 2003a; Donnelly et al., 2015; Heiden et al., 2009). Given that
a majority of signal processing is now performed by commercial
software packages, it is important that clinicians and researchers
have a basic understanding of the underlying mathematical fea-
tures that influence digital filter performance.
Digital filtering is performed twice during sEMG processing; band-pass filtering (i.e., high and low pass filter) to remove system noise and then low pass filtering to create a linear envelope (Merletti and Di Torino, 1999; Stegeman and Hermes, 1999). Underdamped Butterworth filters (Winter, 2009; Robertson and Dowling, 2003) are commonly used in the literature despite having a tendency to 'underdamp' or 'overshoot' high frequency signals (Kreifeldt, 1971; Robertson and Dowling, 2003). Alternatively, critically damped filters are a viable solution to mitigate the 'underdamp/overshoot' artefacts typically observed when using underdamped Butterworth digital filters for the signal processing of sEMG data (Robertson and Dowling, 2003). Interestingly, when used as high pass filters, both critically damped and underdamped Butterworth filters add artefact to high frequency signals in different ways (Murphy and Robertson, 1994). Currently, there are no recommendations from the International Society of Electrophysiology and Kinesiology (ISEK) (Merletti and Di Torino, 1999) or Surface Electromyography for the Non-invasive Assessment of Muscles (SENIAM) (Stegeman and Hermes, 1999) for the type of digital filter to be used for the signal processing of sEMG data. As a result, several different filter types have been used to process sEMG data (Gottlieb and Agarwal, 1970; Halbertsma and De Boer, 1981; Kreifeldt, 1971; Winter and Yack, 1987), which may all introduce unique, non-linear signal processing artefacts to the signal. Though many different filter types have been used for signal processing of sEMG data, there are only a small number of studies that have directly compared the effect of digital filter type and cut-off frequency on the characteristics of a linear enveloped sEMG signal (Hug et al., 2012; Kho, 1992; Skov et al., 1998). Nonetheless, the aforementioned studies neither compared the effect of using an underdamped Butterworth and critically damped filter to separately process sEMG data through the signal processing procedures, nor examined the downstream impact filter type may have on the clinical relevance of processed sEMG data. Research comparing the influence of digital filter type for the signal processing of electromyography data is necessary before data between studies with different signal processing procedures can be compared with confidence.

Amplitude normalisation of sEMG data generally utilise a set of maximal activation tasks and trials to generate reference sEMG templates for each muscle (Burden, 2010). The task and trial types used to produce maximal reference sEMG activation templates differ extensively between studies (Burden, 2010). Previous work has used maximum voluntary isometric contractions (Benoit et al., 2003; Burden, 2010), isokinetic dynamometry (Kold and Baltzopoulos, 1998), functional methods (Yang and Winter, 1984; Benoit et al., 2003; Ball and Scarr, 2011) dynamic calibration trials (Ball and Scarr, 2011; Dore et al., 2012; Ruffet and Hautier, 2008) or a combination of all these methods (Thurral, 2006). Currently, there are no recommendations for the choice of tasks and trials for sEMG normalisation within clinical movement assessments like running or sidestepping tasks. Though established as an important experimental procedure, the effect of different amplitude normalisation procedures on clinically relevant calculations like agonist/antagonist muscle co-contraction ratios and their mean total muscle activation are yet to be determined.

Following amplitude normalisation; co-contraction ratios can be calculated and used to estimate the relative contribution of agonist and antagonist muscle activation relative to external joint moments (Ford et al., 2008). This metric provides researchers with information on the relative mechanical efficiency of a movement (Ford et al., 2008) and joint stabilisation/support offered by muscles (Besi et al., 2003a; Donnelly et al., 2015). General co-contraction (Lloyd and Buchanan, 2001), directed co-contraction (Heiden et al., 2005), and co-activation (Hamstra-Wright et al., 2006) have all been used in the literature to make clinically meaningful interpretations of the efficiency of the neuromuscular system or joint support against external joint loads during dynamic tasks. As different algorithms and muscle groups have been used between studies; comparison of results are challenging (Ford et al., 2008). Hence, it is unknown if the clinical interpretations of these dependent variables are affected by the co-contraction ratio algorithm employed.

In this study, we assessed the impact of digital filter type, amplitude normalisation method, and co-contraction ratio algorithm on the clinical interpretation of sEMG data during a common clinical sidestepping movement assessment task. Sidestepping tasks are clinically relevant as half of all non-contact anterior cruciate ligament (ACL) injuries occur during this sporting task (Gochtane et al., 2007; Donnelly et al., 2012). Measures of agonist/antagonist muscle co-contraction and mean total muscle activation during the pre-contact phase of sidestepping gait have previously been used to assess motor planning, and throughout the weight acceptance phase to estimate muscle support when externally applied knee moments and risk of ACL injury is the greatest (Besi et al., 2003a; Donnelly et al., 2015). Therefore, the aims of this study were to determine if the choice of digital filter, amplitude normalisation method, and co-contraction algorithm influences the clinical relevance of sEMG data (i.e., co-contraction ratio and mean total muscle activation) during the pre-contact and weight acceptance phases of a common sidestepping clinical movement assessment.

2. Methods

Sixteen female athletes (22.2 ± 2.9 years, 167 ± 10 cm, 66.3 ± 6.7 kg) from the Australian National field hockey team participated in this study. Each participant read and signed consent forms approved by the Human Research Ethics Committee at the University of Western Australia (RAH/1/57131). Data for this study were collected as an addendum to a larger biomechanics study. Due to load based restrictions placed by the team physiotherapist, a sample of players (n = 4) were unable to perform the dynamic calibration tasks (described below). All participants were injury free for 12 months before data collection and were participating in normal team training and game play.

During the experimental session, participants performed three classes of movement tasks that we define as (i) isokinetic dynamometry, (ii) dynamic calibration, and (iii) functional movement. The experimental procedures are common and have been described in detail elsewhere (Besi et al., 2003a; Donnelly et al., 2012a,b; Weir et al., 2014). Within the functional movement tasks, participants performed planned straight line running, planned sidestepping, and unplanned sidestepping trials in a random order to mitigate learning effects. To mitigate fatigue effects, a minimum designated rest interval of 60 s (functional movement) and 120 s (isokinetic dynamometry and dynamic calibration) was enforced between trials.

The isokinetic dynamometry and dynamic calibration tasks were performed to elicit maximal muscle activations for normalisation of sEMG data. Participants completed isokinetic dynamometry trials on a Biodesix dynamometer (Biodesix Medical Systems Inc., Shirley, NY, USA). Four repetitions of 60°/s knee flexion-extension were performed each at 50%, 75% and 100% of the participant’s maximum voluntary perceived effort (Fig. 1a). Dynamic calibration trials included three maximal repetitions each of a counter movement jump (Fig. 1b), single leg squat (Fig. 1c), and single leg drop jump (Fig. 1d).

The functional movement trials included (at least) five trials each of a planned straight line running (Fig. 1e), planned sidestepping (Fig. 1f), and unplanned sidestepping (Fig. 1g) performed on a
20 x 15 m runway at 3 m/s. For planned sidestepping trials, the sidestep direction was displayed on a projector screen before the participant began advancing along the runway, whereas for unplanned sidestepping trials, the direction of sidestep was displayed when the participant was approximately 1.5 m from the force plate.

Marker trajectories and ground reaction forces (described below) were used to define two time ranges that were used for analysis of the unplanned sidestepping task. Pre-contact, which was defined as 50 ms before and up to foot contact, and weight acceptance, which was defined as the time between foot contact and the first trough of the vertical ground reaction force (Beier et al., 2003).

During the functional movement, a full-body marker set (Beier et al., 2003) was attached to the participant. Marker trajectories (250 Hz) and ground reaction forces (2000 Hz) were synchronously collected using a 12-camera Vicon MX motion capture system (Vicon, Oxford Metrics Ltd., UK) and an AMTI force plate (AMTI, Watertown, MA, USA). Marker trajectories and ground reaction forces were processed using Vicon Nexus 1.8 software.

Participants had sEMG data collected for nine leg muscles of their preferred limb across all tasks and trials during the experimental session. The sEMG electrode placement sites were prepared by shaving the skin, exfoliating with a rough pad, and then sterilizing with an alcohol swab. Two bipolar disc-shaped (10 mm diameter) disposable surface electrodes (Cleartrace EM Ag/AgCl, ConMed, Utica, NY, USA) with a centre to centre electrode distance of 30 mm (Winter et al., 1994) were placed over muscle bellies. The muscles of interest were: semimembranosus, short head of biceps femoris, vastus lateralis, vastus medialis, rectus femoris, gluteus maximus.
mus, glutus medius, medial gastrocnemius, and lateral gastrocnemius. Electrode placement was performed according to the methods published by Perotto and Delagi (2005). sEMG data was collected using a 16 channel telemetry system (Tektronic 2400 G2, Noraxon, Scottsdale, Arizona, USA) at 2000 Hz with a 16 bit A/D card (Power 1401, Cambridge Electronic Design, UK). The input impedance was >100 kΩ, common mode rejection ratio (CMRR) was >100 dB at 50 Hz and the amplifier gain was set at 100 (Merletti and Di Taranto, 1999).

The effect of filter type for sEMG processing, independent of amplitude normalisation method and choice of co-contraction algorithm was assessed. The sEMG data recorded for the nine muscles were processed separately using a 2nd order zero-lag underdamped Butterworth and 2nd order zero-lag critically damped digital filter (Fig. 2), using custom Matlab software (Mathworks Inc., Natick, MA, USA). Using the guidelines specified by SINIAM (Stegeman and Hermsen, 1999) and SEK (Merletti and Di Taranto, 1999), sEMG data were processed by removing the direct current offset, band pass filtering between 30 Hz (Sartoris et al., 2012; Reindl and Brown, 2004) and 400 Hz, rectifying the waveform, and then low-pass filter to 6 Hz. All trials, across all tasks, were pooled to find the peak sEMG reference values for each muscle. We normalised each muscle's sEMG in the resulting two sets of processed data by dividing each by the corresponding reference values. The normalised sets of sEMG data were used to compute participant-specific directed co-contraction ratios (described below) and mean total muscle activation during pre-contact and weight acceptance. We calculated total muscle activation using normalised sEMG for the glutus (gluteus maximus and medius), quadriceps (vastus lateralis, medialis and rectus femoris), hamstrings (semimembranous and biceps femoris), gastrocnemius (medial and lateral gastrocnemius), and seven muscles crossing the knee joint (IJM; semimembranous, biceps femoris, vastus lateralis, and medialis, rectus femoris, medial and lateral gastrocnemius). Directed co-contraction ratio and mean total muscle activation obtained using an underdamped Butterworth and critically damped filter was compared using paired sample t-test (parametric data) and Wilcoxon signed-rank test (non-parametric data) (α = 0.05). All statistical analysis was performed with SPSS (Version 22.0; SPSS, Chicago, IL, USA).

