Lumbopelvic instability: A key in injury risk among pre-elite youth athletes?

A thesis submitted in fulfilment of the requirements for the award of the degree

Doctorate of Philosophy

from

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by

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Dedication

I dedicate this thesis to my beautiful little boy, Kobey. Although you only came along half way through my Ph.D., you were the light to keep me going through the hard times. You became my motivation to finish to make the best possible life I could for you. I love you more than words can explain! Love Mummy.
Declaration

I Kerry Mann, hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person nor material which to a substantial extent has been accepted for the award of any other degree or diploma at Charles Sturt University or any other educational institution, except where due acknowledgment is made in the thesis “Lumbopelvic stability: The primary cause of lower limb injuries in pre-elite youth athletes?”. Any contribution made to the research by colleagues with whom I have worked at Charles Sturt University or elsewhere during my candidature is fully acknowledged. I agree that this thesis be accessible for the purpose of study and research in accordance with the normal conditions established by the Executive Director, Library Services or nominee, for the care, loan and reproduction of theses.

Kerry Mann

23rd March 2018
Publications and Conferences


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I would like to acknowledge all the following people who made this thesis possible.

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Abstract

Background

Sporting injuries can result in substantial financial and physical detriments to an athlete, including pain, loss of game and/or training time, costly rehabilitation and/or medical attention, and even cause long-term disability. To reduce these substantial injury rates, many sporting teams have adopted movement screening tools for injury risk management purposes. This early identification of athletes with “poor” movement competency, can then allow intervention strategies to be implemented, potentially preventing the injury from occurring and thus reducing the injury rate seen among the sporting population. Implementation of neuromuscular training interventions programs in athletes at increased risk of sporting injuries have been widely utilised. However, the current local focus on injury prevention at specific joints, when compared to a focus on the global kinetic chain, is less effective, as evidenced by high rates of re-injury. Research suggests that lumbopelvic stability may be critical in the prevention of lower limb injuries in athletes; however, it is unknown how much of an effect lumbopelvic instability has on lower limb injury risk.

Thesis Aim

The first purpose of this thesis was to determine the inter- and intra-rater reliability of a field-based movement screen in novice and expert raters using different viewing methods, and evaluate the presence of a familiarisation effect (Manuscript 1). A second aim of this thesis was to determine the effect of different 12-week intervention programs to modify a stop-jump (Manuscript 2) and reactive change-of-direction (R-COD) (Manuscript 3) in pre-elite youth athletes. A third aim of this thesis was to determine the effect, if any, trunk abdominal segment relative to the pelvis segment (trunkab-pelvis) range of motion had on lower limb injury risk factors (Manuscript 4).

Methods

For Manuscript 1, 55 pre-elite youth athletes performed a movement screen on three separate occasions and videos of their performance were rated three times in randomised order by 18 raters. Reliability was established using inter- and intra-rater reliability of novice and expert raters, with learning effects and familiarisation measured across repeated exposure of both raters and athletes, respectively. Within Manuscript 2 to 4, eighty-nine junior pre-elite athletes with no current signs or symptoms of injury were recruited from the Western Region Academy of Sport. Biomechanical analysis of five successful stop-jump and five R-COD experimental tasks were completed both before and after exposure to one of three different 12-week training programs, or the control program, in conjunction with a strength and conditioning program for each participant. Mixed effect repeated measures analysis of variance (ANOVA) was used to determine statistically significant between-group differences ($P \leq 0.05$).

Major Conclusions

Results of this study indicate that movement screening experience does not affect rater reliability; however, familiarisation is required for athletes performing the movement screening. Total movement screening score can be reliably used to determine movement competency; however, individual movements scores should not be relied on. When implementing strength and conditioning programs in pre-elite youth athletes to modify jump-landing technique, a simple strength and conditioning program comprising of four exercises with limited equipment required, can be implemented in pre-elite youth athletes with poor movement competency to modify their landing patterns. As a result of these interventions, athletes displayed a more upright trunkab-pelvis segment at landing that was not shown to alter
the risk of lower limb injury; however, it is unknown whether this movement strategy is beneficial or detrimental to athletic performance. This current study failed to identify links between trunk-pelvis ROM, injury risk and/or performance. It is suggested that further research is needed to determine how trunk ROM during landing tasks affects these factors influence lower limb injury risk and athletic performance.
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<td>3D</td>
<td>Three-dimensional</td>
</tr>
<tr>
<td>ANOVA</td>
<td>Analysis of Variance</td>
</tr>
<tr>
<td>AB</td>
<td>Abduction</td>
</tr>
<tr>
<td>ACL</td>
<td>Anterior Cruciate Ligament</td>
</tr>
<tr>
<td>AD</td>
<td>Adduction</td>
</tr>
<tr>
<td>BM</td>
<td>Body Mass</td>
</tr>
<tr>
<td>C</td>
<td>Core Training Program Group</td>
</tr>
<tr>
<td>C&amp;L</td>
<td>Core and Landing Re-training Group</td>
</tr>
<tr>
<td>CD</td>
<td>Compact Disk</td>
</tr>
<tr>
<td>COD</td>
<td>Change-of-Direction</td>
</tr>
<tr>
<td>DF</td>
<td>Dorsiflexion</td>
</tr>
<tr>
<td>E-1-Single</td>
<td>Expert rater, Session 1 only, Single video viewing</td>
</tr>
<tr>
<td>E-123-Single</td>
<td>Expert rater, Session 1,2&amp;3, Single video viewing</td>
</tr>
<tr>
<td>ER</td>
<td>External Rotation</td>
</tr>
<tr>
<td>EV</td>
<td>Eversion</td>
</tr>
<tr>
<td>EX</td>
<td>Extension</td>
</tr>
<tr>
<td>FL</td>
<td>Flexion</td>
</tr>
<tr>
<td>FMS</td>
<td>Functional Movement Screen</td>
</tr>
<tr>
<td>F\text{\scriptsize{ANT}}</td>
<td>Peak Anterior Force on the Anteroposterior Ground Reaction Force-Time Curve</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
</tr>
<tr>
<td>--------------</td>
<td>-------------</td>
</tr>
<tr>
<td>F&lt;sub&gt;POST&lt;/sub&gt;</td>
<td>Peak Posterior Force on the Anteroposterior Ground Reaction Force-Time Curve</td>
</tr>
<tr>
<td>F&lt;sub&gt;v&lt;/sub&gt;</td>
<td>Vertical Force</td>
</tr>
<tr>
<td>F&lt;sub&gt;v1&lt;/sub&gt;</td>
<td>First Peak on the Vertical Ground Reaction Force-Time Curve</td>
</tr>
<tr>
<td>F&lt;sub&gt;v2&lt;/sub&gt;</td>
<td>Local Minimum on the Vertical Ground Reaction Force-Time Curve</td>
</tr>
<tr>
<td>F&lt;sub&gt;v3&lt;/sub&gt;</td>
<td>Second Peak on the Vertical Ground Reaction Force-Time Curve</td>
</tr>
<tr>
<td>GRF</td>
<td>Ground Reaction Force</td>
</tr>
<tr>
<td>IC</td>
<td>Initial Contact</td>
</tr>
<tr>
<td>IC-F&lt;sub&gt;v1&lt;/sub&gt;</td>
<td>Time from Initial Contact to the First Peak in the Vertical Ground Reaction Force-Time Curve.</td>
</tr>
<tr>
<td>ICC</td>
<td>Intra-class Correlations</td>
</tr>
<tr>
<td>IR</td>
<td>Internal Rotation</td>
</tr>
<tr>
<td>IN</td>
<td>Inversion</td>
</tr>
<tr>
<td>L5-S1</td>
<td>Lumbo-sacral Intervertebral Joint Space</td>
</tr>
<tr>
<td>LAT FLEX</td>
<td>Lateral Flexion</td>
</tr>
<tr>
<td>LR</td>
<td>Loading Rate</td>
</tr>
<tr>
<td>MDS</td>
<td>Movement Dysfunction Screen</td>
</tr>
<tr>
<td>MS</td>
<td>Movement Screen</td>
</tr>
<tr>
<td>N</td>
<td>No Additional Training</td>
</tr>
<tr>
<td>N-1-Single</td>
<td>Novice rater, Session 1 only, Single video viewing</td>
</tr>
<tr>
<td>N-1-Multiple</td>
<td>Novice rater, Session 1 only, Multiple video viewing</td>
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<tr>
<td>Acronym</td>
<td>Description</td>
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<tr>
<td>N-123-Multiple</td>
<td>Novice rater, Session 1,2&amp;3, Multiple video viewing</td>
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<tr>
<td>N-123-Single</td>
<td>Novice rater, Session 1,2&amp;3, Single video viewing</td>
</tr>
<tr>
<td>NMT</td>
<td>Neuromuscular Training</td>
</tr>
<tr>
<td>PF</td>
<td>Plantarflexion</td>
</tr>
<tr>
<td>PT</td>
<td>Patellar Tendinopathy</td>
</tr>
<tr>
<td>R-COD</td>
<td>Reactive Change-of-Direction</td>
</tr>
<tr>
<td>ROM</td>
<td>Range of Motion</td>
</tr>
<tr>
<td>ROT</td>
<td>Rotation</td>
</tr>
<tr>
<td>SD</td>
<td>Standard Deviation</td>
</tr>
<tr>
<td>SE</td>
<td>Standard Error</td>
</tr>
<tr>
<td>T12-L1</td>
<td>Thoraco-lumbar Intervertebral Joint Space</td>
</tr>
<tr>
<td>Thoracic Ab-Pelvis</td>
<td>Angles of the Trunk Relative to the Pelvis</td>
</tr>
<tr>
<td>TrunkAb-pelvis</td>
<td>Trunk Abdominal Segment Relative to the Pelvis Segment</td>
</tr>
<tr>
<td>TO</td>
<td>Take Off</td>
</tr>
</tbody>
</table>
Chapter 1. The Problem