The effect of normalisation methods, independent of filtering and co-contraction method was also assessed. The sEMG data was processed using a 2nd order zero-lag underdamped Butterworth filter, as described above. The underdamped Butterworth processed sEMG data were amplitude normalised using three different normalisation methods (Fig. 2): functional movement tasks (Ball and Sour, 2011; Winter and Yack, 1997), mean peak values from planned straight line running trials (SLRs) (Boyer et al., 2003a; Donnelly et al., 2015) and the combination of all functional movement, dynamic calibration, and isokinetic dynamometry trials (Rudolph et al., 2006). The three sets of normalised sEMG data were used to compute participant-specific directed co-contraction ratios and mean total muscle activation during pre-contact and weight acceptance. Mean total muscle activation and directed co-contraction ratio obtained from the three amplitude normalisation methods were compared using one-way repeated measures ANOVA and Sidák post hoc analysis in SPSS (α = 0.05).

To assess the effect of co-contraction ratio algorithm, independent of filtering and normalisation methods, three different algorithms were applied to the same sEMG data (i.e., the same signal processing and amplitude normalisation method). The three muscle co-contraction ratio algorithms used were (1) directed co-contraction ratio as described by Reindl et al. (2009), (2) general co-contraction ratio as described by Lloyd and Buchanan (2001), and (3) the co-contraction ratio described by Hamastra-Wight et al. (2006). For each co-contraction method, muscles were grouped by their ability to generate moment about knee flexion/extension, varus/valgus, and internal/external rotation (see Supplementary S6 for details). Descriptive statistics were used (mean and standard deviation) to compare the co-contraction methods.

We could not perform statistical analyses as the three algorithms use different continuous scales. For instance, general co-contraction ratio ranges between 0 and 1; directed co-contraction ranges between −1 and 1, and co-activation method ranges from 0 to 6.

3. Results

For space considerations, only results associated with unplanned side-step trials are described below. Interested readers can find results for the planned straight-line run and planned side-step conditions in Supplementary materials (Appendix A).

The majority of participants were able to elicit peak muscle activation values within the experiment for gluteus maximus, gluteus medius, quadriceps (vastus lateralis, vastus medialis),
and gastrocnemius (medial gastrocnemius, lateral gastrocnemius) muscles from the dynamic calibration trials (Fig. 3). Most participants elicited peak muscle activation for the semimembranosus and biceps femoris muscles from the isokinetic dynamometry trials (Fig. 3). A small number of subjects were able to elicit peak muscle activations for gluteus, quadriceps (except vastus femoris), hamstrings, and gastrocnemius muscles from the functional movement trials (Fig. 3).

The effect of filter type for eSMG processing, independent of amplitude normalisation and co-contraction method is reported in Fig. 4. We observed that the choice of digital filter type did not influence the clinical relevance of directed co-contraction ratio and mean total muscle activation values assessed (Fig. 4, panel c and d). These results were consistent across both the phases and trials analysed.

The effect of amplitude normalisation methods, independent of filtering and co-contraction method is reported in Fig. 5. There were no significant differences in knee flexion/extension (FE), medial/lateral (ML), and semimembranosus/biceps femoris (SM/BF) directed co-contraction ratios between the normalisation methods assessed during the pre-contact and weight acceptance phase (Fig. 5, panel a and b). A significant main effect was observed for the mean total muscle activation estimates of the gluteus, quadriceps, hamstrings, gastrocnemius, and knee during the pre-contact and weight acceptance phase of unplanned sidestepping trials assessed (p < 0.01). Post-hoc analysis revealed that the combination method of normalisation produced lowest estimates of mean total muscle activation for all five muscle groups across both phases (Fig. 5, panel c and d).

During the pre-contact phase of unplanned side stepping trials, the functional method of amplitude normalisation produced significantly lower estimates of mean total muscle activation for the quadriceps muscle group when compared with those estimates obtained by using the SLM method (p = 0.007). During the weight acceptance phase of unplanned sidestep trials, the functional method of amplitude normalisation produced significantly lower estimates of mean total muscle activation for all muscle groups (p < 0.01) (refer to Fig. 5, panel a and d).

The effect of co-contraction methods, independent of filtering and amplitude normalisation method, is reported in Fig. 6. During the pre-contact phase of unplanned sidestepping trials, the following were the F/E co-contraction values obtained using directed co-contraction (0.60 ± 0.24), general co-contraction (0.37 ± 0.18), and co-activation method (0.36 ± 0.17) (Fig. 6a). The F/E co-contraction values obtained during the weight acceptance phase of unplanned sidestepping are directed co-contraction (−0.01 ± 0.28), general co-contraction (0.72 ± 0.14), and co-activation method (1.11 ± 0.41) (Fig. 6b).

4. Discussion

The aims of this study were to determine the influence of co-contraction method, amplitude normalisation method, and co-contraction algorithm on the clinical relevance of co-contraction ratios and total muscle activation estimates in the muscles controlling the knee joint during the clinical movement assessment of unplanned sidestepping. The results showed that the filter type did not influence the clinical interpretation of the data. However, both the amplitude normalisation method and the choice of co-contraction algorithm influenced the clinical relevance of processed eSMG data.

Results showed that the choice of digital filter type (2nd order zero-lag undamped Butterworth vs. 2nd order dual pass critically damped) for the signal processing of eSMG data did not affect the clinical interpretation of directed co-contraction and total muscle activation estimates during sidestepping or running. In an applied or clinical context, these results suggest that a researcher’s choice of digital filter type (2nd order zero-lag undamped Butterworth vs. 2nd order dual pass critically damped) is unlikely to have a practical or clinically meaningful impact on the interpretation of eSMG data. The practical interpretation of these data suggests that data from different digital filter types, but similar methodological procedures and signal processing/analysis methods can be compared with confidence. As directed co-contraction ratios and total muscle activation estimates are derived from time normalised waveforms and averaged between multiple trials of the same type (i.e., running or sidestepping), it is possible that small differences that can occur as a result of choice of digital filter type are severely attenuated through these data analysis procedures.

When attempting to apply a low-pass critically damped filter at 50 Hz to a eSMG signal collected at 2000 Hz, an interesting consistency between the recommended sampling rates for surface and fine-wire EMG and the ISEE/SENAM low-pass cut-off frequency recommendations was observed. Specifically, the ISEE guidelines

<table>
<thead>
<tr>
<th>Muscles</th>
<th>Participants (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gastrocnemius</td>
<td>20</td>
</tr>
<tr>
<td>Gluteus Medius</td>
<td>40</td>
</tr>
<tr>
<td>Vastus Medialis</td>
<td>60</td>
</tr>
<tr>
<td>Rectus Femoris</td>
<td>80</td>
</tr>
<tr>
<td>Vastus Lateralus</td>
<td>100</td>
</tr>
<tr>
<td>Medial Hamstrings</td>
<td>100</td>
</tr>
<tr>
<td>Lateral Hamstrings</td>
<td>100</td>
</tr>
<tr>
<td>Medial Gastrocnemius</td>
<td>100</td>
</tr>
<tr>
<td>Lateral Gastrocnemius</td>
<td>100</td>
</tr>
</tbody>
</table>

Study conducted using an integrated isokinetic dynamometry, dynamic calibration, functional tasks, and functional movement trials. Dynamometry trials were not used for gluteus and hamstrings groups maximal muscle activation only.

![Graph](image-url)
state that the surface and fine-wire EMG have upper bandwidths of 350 Hz and 750 Hz, respectively. The SNIAM guidelines for upper bandwidth surface and fine wire EMG are 500 Hz and 1000 Hz, respectively. To abide by the Nyquist theorem, the SNIAM correctly recommends that EMG data is sampled at, or greater than twice the highest frequency observed within the signal’s bandwidth, which is why the ISEK correctly recommend a sampling frequency of 2500 Hz or above. It should be noted that the corrected cut-off frequencies of a 4th order zero-lag critically damped low-pass filter applied at 500 Hz would be 1662 Hz (product of correction factor and cut-off frequency) (Robertson and Dowling, 2003) meaning a sample rate >3344 Hz is necessary if a researcher wishes to follow the SNIAM guidelines and low pass filter their sEMG signal at 500 Hz. If fine-wire EMG were measured, researchers would need to increase their sampling rate to 4996 Hz or above (ISEK recommendations are 2500 Hz or above) if they wished to low pass filter at 750 Hz (Merletti and Di Tomaso, 1998). However, when an underdamped zero-lag low pass Butterworth filter is used, the sample rate aligning with the correction factor required to low pass filter surface and fine wire EMG data at 500 or 750 Hz would be 1516 Hz and 2274 Hz respectively. This means it is possible to low pass filter a signal at 500 Hz or 750 Hz using current the ISEK recommended sample rates of 2500 Hz, which again is solely based on the Nyquist theorem. These unexpected findings show that ISEK/SNIAM signal processing guidelines should either explicitly state that an underdamped Butterworth filter should be used during the signal processing of surface and fine wire EMG data, or if the researcher chooses to use a digital filter other than an underdamped Butterworth, like a critically damped filter, the ISEK/SNIAM sampling rate recommendations have to be amended. Future research is recommended to determine if different digital filter order, digital filter type and/or cut-off frequency combinations influence excitation/activation variables like muscle onset-offset, peak amplitude, and integrated EMG. Different amplitude normalisation methods were shown to have an impact on the clinical interpretation of the directed co-contraction ratios and total muscle activation estimates obtained during unplanned sidestepping assessments. The differences in the clinical interpretation of the directed co-contraction ratios following different amplitude normalisation methods were apparent in some instances. For example, the combination and functional movement method of amplitude normalisation would have suggested there was maximal co-contraction between the flexors and extension during the weight acceptance phase of unplanned sidestepping whereas the SIBR amplitude normalisation method would have suggested the extensors were more active relative to the flexors. Similarly, the combination method of amplitude normalisation indicated the biceps femoris muscle was more active when compared with semimembranosus during the pre-contact and weight acceptance phase of sidestepping, whereas the other two methods for amplitude normalisation would have suggested the semimembranosus muscle was more active. We recommend that comparison of directed co-contraction ratio data between studies are conducted with consideration of the amplitude normal-
isation method used, as it is clear that the methodological procedures used to obtain maximal voluntary contractions can influence the co-contraction estimates of agonist and antagonist muscle groups.