1.1 Introduction

1.1.1 Sporting Injuries

Sporting injuries can result in substantial financial and physical detriments to an athlete, including pain, loss of game and/or training time, costly rehabilitation and/or medical attention, and in some cases even cause long term disability (Caine, Maffulli et al. 2008). In 2001, an estimated 367,200 people, of which two-thirds were male, reported an injury as a consequence of organised sport participation, and 24% of these injuries were reported as long term injuries (approximately 545,200) that were sustained during sport or exercise (Statistics 2011). Not only is this high prevalence of injury a concern, but also the concern of the cost of sporting injuries that is increasing in Australia, estimated at 1.5 billion dollars in 2003 (Medibank Private 2003) rising to 2 billion dollars in 2006 (Medibank Private 2006). While these statistics represent all age groups, the individuals aged between 18 and 24 years more likely to require medical assistance due to a sporting injury than any other age group (Medibank Private 2006, Kreisfeld, Harrison et al. 2017). Pre-elite youth athletes (<18 years) are suggested to be a target age for injury reduction strategies, due to the increased injury risk and extremely high training volume and risk of burnout (DiFiori, Benjamin et al. 2014).

Young athletes are predisposed to injury due to the identified relationship between growth, maturation and age (Emery 2003, Myer, Chu et al. 2008), specifically lower limb injuries that are more prevalent following adolescence (Finch, Valuri et al. 1998). During the adolescent period, rapid increases in height and body mass occur in response to the increase in length of the long bones of the lower limbs, that in-turn, results in an increase in height of the location of centre of gravity of the adolescent (Myer, Chu et al. 2008). This higher centre of gravity
together with a lack of neuromuscular control and strength that has yet to catch up with these rapid changes, is suggested to pose a challenge for trunk stabilisation during motion in adolescents (Myer, Chu et al. 2008), identifying this age group as a critical population for injury risk identification and prevention strategies to be implemented.

1.1.2 Lumbopelvic Region

Extensive previous research (Beckman and Buchanan 1995, Beynnon, Murphy et al. 2002, Cowan, Schache et al. 2004, Sherry and Best 2004, Willson, Dougherty et al. 2005, Chumanov, Heiderscheit et al. 2007, Edwards, Steele et al. 2010, Hewett and Myer 2011, Mann, Edwards et al. 2012, Edwards, Brooke et al. 2017) has implicated the lumbopelvic region in a range of lower limb injuries, including both acute and overuse injury. The lumbopelvic region, also referred as a number of other terms such as the lumbopelvic-hip complex or “core” (Edwards, Austin et al. 2017), is composed of the lumbar vertebrae, the pelvis, the hip joints, and the active and passive structures that either produce or restrict movement of these segments (Willson, Dougherty et al. 2005). Comparison of literature investigating the lumbopelvic region is difficult due to the between-study varied definitions of lumbopelvic control/stability that have been adopted (Table 1–1) and the limitations of these definitions. However, based on previous research, lumbopelvic stability can be defined as to obtain and maintain the alignment of the body segments in a task dependant manner without substitution strategies, in both static positions and during dynamic movements.