Muscle activation was significantly affected by the choice of amplitude normalisation method used. Unsurprisingly, the combined normalisation method always provided peak sEMG reference values and, accordingly, the lowest calculated total muscle activation measurements during the unplanned sidestepping task. In the present study, each participant’s peak muscle activation was obtained from different combinations of isokinetic dynamometry, dynamic calibration, and functional movement trials. The isokinetic dynamometer trials were only used in the combination method, which consistently produced the highest muscle activation for the hamstrings. By using different types of trials to elicit a maximal muscle activation estimate or reference values, the probability a researcher will obtain the highest muscle activation value possible for each muscle is increased. This is the reason why the combination amplitude normalisation method provided significantly lower total muscle activations than both the functional and SIRm amplitude normalisation method. It is then appropriate, if the experimental conditions allow (i.e., clinical population, available experimental equipment, etc.) to have participants perform a variety of amplitude normalisation tasks to obtain peak muscle reference activations. This supports findings by Rudolph et al. (2000) that showed normalising sEMG signals with maximal voluntary isometric contractions alone does not give true maximal reference values and will most likely lead to muscle activation values exceeding 100% during clinically relevant trials.

Despite previous work discussing the benefits of multi-task combination normalisation methods, the SIRm method remains the preferred method for clinical tasks (Beier et al, 2003a; Donnelly et al., 2015). We showed that the SIRm amplitude normalisation method consistently produced the lowest peak reference activations; resulting in the highest mean total muscle activation values when compared to the other two methods. These results show that SIRm amplitude normalisation should be deemed the least preferred method for normalising muscle activation data during sidestepping and running clinical movement assessments. This is an important consideration for researchers comparing data using different amplitude normalisation methods as results from this investigation have shown that the choice of normalisation...
method can change the sign of directed co-contraction values, which can result in different clinical interpretations of muscle support when externally applied knee moments are elevated during dynamic sporting tasks like unplanned sidestepping. Future research is recommended to determine if an additional dynamic normalisation task (i.e., Nordic hamstring curls (Van der Horst et al., 2014)) focused on eliciting the maximal activation of the hamstrings, might be used in place of time and cost expensive isokinetic dynamometry normalisation protocols.

From the three co-contraction algorithms assessed in this manuscript, the clinical interpretation of a given antagonist muscle activation differed substantially when analysed within the pre-contact and weight acceptance phases of unplanned sidestepping tasks. Of the three co-contraction algorithms assessed, directed co-contraction ratios would be considered the most clinically relevant as these outputs contain information on both direction and scaled magnitude of this directionality (i.e., −1 to +1). For example, directed F/E co-contraction values would allow for an individual to observe the flexors muscles are more active than the extensor muscle groups during the pre-contact (e.g., +0.6 to +0.8) phase of unplanned sidestepping, and a greater level of co-contraction between these muscle groups during the weight acceptance phase (e.g., −0.1 to −0.1). By providing both direction and the scaled magnitude of direction, more practically relevant clinical information is provided when evaluating an individual’s muscle support strategies during the preparatory phases of a movement or when externally applied joint loads are elevated during sporting tasks like unplanned sidestepping and running.

The general co-contraction algorithm presented by Hamstra-Wright et al. (2006) (co-activation) provided information on directionality; however, the F/E co-activation values obtained were not scaled to a set range. For example, during the pre-contact and weight acceptance phases of unplanned sidestepping trials, F/E co-activation ratios ranged from 3.0–6.0 and 0.7 and 1.5 respectively, making it difficult for the researchers to clinically interpret co-contraction values beyond a particular range (i.e., >3). Unlike the directed co-contraction ratio method and general co-contraction ratio method, the co-activation method defined by Hamstra-Wright et al. (2006) does not have a well-defined scale to infer magnitude of directionality, which can range from 3.0–6.0 (pre-contact) and 0.7 and 1.5 (weight acceptance). This then means that the range is dependent on the task (i.e., running vs. sidestepping) and phase (i.e., the pre-contact and weight acceptance) of a movement being assessed.

A parallel application for sEMG estimates is within the field of neuro-musculoskeletal modelling. Processed and normalised sEMG data are commonly used to validate muscle activation estimates derived using static optimisation algorithms (Sterle et al., 2012), computed muscle control algorithms (Hammer et al., 2010), and it is also a critical input parameter for EMG informed/directed neuro-musculoskeletal simulations (Lloyd and Besier, 2003, Sartori et al., 2012, Pizzolato et al., 2015). Since EMG driven simulations rely heavily on accurate representations of a participant’s unique muscle activity during different movement tasks, it is crucial to understand that the choice of normalisation method might have large effects on predicted muscle force computations from these simulations. Indeed, Mastoan et al. (2015) found that model estimates of muscular force during walking gait vary as a function of whether normalisation was performed with functional or isokinetic dynamometry methods. EMG driven modelling also requires the additional signal processing to model the electromechanical delay between muscle excitation and force transmission through a musculoskeletal unit. This can be achieved by using a single pass digital filtering when processing the linear envelope (Lloyd and Besier, 2003).

The protocols for amplitude normalisation used in this study were for an elite level athletic participant cohort. For the clinical movement assessment of pathological populations, performing maximum effort dynamic calibration tasks like counter movement jumps may not be possible. In these scenarios, we recommend functional normalisation methods be adopted as these tasks were most suitable in identifying maximum muscle activity without the need for additional clinical trials (i.e., isokinetic dynamometry, manual muscle testing). If a wide variety of dynamic calibration tasks are performed by participants for the purpose of eliciting maximal muscle activation values; we recommend that research include a minimum rest interval of 60–120 s in order to diminish potential effects of fatigue.
S. Conclusion

The choice of Butterworth or critically damped digital filters for the signal processing of sEMG data does not influence the clinical relevance of total muscle activation and directed co-contraction ratio variables assessed during running and sit-desk stepping clinical movement assessments. The choice of amplitude normalization method/procedure may result in different interpretations of directed co-contraction during clinical movement assessments. The choice of amplitude normalization method has a strong and significant influence on total muscle activation during running and sit-desk stepping clinical movement assessments. The choice of co-contraction algorithm will also influence an individual’s ability to obtain clinically meaningful information from sEMG data during clinical movement assessments. These results support a rationale for sEMG signal processing guidelines like those published by the ISSEK (Merletti and Di Toro, 1999) and SENIAM (Stegeman and Hermens, 1999) to consider making recommendations on amplitude normalization methods/procedures and co-contraction algorithms for the analysis of sEMG data in clinical settings/research environments.

Conflict of Interest

The authors declare that they have no conflict of interest.

Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version, at http://dx.doi.org/10.1016/j.jelekin.2016.10.001.

References

Burdon, A. 2010. How should we normalise electromyography data from healthy participants? What have we learned from over 25 years of research? J. Electromyogr. Kinesiol. 20 (6), 1023–1035.
Daniel Despuckash has completed Master's degree in the field of exercise science (Biomechanics) at the University of Western Australia in 2015. Prior to his postgraduate study, he completed his undergraduate study in the field of Biomechanics at SATTRA University, India. His research interests include the use of surface electromyography to study muscle function in human locomotion.

Dr. Jacqueline Warun is an Associate Professor at the University of Western Australia. She is interested in obtaining a fundamental understanding of human motion with a specific interest in the technologies and methodologies used to record, measure and report it. From an application perspective, she is interested in research that seeks to understand the mechanism behind injury and disease in sporting and clinical domains.

Gillian Weir is a PhD candidate in Biomechanics at the University of Western Australia. She has also completed an honours degree in Sport Science, Exercise and Health at the University of Western Australia in 2018. Her research interests lie within movement optimization strategies, particularly to reduce injury and improve performance in sport.

Dr. Donnelly is a Canadian researcher working as an Assistant Professor at the University of Western Australia. He holds a Bachelor of Kinesiology degree from McMaster University, a Master of Science degree from the University of Waterloo and a Doctorate of Philosophy in Biomechanics from the University of Western Australia. Dr. Donnelly uses musculoskeletal modelling and simulation to inform best practice injury prevention, disease prediction, and subject-specific movement prescription(s). With the help of his growing research team, which includes 26 honours students, a MSc. Student and 14 PhD students, Dr. Donnelly’s overarching research goal is to understand the mechanical etiology of musculoskeletal injury and disease. It is with this empirical information Dr. Donnelly argues, we can help inform best practice injury and disease management among sporting and clinical populations.

James Durne is a Research Associate for the National Centre for Simulation in Rehabilitation Research (NCSRR) at Stanford University. He supports the efforts of the NCSRR by providing technical and research aid for users of Osprey, a musculoskeletal simulation software framework. His research interests include the development and application of computational modeling to aid the identification and treatment of movement pathology.
Saving Gold Medal Knees  
Written by Mr Peter McClelland  
Wednesday, 01 October 2014

The Hockeyroos’ path to their next gold medal may seem like a straight line. But for the players on the field there are rapid and frequent changes of direction with complex and potentially adverse bio-mechanical load patterns leading to career-threatening anterior cruciate ligament (ACL) injuries.

The combination of effective surgery and a sophisticated training program helped one Hockeyroo make a speedy return to the Astro-Turf.

The 23-year-old forward Kellie White has been capped on 89 occasions but there have been times when her future at an elite level was under a cloud.

“From the age of 16 I had a few injuries that took me out of competitive hockey. They were mainly ankle issues but in 2010 I began having more serious knee problems. I was playing in New Zealand, sidestepped quickly and partially tore ligaments in my left knee. I played on and carried the injury for another two years but in 2012, just before the London Olympics, I ruptured my left ACL.”

“It was a pretty devastating time and a hard slog during the recovery period. The rehab sessions required every movement to be exact and consciously monitored. I had to tick all the boxes to have any hope of career longevity.”

**LARS benefits long-term**

As Kellie points out, a skilled orthopaedic surgeon is an integral part of the package in getting back out on the field.

“Greg Witherow has been fantastic for me. He suggested the LARS procedure for my particular injury because, in his opinion, other treatment options might well prove to be a ticking time-bomb. Greg felt my best option was a hamstring or patella tendon graft. I ruptured my knee on the 6th February, 2012, and I was in surgery three days later.”
A new training program devised by sports scientists at UWA and specifically linked with the Hockeyroos is proving to be successful.

“I’ve been working with Gillian Weir and it is producing great results. I started about 12 months after the ACL rupture when I was just beginning to come back into competition. I lacked confidence in my knee’s ability to cope in those high-pressure situations.”

“There’s been a massive improvement in my core stability and gluteal strength. My knee is as strong as it’s ever going to be and I’m much more confident running on to the field.”

From left: Mr David Edmonds (UWA Masters student), Ms Gillian Weir (PhD Candidate) and Assist/Prof Cyril J Donnelly with a wired up Hockeyroo, Anna Flanagan, at the UWA School of Sport Science, Exercise and Health.

ACL ruptures prompt action
PhD candidate Gillian Weir and her fellow researchers at UWA’s School of Sport Science, Exercise and Health, building on 15 years of research into lower-limb injury prevention, began their association with the Hockeyroo squad and team doctor Carmel Goodman in early 2013.

Five members of the team suffered ACL injuries in one season, a much higher rate compared with similar sports such as soccer.

“Hockey at the top level is played at a very fast pace. It’s a non-contact sport, in fact around 60% of ACL injuries fall within that category, but there’s a lot of side-stepping and cutting away from opponents. The knee is a highly complex joint with a lot of different load patterns occurring at the same time.”

“In a squad of 30 players, five serious injuries is incredible! A more typical rate would be 1.33/team in a season so these are nightmare figures but you do need to build in the gender factor. Females are almost six times more likely to rupture an ACL because the male body, at a similar stage of physical development, is in general better able to handle this type of stress load.”

Competition at Olympic level is intense so it’s vital that elite athletes have access to sophisticated strength and training programs.
**Controlling movement**

“The research we’re doing focuses on a player’s directional changes during competition.

We delved into the literature, looked at the probable causes of injury and found they were linked with the degree of control in the upper body and hip areas. We’ve had some positive results using different modalities that include balance, plyometric and resistance exercises targeting the hip and trunk areas.”

“Following our hip and trunk focused training intervention, gluteal activation has increased by 30% which is vital for neuromuscular control and the forces exerted through the knee have been minimised. Essentially, we’re attempting to reduce the loads in the knee and transfer them to the hip.”

“We’ve designed a program based around body-weight exercises so expensive equipment isn’t required. Another researcher is looking at injury minimisations at an amateur level and it will be designed for delivery via an online platform.”

“As far as GPs are concerned it’s important they’re aware of the causal factors linked with the upper body and hip. Appropriate exercises and rehabilitation after an ACL injury is important but if it’s recurrent there may well be lingering biomechanical patterns that need to be addressed.”

**Facts**

- *Australia has the highest rates of ACL injury in the world.*
- *Most occur during a non-contact change of direction or unstable landing.*
- *AFL 2013 Season: 23 knee reconstructions and ACL injury rate 0.9/club.*
Sport scientists work with Hockeyroos to prevent knee injuries

Friday, 15 August 2014

A new training program devised by researchers at The University of Western Australia has significantly reduced the risk of knee injuries among the Australian Commonwealth Games gold medal-winning women’s hockey team, the Hockeyroos.

Researchers Assistant Professor Cyril Donnelly, Associate Professor Jacqueline Alderson, Emeritus Professor Bruce Elliott and Gillian Weir, from UWA’s School of Sport Science, Exercise and Health, began working with the 30-member Hockeyroos squad in early 2013 after five athletes suffered anterior cruciate ligament (ACL) injuries in one season.

Ms Weir, a PhD candidate, said the rate of ACL injury among the Hockeyroos was high compared to other team sports such as soccer, which reported 1.12 such injuries per team each year. The AFL’s 2013 injury report revealed there were 23 knee reconstructions performed on AFL players last year following serious knee injury and the rate of ACL injury was 0.9 injuries per club.

“Australia currently has the highest ACL rates in the world, with the majority occurring during non-contact change of direction or landing sporting tasks, which means that these injuries can be prevented,” she said.

Ms Weir said ACL injury risk and the biomechanical factors that contributed to this risk were influenced by an athlete’s technique during dynamic change of direction sporting movements.

“Hip and trunk neuromuscular training can be used to improve the dynamic control of the trunk and hip as well as support the knee from external loading, subsequently reducing ACL injury risk during sporting movements,” she said.

With great support from head coach Adam Commens and high performance director Trish Heberle, and in collaboration with medical and coaching staff Kate Starre (Strength and Conditioning) and Jen Cooke (Physiotherapist) from Hockey Australia and the Australian Institute of Sport, the UWA researchers devised a nine-week training program for the Hockeyroos to reduce their risk of ACL injury, with athletes tested before and after the training program.

“We tested 16 athletes at the sports biomechanics lab at UWA where we measured muscle activation, joint angles and forces during a number of change of direction running and jumping tasks,” Ms Weir said.

“The intervention was successful in modifying the biomechanical risk factors associated with ACL injury. Following training we found a 30 per cent increase in gluteal muscle activation and a 10 per cent increase in the forces at the hip, which were transferred away from the knee - all desirable in reducing risk of injury.”

Four of the 16 who were tested had above average loading at the knee before testing, which was then dramatically reduced after the training. Ms Weir said there had not been a single non-contact ACL injury within the team since they had taken part in the training program, as part of their regular pre and in-season training. They were tested in Liverpool after their gold medal performance at the Glasgow Commonwealth Games.

Assistant Professor Donnelly received a UWA Research Collaboration grant with Mark Robinson of Liverpool John Moores University and Scott Delp of Stanford University to enable him to develop the project and create an international biomechanical database.
APPENDIX D - EXTENDED METHODS

D.1 INTRODUCTION

The following methods describe those used within biomechanical analysis of unplanned sidestepping utilised in Study’s One, Two and Three. The training intervention prescribed in Study Two and Study Three is presented in section D.6. Pilot/preliminary methods and results specific to Study Three are presented in section D.7.

D.2 LABORATORY SETUP

The laboratory setup included two infrared timing gates, a force plate, a projection screen and two cones (Figure D.1). The first timing gate was used as a trigger to initiate the stimulus in the unplanned sidestepping task, and in conjunction with the second timing gate to be used to measure approach velocity. If velocity is outside of the predetermined velocity threshold of 3.5 – 4.5 ms-1, the participant was required to repeat the trial. Participants were asked to run through the two timing gates before performing a sidestep or crossover cut manoeuvre over the force plate (marked x), in relation to the arrow projected on the screen during unplanned sidestepping.

The cones were positioned at a 45 degree angle from the centre of the force plate and used as visual markers for the participant to direct their sidestep. The participant was required to plant and push off on their self-selected preferred leg. Force plate ground reaction force data was used in conjunction with a customised full body kinematic model \(^1\)\(^2\) to calculate peak knee moments via inverse dynamics in Vicon bodybuilder (Vicon Peak, Oxford Metrics Ltd., UK).
D.2.2 Calibration

D.2.2.1 Camera Calibration

In accordance with the standard calibration procedures of Vicon Motion Systems Limited, dynamic calibration of the Vicon® T-series motion analysis system (model: T40S cameras) was performed using a Vicon® MX-wand® to calculate the relative positions and orientations of the cameras. The dynamic calibration was completed when the image error residuals from each camera were lower than 0.30mm.

A still frame of the 5-marker Vicon® MX-wand® placed at the top right hand corner of the 1.2m x 1.2m AMTI (Advanced Mechanical Technology Inc., Watertown, MA) force plate is recorded to calculate the laboratory global reference, which is the laboratory origin of the motion system.
D.2.2.2 PARTICIPANT PREPARATION AND CALIBRATION

According to a customised kinematic full body model (excluding upper limbs), a total of 40 retro-reflective markers (14mm in diameter), in the form of individual markers and marker clusters were affixed onto the participants’ skin to represent the underlying body landmarks and segments. Marker cluster sets were arbitrarily placed on the segments to establish the technical coordinate systems (TCS) of the respective segments. Participant-specific calibration trials were performed with participants assuming the anatomical position (Figure D.2). Full list of retro-reflective markers and their positions are listed in Table D.1.

Figure D.2. Participant in anatomical position with the customized full-body marker set.
<table>
<thead>
<tr>
<th>Segment</th>
<th>Markers</th>
<th>Definitions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Head</td>
<td>LBHD</td>
<td>Left back head</td>
</tr>
<tr>
<td></td>
<td>LFHD</td>
<td>Left front head</td>
</tr>
<tr>
<td></td>
<td>RBHD</td>
<td>Right back head</td>
</tr>
<tr>
<td></td>
<td>RFHD</td>
<td>Right front head</td>
</tr>
<tr>
<td>Trunk</td>
<td>C7</td>
<td>Spinous process of the 7th cervical vertebrae</td>
</tr>
<tr>
<td></td>
<td>T10</td>
<td>Spinous process of the 10th thoracic vertebrae</td>
</tr>
<tr>
<td></td>
<td>CLAV</td>
<td>Clavicle</td>
</tr>
<tr>
<td></td>
<td>STRN</td>
<td>Sternum</td>
</tr>
<tr>
<td>Shoulders</td>
<td>LACR</td>
<td>Left acromion process</td>
</tr>
<tr>
<td></td>
<td>LASH</td>
<td>Left anterior shoulder</td>
</tr>
<tr>
<td></td>
<td>LPSH</td>
<td>Left posterior shoulder</td>
</tr>
<tr>
<td></td>
<td>RACR</td>
<td>Right acromion process</td>
</tr>
<tr>
<td></td>
<td>RASH</td>
<td>Right anterior shoulder</td>
</tr>
<tr>
<td></td>
<td>RPSH</td>
<td>Right posterior shoulder</td>
</tr>
<tr>
<td>Pelvis</td>
<td>LASI</td>
<td>Left anterior superior iliac spine</td>
</tr>
<tr>
<td></td>
<td>LPSI</td>
<td>Left posterior superior iliac spine</td>
</tr>
<tr>
<td></td>
<td>RASI</td>
<td>Right anterior superior iliac spine</td>
</tr>
<tr>
<td></td>
<td>RPSI</td>
<td>Right posterior superior iliac spine</td>
</tr>
<tr>
<td>Thigh</td>
<td>LTH1</td>
<td>Left thigh (superior)</td>
</tr>
<tr>
<td></td>
<td>LTH2</td>
<td>Left thigh (middle)</td>
</tr>
<tr>
<td></td>
<td>LTH3</td>
<td>Left thigh (inferior)</td>
</tr>
<tr>
<td></td>
<td>RTH1</td>
<td>Right thigh (superior)</td>
</tr>
<tr>
<td></td>
<td>RTH2</td>
<td>Right thigh (middle)</td>
</tr>
<tr>
<td></td>
<td>RTH3</td>
<td>Right thigh (inferior)</td>
</tr>
<tr>
<td>Shank</td>
<td>LTB1</td>
<td>Left tibia (superior)</td>
</tr>
<tr>
<td></td>
<td>LTB2</td>
<td>Left tibia (middle)</td>
</tr>
<tr>
<td></td>
<td>LTB3</td>
<td>Left tibia (inferior)</td>
</tr>
<tr>
<td></td>
<td>RTB1</td>
<td>Right tibia (superior)</td>
</tr>
<tr>
<td></td>
<td>RTB2</td>
<td>Right tibia (middle)</td>
</tr>
<tr>
<td></td>
<td>RTB3</td>
<td>Right tibia (inferior)</td>
</tr>
<tr>
<td></td>
<td>LLMAL</td>
<td>Left lateral malleolus</td>
</tr>
<tr>
<td></td>
<td>LMMAL</td>
<td>Left medial malleolus</td>
</tr>
<tr>
<td></td>
<td>RLMAL</td>
<td>Right lateral malleolus</td>
</tr>
<tr>
<td></td>
<td>RMMAL</td>
<td>Right medial malleolus</td>
</tr>
<tr>
<td>Feet</td>
<td>LCAL</td>
<td>Left calcaneus</td>
</tr>
<tr>
<td></td>
<td>LMT1</td>
<td>Left head of 1st metatarsal</td>
</tr>
<tr>
<td></td>
<td>LMT5</td>
<td>Left head of 5th metatarsal</td>
</tr>
<tr>
<td></td>
<td>RCAL</td>
<td>Right calcaneus</td>
</tr>
<tr>
<td></td>
<td>RMT1</td>
<td>Right head of 1st metatarsal</td>
</tr>
<tr>
<td></td>
<td>RMT5</td>
<td>Right head of 5th metatarsal</td>
</tr>
</tbody>
</table>
Calibrated anatomical system technique (CAST) was adopted using a customised 6-marker pointer device to establish anatomical landmarks on the femur, hence minimising skin movement artefacts in the static trials. The tip of the pointer was held against the medial and lateral epicondyles of both the right and left femurs. Anatomical coordinate systems of the femurs were held relative to the TCS of the respective thigh marker clusters. List of virtual markers are shown in Table D.2.