Table 1-1 Definitions of lumbopelvic control.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Definition</th>
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<tr>
<td>Mills et al., (2005)</td>
<td>The ability to control motion of the lumbar spine and pelvis relative to an arbitrarily defined neutral position</td>
</tr>
<tr>
<td>Panjabi (1992)</td>
<td>The normal function of the three-component stabilizing system is to provide sufficient stability to the spine to match the instantaneously varying stability demands due to changes in spinal posture, and static and dynamic loads.</td>
</tr>
<tr>
<td>Kibler, et al., (2006)</td>
<td>The interaction between the pelvis and lumbar and thoracic spine, and between the pelvis and the hip joint</td>
</tr>
</tbody>
</table>

The active structures of this lumbopelvic system play the primary role in maintaining stabilisation during gross motor movements, including transverse abdominus, multifidi, internal oblique, deep transversosponalis, erector spinae, external oblique, rectus abdominus muscles, quadrates lumborum and the pelvic floor muscles. Spinal stability during dynamic movements that involve the transfer of forces require the interaction of two systems (Bergmark 1989), the local and the global system, also referred to as the deep or superficial systems (Kuszewski, Gnat et al. 2009). The local system’s role is to maintain spinal curvature and provide lateral and sagittal stiffness to the lumbar spine to retain mechanical stability (Bergmark 1989), and therefore responds to changes in the posture of the lumbar spine. This local system comprises the muscles with an origin or insertion at the vertebra, with the
exception of the Psoas that is part of the global system. Core stabilising muscles, including the Psoas, and intra-abdominal pressure that directly transfer load between the thoracic cage and the pelvis are considered to be part of the global system (Bergmark 1989), and is thought to respond to changes of the line of action of an externally applied load. It is also responsible for changing the position of the thoracic cage in relation to the pelvis, however, both systems respond to the magnitude of external load (Bergmark 1989).

1.1.3 Movement Screening

To implement a prevention strategy, we first must identify those athletes who are at an increased risk of injury. As many movement screening procedures require three-dimensional motion analysis (Hewett, Myer et al. 2005, Edwards, Steele et al. 2010, Mann, Edwards et al. 2013), there is a need for field-based movement screening that can be more easily implemented by coaches and clinicians. To effectively predict injury risk and guide prevention strategies within sporting communities, movement screening protocols must be injury specific, simple, validated, reliable, cost effective and easily implemented. Despite a lack of longitudinal evidence of the reliability and validity pertaining to the various movement screening procedures that are available, many sporting teams have adopted these tools. Generally, these are designed with one of two aims in mind: (1) injury risk management; and/or (2) performance enhancement (Mottram and Comerford 2008). Specifically for injury risk management, early identification of athletes with “poor” movement competency, yet never actually been defined within the literature, can allow intervention strategies to be implemented to potentially prevent the injury from occurring or re-occurring, and thus reduce the injury rates seen among the sporting population (Parkkari, Kujala et al. 2001). Currently, movement screening tools for injury prevention include use of dynamic movements such as jumping and landing tasks (Myer, Ford et al. 2008, Padua, Marshall et al. 2009) or dynamic postural stability exercises (Kinzey

One of the most popular movement screens widely employed in clinical and sporting situations, is the Functional Movement Screen (FMS) (Cook, Burton et al. 2006, Cook, Burton et al. 2006), which has also excluded lumbopelvic stability assessment. The FMS comprises of seven dynamic movement tasks aimed to test functional movement capacity, including the: deep squat; hurdle step; inline lunge; shoulder mobility test; active straight leg raise; trunk stability push-up; and rotary stability test. These movements are each scored on an ordinal scale from 0 to 3 with four categories. With a compensation defined as not complying with standard movement expectations associated with each test (Cook, Burton et al. 2006). A score of 3 indicates the participant’s ability to perform the movement as described with no compensations. A score of 2 denotes the participant is performing some type of compensation while completing the movement. While a score of 1 signifies the participant is unable to perform the movement, and a score of 0 indicated there was pain associated with performance of the movement (Cook, Burton et al. 2006, Cook, Burton et al. 2006). The categorical scores for each movement are summed together for a total score out of 21. Whilst previous research has suggested that if this total composite score falls below 14, an increased injury risk is present (Kiesel, Plisky et al. 2007, Chorba, Chorba et al. 2010), recent research has contested this
notion demonstrating that the FMS is unable to predict injury risk (Bardenett, Micca et al. 2015, Bushman, Grier et al. 2016).