**Table D.2 Virtual Markers**

<table>
<thead>
<tr>
<th>Segment</th>
<th>Virtual Markers</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thigh</td>
<td>LLFC</td>
<td>Left lateral femoral condyle</td>
</tr>
<tr>
<td></td>
<td>LMFC</td>
<td>Left medial femoral condyle</td>
</tr>
<tr>
<td></td>
<td>RMFC</td>
<td>Right lateral femoral condyle</td>
</tr>
<tr>
<td></td>
<td>RLFC</td>
<td>Right medial femoral condyle</td>
</tr>
</tbody>
</table>

To determine alignment and anatomical coordinate systems of the feet, a customised calibration rig and an inclinometer were used. Participants stood in a comfortable position with the heel against the back of the rig. Feet abduction/addiction were established by aligning the arms of the goniometers between the third and fourth metatarsals. Feet eversion/inversion were established by recording the angle of the relative calcanei orientations with respect to the lower limbs by aligning the inclinometer with the Achilles tendon above the calcanei. All static and pointer calibration trials were captured for approximately five seconds.

Several functional dynamic movement trails were conducted to determine hip and knee joint centres. Firstly, the hip swinger trials were conducted to determine the origin of the ball and socket joint between the acetabulum and the greater trochanter. Participants performed a series of single leg hip movements, namely hip flexion to 60°, hip abduction to 30°, hip extension to 60° and circumduction consecutively without bearing weight on the moving leg. Next, body weight squats with 60° knee flexion, were conducted to determine the functional axis of the knee joint (Figure D.3).
D.3 SIDESTEPPING PROTOCOL

Following familiarisation, participants were asked to perform a series of randomised movement tasks; planned and unplanned sidestepping and straight line running. Movement tasks were performed in random order to account for fatigue. Participants were to run through two pairs of timing gates towards the force plate. Infrared timing gates were used to monitor the approach running speed, which was delimited to 3.5 – 4.5 ms⁻¹ (12.6 - 14.4kph).

In planned movement tasks, participants were to follow the arrow displayed on the projector, indicating to complete either a sidestep to the participant’s non dominant side, crossover to participant’s dominant side or a straight line run. In unplanned movement tasks, the arrow is triggered to display only when the
participant was approximately 1.5m prior to the force plate, a time coinciding with contralateral limb toe-off. Sixty second intervals were given between each trial to reduce the effects of fatigue.

Trials were only deemed successful when participant’s dominant leg contacted the force plate and when the angles of sidestep were 45±5°. A total 12 successful trials were recorded (four planned sidestep, four unplanned sidestep, four planned straight line runs) for each session.

D.4 DATA PROCESSING

The data processing pipeline for all dynamic trials comprised of 6 steps: (1) labelling of markers and trajectory filling, (2) identification of events, (3) residual analysis and filtering, (4) modelling and (5) exporting discrete and continuous data.

D.4.1 LABELLING OF MARKERS AND TRAJECTORY FILLINGS

All dynamic trials were visually inspected to ensure that all markers were present in the required frames in each trial. Markers were labelled according to a customised kinematic model (Table X and XX). Any gaps and errors present in the trajectories were corrected using an in-built cubic spline fill function within Vicon® Nexus® (Version 1.8.5).

D.4.2 IDENTIFICATION OF EVENTS

Identification of events required for modelling and exporting data, was conducted within Vicon® Nexus® (Version 1.8.5).

In the functional trials, three events were identified:

1. First frame
2. Start of functional movement
3. End of functional movement

In dynamic trials, five events were identified:

1. Foot off of non-dominant foot – Trajectory of the 1st metatarsal in the z plane
2. Foot strike of dominant foot – Ground reaction force (vGRF) departs from zero
3. End of weight acceptance phase – 30% of stance phase
4. Foot off of dominant foot – Ground reaction force (vGRF) returns to zero
5. Foot strike of non-dominant foot – Trajectory of the calcaneus in the vertical plane

D.4.3 RESIDUAL ANALYSIS AND FILTERING

A residual analysis was conducted on the trajectory (z coordinate) of the dominant leg’s calcaneus during the weight acceptance phase of an unplanned sidestep. Using Microsoft® Excel® (Version 14.4.5), a Butterworth low-pass filter was applied to the raw data with cut-off frequencies 1-30Hz, at a sampling rate of 250Hz. Root mean squared values were calculated and graphed for each cut-off frequencies. An optimal cut-off frequency of 14Hz was determined. The filtering process was performed using a 4th order, zero-lag Butterworth low-pass filter embedded within the Vicon® Nexus® pipeline.

D.4.4 MODELLING

Using the in-built PECs Plug-In feature in Vicon® Nexus® and MATLAB® (Version R2010a, The MathWorks, Inc., Natick, Massachusetts, United States) functional hip and knee joint centres were defined. UWA lower body static-modelling codes were used to process the knee-pointer trials whereby the virtual medial and lateral femoral epicondyles markers were established to facilitate the calculation of the left and right knee joint centres. Following, the UWA upper and lower body static codes were used to model the static rig trial (anatomical position) to establish participant-specific anatomical coordinate systems (relative to the TCSs). All dynamic gait trails were then modelled using the UWA lower and upper body dynamic code with the embedded Vicon® Nexus® pipeline.

D.4.5 EXPORTING DISCRETE AND CONTINUOUS DATA

Discrete and Continuous data were exported into Microsoft® Excel® for all kinetic and kinematic variables using a MATLAB® (Version R2010a, The MathWorks, Inc., Natick, Massachusetts, United States) customised temporal normalised graphical user interface (TempNormGUI).

D.5 STATISTICAL ANALYSIS

D.5.1 POWER ANALYSIS
Using partial eta squared generated by SPSS Statistics (SPSS Inc, IBM Headquarters, Chicago, Illinois) of knee valgus moments of the responder group during unplanned sidestepping, post hoc power analyses were conducted with the program G*Power 4 to compute achieved power. In the intensive training phase, with sample size of five, the effect size of this particular contrast was 1.98 (i.e., a very large effect, according to Cohen, 1988). The power to detect an effect of this size was determined to be 0.99. In maintenance phase, with sample size of two, the effect size was 0.01 and the power was determined to be 0.05.

**D.5.2 Effect Size Calculation**

Effect sizes were calculated using Hedges’ g (Hedges, 1981), formulae shown in Equation D.1 and D.2.

\[
SD_{pooled}^* = \sqrt{\frac{(n_1 - 1)SD_1^2 + (n_2 - 1)SD_2^2}{n_1 + n_2 - 2}} \quad (D.1)
\]

\[
Hedges'g = \frac{M_1 - M_2}{SD_{pooled}^*} \quad (D.2)
\]

The magnitude of Hedges’ g may be interpreted using Cohen’s convention; an effect size of \(0.2 \leq g < 0.5\) will be considered a "small" effect, \(0.5 \leq g < 0.8\) a "medium" effect and \(0.8 \leq g\), a "large" effect.

**D.5.3 Linear Regression**

Linear regression assesses the linear relationship between two continuous variables to predict the value of a dependant variable based on the value of an independent variable. More specifically, it will let you:

determine how much of the variation in the dependent variable is explained by the independent variable,
understand the direction and magnitude of any relationship and predict values of the dependent variables based on different values of the independent variable.
A simple model is written as:

\[ y = \beta_0 + \beta_1 x + \beta_2 x^2 + \epsilon \]  

Backward elimination was selected for this analysis which involves starting with all candidate variables, testing the deletion of each variable using a chosen model comparison criterion, deleting the variable (if any) that improves the model the most by being deleted, and repeating this process until no further improvement is possible. In this case, removal was performed by eliminating the predictor with the highest p value greater than \( \alpha_{\text{crit}} \).

Fixed and random factors may also be used within these kinds of models to test any interactions. In Chapter 5 of this thesis, fixed factors entered into the model were kinematic independent variables and athlete level (junior and senior). Participant ID was entered as a random factor to account for the variance within an individual's trials.

This model is written as:

\[ y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_{11} x_1^2 + \beta_{22} x_2^2 + \beta_{12} x_1 x_2 \]  

Where

- \( y \) = prediction
- \( B \) = intercept
- \( X_1 \) = independent variable
- \( X_2 \) = athlete level
- \( X_1 X_2 \) = independent variable*athlete level

In the case of this interaction, \( x_1 \) would not be removed unless \( x_1 x_2 \) had been removed.
### D.6 Training Intervention

**Table D.3.** Prescribed training intervention. Initial training is broken up into four stages, each with an individual goal in progressing intensity; *Stage 1:* Master basic techniques through unilateral tasks; *Stage 2:* Integration of additional component or direction to task to decrease stability; *Stage 3:* Introduction of secondary perturbation; *Stage 4:* Increase explosiveness of multidirectional tasks and have the ability to respond to quick external perturbations; *Stage 5:* Maintain responses and techniques to rapid external perturbations.

<table>
<thead>
<tr>
<th>Modality</th>
<th>Exercise</th>
<th>Initial (Stage 1 Wk 1-2)</th>
<th>Stage 2 (Wk 3-4)</th>
<th>Stage 3 (Wk 5-6)</th>
<th>Stage 4 (Wk 7-8)</th>
<th>Stage 5 (Wk 9-25)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Balance</td>
<td>Wall sit (double and single leg)</td>
<td></td>
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<tr>
<td></td>
<td>Reverse cross over lunge</td>
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<td></td>
<td>Single leg stance with</td>
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</tr>
<tr>
<td></td>
<td>i. Knee and hip flexion</td>
<td></td>
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<tr>
<td></td>
<td>ii. Knee flexion and hip abduction</td>
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<td></td>
<td>iii. Hip abduction</td>
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<td></td>
<td>Single leg deadlift;</td>
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<tr>
<td></td>
<td>i. With arm raise and hop</td>
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<td></td>
<td>Single leg squat</td>
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<td></td>
<td>Single leg overhead ball toss</td>
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<td></td>
<td>45, 60 &amp; 180 degree jumps</td>
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<tr>
<td></td>
<td>i. Double Leg</td>
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<td>ii. Single leg</td>
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<td></td>
<td>Single leg lateral ball throw</td>
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<tr>
<td>Plyometric</td>
<td>Karaoke</td>
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<td>Lateral Shuffle</td>
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<td>Skiiers</td>
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<td>Skaters</td>
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<td>Star Jumps</td>
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<td>Box Jumps</td>
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<td>i. Double Leg</td>
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<td>ii. Single Leg</td>
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<td>4 way hop</td>
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<td>Split lunge jumps</td>
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<td>Heisman Holds</td>
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<td>Bounding</td>
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<tr>
<td></td>
<td>i. Double Leg</td>
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<td>ii. Single Leg</td>
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<td></td>
<td>Single Leg Ball Slams</td>
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<td></td>
<td>Tuck Jumps</td>
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<td>i. Double Leg</td>
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<td>ii. Single leg</td>
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<td>Squat Jumps</td>
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<td>Burpees</td>
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<td></td>
<td>Mountain Climbers</td>
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<td></td>
<td>Step-up and Jump</td>
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<td></td>
<td>Split jump with 180 turn</td>
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<td></td>
<td>Lateral Box Jumps</td>
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<tr>
<td></td>
<td>Pike Jump</td>
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<tr>
<td>Resistance</td>
<td>Bird Dog</td>
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</tbody>
</table>

219
<table>
<thead>
<tr>
<th>Modality</th>
<th>Exercise</th>
<th>Initial</th>
<th>Maintenance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Stage 1 (Wk 1-2)</td>
<td>Stage 2 (Wk 3-4)</td>
</tr>
<tr>
<td></td>
<td>Plank (prone and lateral)²,³,⁴</td>
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</tr>
<tr>
<td></td>
<td>Double Leg Raise²</td>
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<tr>
<td></td>
<td>Core rotators²</td>
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</tr>
<tr>
<td></td>
<td>Walkouts²</td>
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<tr>
<td></td>
<td>Banana Hold²</td>
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<tr>
<td></td>
<td>Kettle Bell Swings²,³,⁴</td>
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<tr>
<td></td>
<td>X – ups²</td>
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<td></td>
<td>V – sits²</td>
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<tr>
<td></td>
<td>Bicycles²</td>
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<tr>
<td></td>
<td>Sit up with twist²</td>
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<tr>
<td></td>
<td>Clams⁴</td>
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<tr>
<td></td>
<td>Sitting Tucks²</td>
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<tr>
<td></td>
<td>Squat hold²,³,⁴</td>
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<tr>
<td></td>
<td>Double leg raise with partner</td>
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<td></td>
<td>push down²</td>
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<tr>
<td></td>
<td>Lateral Squat²,³,⁴</td>
<td></td>
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</tr>
</tbody>
</table>

¹Knee Flexion Dynamics | ²Dynamic Trunk Control | ³Gastrocnemius muscle strength | ⁴Hip external rotator strength
Table D.4. Delivered training intervention. Each session was written and delivered by team strength and conditioning coaches during gym sessions or as a warm up. Training modality is written in bold at the top of each session where B=Balance, R=Resistance, P=Plyometric and Y=Yoga. Technique feedback was delivered using internal and external cueing from the strength and conditioning coach.

<table>
<thead>
<tr>
<th>Week</th>
<th>Session 1 - Gym</th>
<th>Session 2 – Warm Up</th>
<th>Session 3 – Warm Up</th>
<th>Session 4 - Gym</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 &amp; 2</td>
<td><strong>Modality: B, R, P</strong>&lt;br&gt;3 rounds of 30sec&lt;br&gt;Bird dogs&lt;br&gt;Walk and hug&lt;br&gt;Wall sit DL R/L&lt;br&gt;Wall sit SL&lt;br&gt;Plank&lt;br&gt;KB&lt;br&gt;Double leg raise&lt;br&gt;Karaoke&lt;br&gt;Lateral shuffles (side squats)</td>
<td>P, R, B&lt;br&gt;4 rounds 16 yards&lt;br&gt;Marching (40 on spot)&lt;br&gt;Walking knee/hip flexion&lt;br&gt;Karaoke&lt;br&gt;8 min AMRAP&lt;br&gt;40 Skiers (Karaoke)&lt;br&gt;40 Skaters (Lat shuffle)&lt;br&gt;40 Star jumps (SLDL/Squat)&lt;br&gt;20 Core rotators&lt;br&gt;10 Walkouts&lt;br&gt;RL extra mods&lt;br&gt;Plank&lt;br&gt;Side plank&lt;br&gt;SLDL&lt;br&gt;Core rotators</td>
<td>P, B, R&lt;br&gt;4 rounds 30sec&lt;br&gt;Jog on spot&lt;br&gt;Walking knee/hip flexion&lt;br&gt;Butt kicks&lt;br&gt;3 rounds&lt;br&gt;P1 50 Skiers (8x4 way hop)&lt;br&gt;P2 hollow hold/banana hold (change @25)&lt;br&gt;P1 50 Star jumps (SLDL/Squat)&lt;br&gt;P2 Plank&lt;br&gt;P1 50 Star jumps (SLDL/Squat)&lt;br&gt;P2 Reverse x-over lunge</td>
<td>R, B, P, Y&lt;br&gt;2 rounds&lt;br&gt;1min&lt;br&gt;Up and down plank&lt;br&gt;KB&lt;br&gt;Walkouts&lt;br&gt;Double leg raise&lt;br&gt;Wall sit SL (standing disc)&lt;br&gt;Reverse x-over lunge&lt;br&gt;Star jumps (SLDL/Squat)&lt;br&gt;Skaters (Lat shuffle)&lt;br&gt;Yoga sequence ~ 5min&lt;br&gt;Downward dog-upward dog-runners pose-warrior I- warrior II- warrior III</td>
</tr>
<tr>
<td>Week</td>
<td>Session 1 - Gym</td>
<td>Session 2 – Warm Up</td>
<td>Session 3 – Warm Up</td>
<td>Session 4 - Gym</td>
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</tr>
<tr>
<td></td>
<td>2 rounds</td>
<td>3 rounds 16 yards</td>
<td>3 rounds</td>
<td>3 rounds</td>
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<tr>
<td></td>
<td>10 Walking knee/hip flexion</td>
<td>Walk and hug</td>
<td>Wide leg marching (40 on spot)</td>
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<tr>
<td></td>
<td>15m Karaoke</td>
<td>Lunge to high knee</td>
<td>40 KB mimic</td>
<td></td>
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<tr>
<td></td>
<td>5 double leg raise</td>
<td>Butt kicks</td>
<td>10 Walking knee/hip flexion</td>
<td></td>
</tr>
<tr>
<td></td>
<td>15min AMRAP</td>
<td>Ankle bounces</td>
<td>10 v-sits</td>
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<tr>
<td></td>
<td>10 KB</td>
<td>3min</td>
<td>20 Heisman (walking)</td>
<td></td>
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<tr>
<td></td>
<td>20 X-ups</td>
<td>4 4 way hop (star excursion)</td>
<td>30 Bicycles</td>
<td></td>
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<tr>
<td></td>
<td>10 Box jumps (step ups)</td>
<td>6/leg Split lunge jumps (lunge)</td>
<td>40 SL deadlifts</td>
<td></td>
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<tr>
<td></td>
<td>10 SL deadlifts</td>
<td>8 SL squat (alt legs each round) (double)</td>
<td>50 Reverse x-over lunge</td>
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<tr>
<td></td>
<td>10 SL squat double reduced ROM)</td>
<td>10 Mountains (slow &amp;/or reduced ROM)</td>
<td>40 SL deadlifts</td>
<td></td>
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<tr>
<td></td>
<td>5 Walkouts</td>
<td>20 x-ups</td>
<td>30 Bicycles</td>
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<td></td>
<td></td>
<td>30sec rest</td>
<td>20 Heisman (walking)</td>
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<td></td>
<td></td>
<td>repeat</td>
<td>10 v-sits</td>
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</tbody>
</table>