Inter- and inta-rater reliability is a key consideration for movement screens, given the subjective nature of rating (Tinsley and Weiss 1975). A high level of agreement between different raters (McHugh 2012) and high test-retest reliability of individual raters (Teyhen, Shaffer et al. 2012) is desirable. As such, researchers have attempted to determine the reliability in movement screening protocols that are currently used (Chorba, Chorba et al. 2010, Gribble, Brigle et al. 2013, Gribble, Brigle et al. 2013, Smith, Chimera et al. 2013). Reliability requires repeatability in both raters and participants, and although research has demonstrated good reliability within some field-based movement screens (Chorba, Chorba et al. 2010, Minick, Kiesel et al. 2010), there are limitations within both the methodology for assessing reliability and the screening protocols themselves. Many of these studies employ the use of intra-class correlations (ICC) to analyse and interpret inter- and intra-rater reliability (Chorba, Chorba et al. 2010, Gribble, Brigle et al. 2013, Gribble, Brigle et al. 2013, Smith, Chimera et al. 2013). However, this statistical method is inappropriate method, as ICC’s should only be applied to continuous scalar data, not ordinal data in which these movement screens provide (Sim and Wright 2005). Inter-rater reliability using Kappa scores have also been reported for the FMS (Minick, Kiesel et al. 2010, Onate, Dewey et al. 2012, Teyhen, Shaffer et al. 2012), with authors suggesting that there is a high reliability despite some relatively low Kappa scores (Minick, Kiesel et al. 2010), which would indicate otherwise. While low Kappa scores have been suggested to relate to poor scoring descriptions inherent to the screening protocols (Minick, Kiesel et al. 2010), the FMS may not be as reliable as has been implied because of inadequate statistical analysis and/or poor interpretation of scores.
Further to concerns with statistical interpretation, the presence of a learning effect may also affect the reliability of a movement screen. The often novel movements required to be performed during screening may be unfamiliar to athletes (e.g. a Tuck Jump (Myer, Ford et al. 2008), which might possibly lead to a familiarisation effect when first performing these tasks. A familiarisation effect is determined by comparing repeated sessions of the same task (Hopkins 2000), and is identified when a change in performance from session 1 to session 2 occurs due to an effect of practice or experience (Schmidt and Wrisberg 2008). The presence of a familiarisation effect requires a familiarisation session prior to rating in order to establish a reliable measure. It is currently unknown whether athletes require familiarisation with movement screening procedures prior to rating their movement screens as there has been a distinct lack of research in this area.

In addition to questions of familiarisation effect, limited research has investigated effective rater viewing methods for the movement screen, which can also potentially affect the reliability of the movement screening tool. Despite limited research, many sporting teams and clinicians have adopted simple, real-time, single-viewing, field-based procedures involving manual grading methods (Cook, Burton et al. 2006, Cook, Burton et al. 2006, Myer, Ford et al. 2008). It has been suggested by Whiteside, Deneweth et al. (2016) that manual grading may not be effective due to the requirement for multiple error cues relating to the movement, to be identified simultaneously. Concern with the ability to accurately perform manual rating in real time, relates to there being a limited attentional capacity, for example ‘bottleneck’ theories of attention that maintain that only one of multiple high-speed tasks can be performed with accuracy at the same time (Craik 1947). Multiple resource capacities such as Wickens et al. (2002) accommodate the potential for a time-sharing strategy to complete multiple tasks at once; however, the nature of the simultaneous inputs are important. The skill level of the
performer and the bandwidth of information processed are important determinants of simultaneous performance success (Wickens 2002). However, it should be noted the use of multiple visual tasks (as in the multiple error cues required to be simultaneously detected in a real-time FMS), will likely lead to reduced performance due to interference between tasks competing for the same processing resources (Wickens 2002). Given manual grading of movement performance requires multiple visual cues to be detected in a short time, it is suggested that the demands of movement assessment may be reduced by viewing a video of the performance multiple times, focusing on different error cues each time, thereby reducing the attentional demands (Whiteside, Deneweth et al. 2016). This would lead to an increase in reliability of the MS tool, as raters are more accurately able to assess errors in movement.