Notes:
- Bicycles
- 1 round = 5 4way hop
- 10 Walkouts (up/down plank, lat plank)
- 10 Sit up with twist
- 15m SL deadlift = SL squat –lunge
- 10 KB
- 10 box jump (step ups)
- 10 clams
- 15m SL deadlift = SL squat –lunge
<table>
<thead>
<tr>
<th>Week</th>
<th>Session 1 - Gym</th>
<th>Session 2 – Warm Up</th>
<th>Session 3 – Warm Up</th>
<th>Session 4 - Gym</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>7 rounds</td>
<td>30/30</td>
<td>Tabata</td>
<td>21-18-15-12-9-6-3</td>
</tr>
<tr>
<td></td>
<td>7 SL 45 degree turns/leg (SLDL open/close rotation)</td>
<td>30/25</td>
<td>Squat jumps (squat to toes raise)</td>
<td>KB</td>
</tr>
<tr>
<td></td>
<td>7 Up and down planks</td>
<td>30/20</td>
<td>Reverse x-over lunge</td>
<td>Bicycles</td>
</tr>
<tr>
<td></td>
<td>7 Single leg bounds (lunge with high knee raise)</td>
<td>30/15</td>
<td>Sit up with twist</td>
<td>180 jump twists (lat step with high knee - banded)</td>
</tr>
<tr>
<td></td>
<td>7 SL ball slams (SL butt to box)</td>
<td>30/10</td>
<td>SLDL with arm raise and hop (no hop)</td>
<td>SL OH ball toss</td>
</tr>
<tr>
<td></td>
<td>7 Sitting tucks</td>
<td>30/5</td>
<td>Hollow holds</td>
<td>(Cronk bent over row)</td>
</tr>
<tr>
<td></td>
<td>7 tuck jumps (reduced ROM or squat to toes raise)</td>
<td>SLDL with arm raise and hop (no hop)</td>
<td>Burpees (walking burpees)</td>
<td>Yoga sequence ~ 5min</td>
</tr>
<tr>
<td></td>
<td>4 rounds</td>
<td>10min AMRAP</td>
<td>5 rounds</td>
<td>15min AMRAP</td>
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<tr>
<td></td>
<td>P1 20 SL squat butt to box</td>
<td>10 Burpees (walking burpees/MA squat jumps)</td>
<td>90/30</td>
<td>8 SL 180 turns (circle and return) (split squat)</td>
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<tr>
<td></td>
<td>P2 Squat hold (reduced ROM)</td>
<td>10 Suitcases</td>
<td>5 Split jumps 180 (alt leg in the air) (lunge)</td>
<td>10 SL lat ball throw (partner or wall) (banded SL rotation)</td>
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<tr>
<td></td>
<td>P1 10 Reverse x-over lunge/leg</td>
<td>5 Tuck jumps SL landing (squat to toe raise)</td>
<td>10 Sit up with twist</td>
<td>12 Suitcases</td>
</tr>
<tr>
<td></td>
<td>P2 Plank (hollow hold)</td>
<td>10 180 jump twists (lat step with high knee - banded)</td>
<td>10 Walkouts</td>
<td>14 Core rotations</td>
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<tr>
<td></td>
<td>P1 5 SL bounds /leg (lunges/ reduced ROM)</td>
<td>5 SLDL to arm raise and hop/leg (no hop) Spence to take out completely</td>
<td>5 Broad jumps (squat to toes raise)</td>
<td>16 KB (hip raise)</td>
</tr>
<tr>
<td></td>
<td>P2 Mountain climbers (flutter kick)</td>
<td></td>
<td>5 SL DL-squat</td>
<td>Yoga sequence ~ 5min</td>
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<tr>
<td></td>
<td>P110 Step with jump/leg (no jump)</td>
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<td></td>
<td>Downward dog- upward dog- runners pose-warrior I- warrior II- warrior III</td>
</tr>
<tr>
<td></td>
<td>P2 Hollow hold/banana hold</td>
<td></td>
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<td></td>
<td>P1 + 2 10 partner leg push downs/person</td>
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</table>
### Week 8 & 9

<table>
<thead>
<tr>
<th>Session 1 - Gym</th>
<th>Session 2 – Warm Up</th>
<th>Session 3 – Warm Up</th>
<th>Session 4 - Gym</th>
</tr>
</thead>
<tbody>
<tr>
<td>3min on/30sec off</td>
<td>30secs/exercise</td>
<td>10min AMRAP</td>
<td>4 rounds</td>
</tr>
<tr>
<td>5 Sl 180 turns/leg (lat step with high knee - banded)</td>
<td>3 Tuck jump SL landing/leg (rest if there is remaining time) (squat to toes raise)</td>
<td>5 Broad jump (squat to toes raise)</td>
<td>5 SL box jumps/leg (dynamic step up)</td>
</tr>
<tr>
<td>10 Side squats</td>
<td>Partner leg push downs (reverse crunch)</td>
<td>10 V-sits</td>
<td>10 x-ups</td>
</tr>
<tr>
<td>SL dynamic step up/leg (high knee march)</td>
<td>Split jump 180 (land with same leg fwd) (lunge)</td>
<td>5 Single leg bound/leg (lunge)</td>
<td>20 SL ball toss</td>
</tr>
<tr>
<td>6 (total) Lat box jump (with top touch) (Heismans)</td>
<td>Superman</td>
<td>5 Pike jump (lateral squat)</td>
<td>20 burpees (walking)</td>
</tr>
<tr>
<td></td>
<td>Banana</td>
<td>5 SLDL to arm raise and hop/leg (no hop)</td>
<td>10 Partner leg push downs</td>
</tr>
<tr>
<td></td>
<td>High knee skip (high knee march)</td>
<td></td>
<td>5 SLDL to arm raise and hop (no hop)</td>
</tr>
<tr>
<td></td>
<td>SL 180 turns (lateral squat)</td>
<td></td>
<td>Yoga sequence ~ 5min</td>
</tr>
</tbody>
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### D.7 Study Three - Screening Tool Development

Initial kinematic variable selection was developed from previous literature identifying kinematics to be associated with elevated peak knee loading. In the frontal plane, variables measured were peak knee valgus angle, peak dynamic medial knee shift, global measures of peak trunk lateral flexion (TLF), measured both horizontally and vertically, a relative measure of peak TLF, peak mid-pelvis to foot displacement and peak thigh abduction (Table D.5). Sagittal plane variables measured were peak knee flexion, knee flexion at impact, knee flexion ROM, peak trunk flexion and trunk flexion ROM (Table D.5).
Table D.5. 2D kinematic variable measurement conventions used in Silicon Coach 7.0 software.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Measurement Method</th>
<th>Convention</th>
<th>Image</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>FRONTAL PLANE</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
| Lateral Trunk Flexion | - Line 1: global vertical Y axis from midpoint between left and right anterior superior iliac spines (ASIS).  
- Line 2: clavicle marker to midpoint between left and right ASIS’s.  
  Measurement: global vertical angle between line 1 and line 2. | Away from desired direction = +ve  
Towards desired direction = -ve | |
| Global Vertical (°) | | | |
| Global Horizontal (°) | - Line 1: Global horizontal axis from right ASIS.  
- Line 2: acromion kinematic marker to right ASIS.  
  Measurement: relative angle between line 1 and line 2.  
  \[ \text{Angle} = (90° - \text{relative angle}) \] | Away from desired direction = +ve  
Towards desired direction = -ve | |
| Relative (°) | - Line 1: midpoint between left and right ASIS.  
- Line 2: clavicle marker to midpoint of ASIS’s.  
  Measurement: Relative angle from line 1 and line 2.  
  \[ \text{Angle} = (90° - \text{relative angle}) \] | Away from desired direction = +ve  
Towards desired direction = -ve | |
| Dynamic Medial Knee Shift (m) | - Line 1: greater trochanter to lateral malleolus of ankle.  
  Measurement: perpendicular distance from line 1 to mid-patella. | Varus = -ve  
Valgus = +ve | |
Table D.5. (Continued)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Measurement Method</th>
<th>Convention</th>
<th>Image</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>FRONTAL PLANE</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dynamic Knee Valgus Angle (°)</td>
<td>* Line 1: hip joint centre to knee joint centre.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>* Line 2: knee joint centre to ankle joint centre.</td>
<td>Varus = -ve</td>
<td></td>
</tr>
<tr>
<td></td>
<td>* Measurement: relative angle between line 1 and line 2.</td>
<td>Valgus = +ve</td>
<td></td>
</tr>
<tr>
<td></td>
<td>True Angle = (180° - relative angle)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mid-Pelvis-Foot Displacement (m)</td>
<td>* Line 1: left ASIS to right ASIS.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>* Line 2: vertical line from midpoint of line 1 to ground.</td>
<td>Away from</td>
<td>Towards</td>
</tr>
<tr>
<td></td>
<td>* Measurement: discrete perpendicular distance from line 2 to front centre of stance foot.</td>
<td>midline = +ve</td>
<td>midline = -ve</td>
</tr>
<tr>
<td>Thigh Abduction (°)</td>
<td>* Line 1: left ASIS through right ASIS.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>* Measurement: Relative angle from ASIS line to right ASIS, and measure 90° angle.</td>
<td>Adduction = -ve</td>
<td>Adduction = +ve</td>
</tr>
<tr>
<td>Angle 2</td>
<td>* Line 1: 90° angle line from angle 1.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>* Line 2: right ASIS to mid-patella</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>* Measurement: relative angle between line 1 and line 2.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
For each 2D kinematic variable, values at foot strike, peak measurements and range of motion during weight acceptance of pre-planned straight line running (PSLR) and unplanned sidestepping (UPSS) tasks were taken for further investigation. Prior to correlation analysis, all variables were clinically examined, and measures that were considered inaccurate or subject to measurement error were disregarded. Pearson correlations were then used to determine significant associations between all remaining 2D kinematic variables and peak knee extension, valgus and internal rotation moments. Upon review, any non-significant correlations (α = 0.05) were removed prior to regression analysis, specific to each peak knee loading dependent variable. A backward stepwise regression was then run on each 3D peak loading condition to determine whether correlated 2D kinematic variables could predict variation within them. Regression models were run using PSLR and UPSS trials. In this study, two measures of knee valgus motion were measured, being peak knee dynamic valgus angle and peak knee dynamic valgus displacement, and later compared and regressed, in order to determine which measurement would best predict 3D loading. Knee flexion angles at foot strike were also compared between 2D and 3D. Peak knee moments between all running conditions were also compared, and were normalised to body weight and height.