A further limitation of the FMS and other currently available movement screens is their lack of assessment of the stability of the lumbopelvic region, despite the role of trunk stability during force transfer and the importance of this for both performance and injury prevention (Myer, Chu et al. 2008). Given the lumbopelvic region serves to attach the trunk to the lower extremities, it is a key area associated with performance enhancement through its role in force transfer (Hibbs, Thompson et al. 2008). Also related to this force transfer function, it has been shown to be critical in the etiology, rehabilitation and reduction of lower limb injuries (Hewett and Myer 2011), with links to many lower limb injuries (Beckman and Buchanan 1995, Cowan, Schache et al. 2004, Zazulak, Hewett et al. 2007, Kuszewski, Gnat et al. 2009, Edwards, Steele et al. 2010, Hewett and Myer 2011, Mann, Edwards et al. 2013) and low back pain (Akuthota, Ferreiro et al. 2008). It is suggested that athletes who display delayed or poor neuromuscular control of this region during dynamic jump-landing tasks may be predisposed to lower limb injury through poor stability, excess motion and increased forces experienced by joints (Myer, Chu et al. 2008).
Although there is no validated universal definition for lumbopelvic stability, clinically lumbopelvic stability is measured using a range of static tests such as; the straight leg lowering test (Clark 2004), Biering-Sorensen test (Biering-Sørensen 1984), the flexor endurance test or the side bridge test (McGill, Childs et al. 1999). These tests all provide a measure of static lumbopelvic control, which is more appropriate to a rehabilitation setting, in comparison with the dynamic stability that is required in a sport context. Therefore an alternative definition, and measure of lumbopelvic stability, more suitable to athletic populations is required (Hibbs, Thompson et al. 2008). Dynamic measures of lumbopelvic stability have been devised to meet this need include; the lower abdominal neuromuscular assessment (Clark 2004), kneeling arm raise and the quad arm raise test (Liemohn, Baumgartner et al. 2005). However, while including dynamic movement, these tests only challenge lumbopelvic stability within a singular plane, as opposed to demanding both greater magnitude and a requirement for multiple planar stability. Given multi-planar control is required during most sport movements, these tests are still limited in their capacity to provide a sport-specific measure of dynamic lumbopelvic stability. Therefore, a major consideration for all movement screening is the need for a challenging and specific lumbopelvic assessment, such as the single leg squat and/or dip test, which have been shown to be a reliable measure of lumbopelvic control (Perrott, Pizzari et al. 2011).