D.7.1 PRELIMINARY STATISTICAL ANALYSIS

For each 2D kinematic variable, values at foot strike, peak measurements and range of motion during weight acceptance of pre-planned straight line running (PSLR) and unplanned sidestepping (UPSS) tasks were taken for further investigation. Prior to correlation analysis, all variables were clinically examined, and measures that were considered inaccurate or subject to measurement error were disregarded. Pearson correlations were then used to determine significant associations between all remaining 2D kinematic variables and peak knee extension, valgus and internal rotation moments. Upon review, any non-significant correlations (α = 0.05) were removed prior to regression analysis, specific to each peak knee loading dependent variable. A backward stepwise regression was then run on each 3D peak loading condition to determine whether correlated 2D kinematic variables could predict variation within them. Regression models were run using PSLR and UPSS trials. In this study, two measures of knee valgus motion were measured, being peak knee dynamic valgus angle and peak knee dynamic valgus displacement, and later compared and regressed, in order to determine which measurement would best predict 3D loading. Knee flexion angles at foot strike were also compared between 2D and 3D. Peak knee moments between all running conditions were also compared, and were normalised to body weight and height.
D.7.2 Preliminary Results

D.7.2.1 Knee Flexion Angle Comparison

Mean knee flexion angles at foot strike were recorded in 2D and 3D for all running conditions (Figure 7). Similar values were observed across all conditions, although all 2D angles were notably larger than all corresponding 3D values, which is comparable to previous literature.¹⁷

![Figure D.5. Comparison between 2D and 3D mean knee flexion angles for all running conditions during weight acceptance.](image)

D.7.2.2 Pearson Correlations

When reviewing the Pearson correlations table for the PLSR and UPSS conditions, 3D peak knee extension moments were correlated to multiple 2D kinematic variables (Table 3). Significant results with a p < 0.01 were support leg knee flexion ROM (R= 0.530), peak knee flexion (R= 0.355), peak knee valgus angle (R= 0.499), peak dynamic medial knee shift (R= 0.514), a global measure of peak TLF (R= 0.377), peak MPF displacement (R= 0.444) and peak thigh abduction (R= 0.499). Other variables significantly correlated to peak knee extension moments included trunk flexion ROM (R= 0.323, p < 0.05) and a global measure of peak TLF (R= 0.059, p < 0.10). All correlations were positive and relatively strong.
Pearson correlations between the 2D kinematic variables and 3D peak valgus knee moments with a p <0.001 were knee flexion at foot contact (R= -0.381), peak knee valgus angle (R= 0.541), peak dynamic medial knee shift (R= 0.592), peak MPF displacement (R= 0.642) and peak thigh abduction (R= 0.560). Significant correlations also occurred in knee flexion ROM (R= 0.314, p < 0.05), a relative measure of peak TLF (R= -0.245, p <0.10) and trunk flexion ROM (R= 0.227, p < 0.10). All correlations were positive, except that between peak relative TLF and valgus knee moments, and also knee flexion at impact and valgus knee moments, suggesting that reduced knee flexion at impact results in elevated knee valgus moments. To be clear, full extension of the knee was considered to be 0°, meaning that knee flexion values increased as knee flexion increased.

Pearson correlations between the 2D kinematic variables and peak varus knee moments were a relative measure of peak TLF (R= 0.310, p <0.05), peak dynamic medial knee shift (R= -0.215, p < 0.10), a global measure of peak TLF (R= 0.241, p < 0.10) and peak MPF displacement (R= -0.238, p < 0.10). Within internal rotation knee moments, peak knee flexion (R= 0.409, p < 0.001), knee flexion ROM (R=0.364, p < 0.001), peak trunk flexion (R= 0.269, p < 0.05) and trunk flexion ROM (R= 0.271, p < 0.05) were all significantly correlated. Knee flexion at impact (R= -0.323, p < 0.05) and peak knee flexion (R= -0.261, p < 0.10) were found to be correlated with external rotation knee moments.
Table D.6. Correlations between discrete 2D kinematic variables and normalised peak knee moments for PSLR and UPSS conditions calculated during WA phase of stance.

<table>
<thead>
<tr>
<th>2D Kinematics</th>
<th>Extension</th>
<th>Valgus</th>
<th>Varus</th>
<th>Internal Rotation</th>
<th>External Rotation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Knee Flexion Peak (°)</td>
<td>0.355***</td>
<td>0.054</td>
<td>0.179</td>
<td>0.409***</td>
<td>-0.261*</td>
</tr>
<tr>
<td>Knee Flexion ROM (°)</td>
<td>0.530***</td>
<td>0.314**</td>
<td>0.158</td>
<td>0.364***</td>
<td>-0.077</td>
</tr>
<tr>
<td>Knee Flexion Impact (°)</td>
<td>-0.205</td>
<td>-0.381***</td>
<td>0.054</td>
<td>0.127</td>
<td>-0.323**</td>
</tr>
<tr>
<td>Knee Valgus Angle Peak (°)</td>
<td>0.499***</td>
<td>0.541***</td>
<td>-0.142</td>
<td>-0.131</td>
<td>-0.066</td>
</tr>
<tr>
<td>Knee Valgus Displacement Peak (m)</td>
<td>0.514***</td>
<td>0.592***</td>
<td>-0.215*</td>
<td>-0.140</td>
<td>-0.064</td>
</tr>
<tr>
<td>TLF Global Vertical Peak (°)</td>
<td>0.059*</td>
<td>0.040</td>
<td>0.241*</td>
<td>0.025</td>
<td>0.137</td>
</tr>
<tr>
<td>TLF Global Horizontal Peak (°)</td>
<td>0.377***</td>
<td>0.187</td>
<td>0.150</td>
<td>0.098</td>
<td>0.158</td>
</tr>
<tr>
<td>TLF Relative Peak (°)</td>
<td>-0.161</td>
<td>-0.245*</td>
<td>0.310**</td>
<td>0.153</td>
<td>-0.020</td>
</tr>
<tr>
<td>Trunk Flexion Peak (°)</td>
<td>0.084</td>
<td>-0.007</td>
<td>0.030</td>
<td>0.269**</td>
<td>-0.027</td>
</tr>
<tr>
<td>Trunk Flexion ROM (°)</td>
<td>0.323**</td>
<td>0.227*</td>
<td>0.188</td>
<td>0.271**</td>
<td>-0.024</td>
</tr>
<tr>
<td>MPF Displacement Peak (m)</td>
<td>0.444***</td>
<td>0.642***</td>
<td>-0.238*</td>
<td>0.098</td>
<td>-0.027</td>
</tr>
<tr>
<td>Thigh Abduction Peak (°)</td>
<td>0.499***</td>
<td>0.560***</td>
<td>-0.127</td>
<td>0.069</td>
<td>0.013</td>
</tr>
</tbody>
</table>

*** Correlation is significant at the 0.01 level (2-tailed).
** Correlation is significant at the 0.05 level (2-tailed).
* Correlation is significant at the 0.10 level (2-tailed).
D.7.2.3 Regression Analysis

A backward stepwise regression (Table 4) found that 2D knee flexion ROM (p < 0.01), peak dynamic medial knee shift (p < 0.01) and peak global vertical TLF (p = 0.029) were strong predictors of 3D peak extension knee moments, explaining 43.4% of variability. As for the 3D peak valgus knee moments, knee flexion at impact (p < 0.01), trunk flexion ROM (p = 0.038) and peak MPF displacement (p < 0.01) were strong predictors of peak valgus knee moments, explaining 55.7% of the variability. It is interesting to note that frontal plane kinematics such dynamic medial knee shift ($R^2 = 0.434$, $p < 0.001$) and LTF ($R^2 = 0.434$, $p = 0.029$) predicted sagittal plane peak extension moments, while sagittal plane kinematics such as knee flexion ($R^2 = 0.557$, $p < 0.001$) and trunk flexion ($R^2 = 0.557$, $p = 0.038$) predicted frontal plane peak valgus knee moments.

Peak relative TLF ($p = 0.014$) was a poor predictor of peak varus knee moments, explaining 9.6% of the variability. Peak knee flexion was found to be a poor predictor of peak internal rotation knee moments, explaining 16.7% of the variability, while knee flexion at impact ($p = 0.006$) was a poor predictor or peak external rotation knee moments, explaining 11.6% of the variability.
Table D.7. Backwards stepwise linear regression between normalised peak knee loading data (Nm.m-1.kg-1) and 2D kinematic variables during the WA phase of stance in PSLR and UPSS. [n= 15 participants x approximately 4 (out of a possible 6) successful trials each]

<table>
<thead>
<tr>
<th>Moment Type</th>
<th>Total Model</th>
<th>2D Kinematics</th>
<th>n</th>
<th>Adjusted R²</th>
<th>β</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Extension Moment:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(Constant)</td>
<td>63</td>
<td>0.434</td>
<td>0.045*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>p &lt; 0.001**</td>
<td>Knee Flexion ROM</td>
<td>63</td>
<td>0.434</td>
<td>0.336 0.002*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>R²= 0.461</td>
<td>Dynamic Medial Knee Shift Peak</td>
<td>63</td>
<td>0.434</td>
<td>0.444 0.000*</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>TLF Global Vertical Peak</td>
<td>63</td>
<td>0.434</td>
<td>0.228 0.029*</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Valgus Moment:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(Constant)</td>
<td>63</td>
<td>0.557</td>
<td>0.001*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>p &lt; 0.001**</td>
<td>Knee Flexion Impact</td>
<td>63</td>
<td>0.557</td>
<td>-0.385 0.000*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>R²= 0.578</td>
<td>Trunk Flexion ROM</td>
<td>63</td>
<td>0.557</td>
<td>0.182 0.038*</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>MPF Displacement Peak</td>
<td>63</td>
<td>0.557</td>
<td>0.607 0.000*</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Varus Moment:</strong></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(Constant)</td>
<td>63</td>
<td>0.081</td>
<td>0.234</td>
<td></td>
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</tr>
<tr>
<td>p= 0.014*</td>
<td>TLF Relative Peak</td>
<td>63</td>
<td>0.081</td>
<td>0.310 0.014*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>R²= 0.096</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Adjusted R²= 0.081</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Internal Rotation Moment:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(Constant)</td>
<td>63</td>
<td>0.154</td>
<td>0.483</td>
<td></td>
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</tr>
<tr>
<td>p= 0.001**</td>
<td>Knee Flexion Peak</td>
<td>63</td>
<td>0.154</td>
<td>0.409 0.001*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>R²= 0.167</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Adjusted R²= 0.154</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>External Rotation Moment:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(Constant)</td>
<td>15</td>
<td>0.104</td>
<td>0.000*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>p= 0.006**</td>
<td>Knee Flexion Impact</td>
<td>15</td>
<td>0.104</td>
<td>-0.341 0.006*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>R²= 0.116</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Adjusted R²= 0.104</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
</tbody>
</table>
D.8 REFERENCES


**APPENDIX E - CODE**

**APPENDIX E 1 – sEMG PROCESSING FILES**

A digital copy of the sEMG code used in Chapter four can be found on the disc attached with this thesis. This MATLAB code includes script used to calculate directed co-contraction ratios (DCCRs) and total muscle activation (TMA).
APPENDIX E 2 – UWA UPPER AND LOWER BODY MODELS

A digital copy of the UWA upper and lower body models used in chapter three, four and five can be found on the disc attached with this thesis.
APPENDIX E 3 — FUNCTIONAL JOINT CENTRE CODE

A digital copy of the functional joint centre code used in chapter three, four and five can be found on the disc attached with this thesis.
APPENDIX E 4 – TEMPNORMGUI

A digital copy of the software and templates used to export 3D data recorded in Vicon into excel for chapter three, four and five can be found on the disc attached.