To effectively identify athletes presenting an increased injury risk through movement screens and allow intervention strategies to be implemented, it is important to determine which risk factors should and can be identified in movement screening. Risk factors in a sporting context are defined as any factor that may increase the potential for injury (Meeuuiisse 1991) that can be broken down into two categories; modifiable and non-modifiable risk factors (Emery 2003).
Non-modifiable risk factors refer to risks that cannot be altered and modifiable risk factors to those that can potentially be changed or altered through intervention (Emery 2003). For this reason, injury prevention programs have focused on altering modifiable risk factors to reduce the risk of an individual sustaining an injury. A key modifiable risk factor in lower limb injury is an athlete’s landing technique, as the eccentric loading phase of a landing movement is highly influential in the incidence of injury (Boden, Dean et al. 2000, Myer, Ford et al. 2008, Edwards, Steele et al. 2010, Mann, Edwards et al. 2013). Instability or a lack of control of the trunk segment during this phase is suggested to predispose athletes to an increased injury risk (Edwards, Steele et al. 2010, Mann, Edwards et al. 2013). Whereby an increase in trunk motion increases the distance between the GRF vector and joint centres, thus increasing the joint moments and muscle activation requirements (Hewett and Myer 2011). Specifically, factors such as an increase (Dempsey, Lloyd et al. 2009) or decrease (Sheehan, Sipprell III et al. 2012) in trunk flexion during the weight acceptance and at initial contact respectively, increased lateral trunk flexion (Dempsey, Lloyd et al. 2007), trunk rotation (Dempsey, Lloyd et al. 2007) away from the direction of travel during the weight acceptance phase, increased peak hip internal rotation and peak knee valgus angles (McLean, Huang et al. 2005) have been suggested to play a role in increasing an individual’s risk of injury. Commonly performed in dynamic sporting situations, both the stop-jump and unanticipated cutting task movements have been utilised in previous research to investigated landing strategies and lumbopelvic control of athletes at an increased risk of injury (Edwards, Steele et al. 2010, Mann, Edwards et al. 2013, Edwards, Brooke et al. 2017). These movements are suggested to occur in approximately 70% of playing time in a sport such as basketball (Ford, Myer et al. 2005). As these are sport specific movement skills, alternate neuromuscular strategies that have been adopted by the athlete may be observed through biomechanical analysis (Cowley, Ford et al. 2006).
Biomechanical analysis of lumbopelvic control during a COD task must be performed on an unanticipated movement (reactive), as this will place the system under the greatest perturbation to assess lumbopelvic stability. When an athlete is aware of the COD direction they are to perform, as opposed to the R-COD performed in sporting situations, the preplanning of postural and movement strategies changes both the kinematic and kinetics of the movement (Besier, Lloyd et al. 2001). Changes such as the position or movement of the centre of gravity, altered muscle activation timing or amplitude, and modification of reflex muscle activation are suggested to occur when performing an non-reactive COD compared to an R-COD (Besier, Lloyd et al. 2001). Additionally, an reactive movement should be utilised as the experimental movement task to aid in replicating these sporting movements, as during a sporting situation an athlete is required to suddenly respond to external stimulus such as a defender or ball making the movement direction unanticipated (Besier, Lloyd et al. 2001).

1.1.4 Neuromuscular Landing Re-training

Traditionally, injury prevention programs have taken a local focus attempting to modify movement at a specific joint, such as the knee joint for anterior cruciate ligament (ACL) injury (Myer, Chu et al. 2008). However, this may not be the most effective approach as lumbopelvic instability and lack of control has been suggested to be an underlying cause of many injury risk variables throughout the entire lower limb complex (Hewett and Myer 2011). Altered lumbopelvic has stability has links to groin (Cowan, Schache et al. 2004, Edwards, Brooke et al. 2017), hamstring (Sherry and Best 2004, Chumanov, Heiderscheit et al. 2007), knee joint (Edwards, Steele et al. 2010, Hewett and Myer 2011, Mann, Edwards et al. 2013) and ankle joint injuries (Beckman and Buchanan 1995, Beynnon, Murphy et al. 2002). Common plyometric jump training programs have shown conflicting results in their effectiveness to reduce injury (Myer, Ford et al. 2006). Given balance and core stability have been associated
with reduced injury rates (Sherry and Best 2004, Myer, Ford et al. 2006), it may be suggested that purely plyometric programs have neglected a critical component, that being the development of foundational lumbopelvic stability. Previous lumbopelvic intervention programs have elicited a training response suggested to reduce injury risk variables in athletes during the performance of a COD following an intervention program (Bencke, Næsborg et al. 2000, Dempsey, Lloyd et al. 2009, DiStefano, Blackburn et al. 2011). These programs have successfully altered high risk variables such as peak external knee valgus moments (Dempsey, Lloyd et al. 2009, Cochrane, Lloyd et al. 2010) and trunk lateral flexion (Dempsey, Lloyd et al. 2009) during COD.

The mechanisms underlying the link between biomechanical lower limb risk factors and poor lumbopelvic or trunk control have been identified, specifically with links between increased peak internal/external knee and hip adductor moments. Whereby an increase in lateral trunk flexion increases the distance between the GRF vector and the knee joint centre and head of the femur, thus increasing the knee moments and hip adduction muscle activation (Hewett and Myer 2011). Additionally, weak hip extensors can lead to an increased activation requirement of the hip flexors, specifically the iliopsoas, to control the lumbopelvic region and trunk region during landing. This landing strategy is suggested to ‘stiffen’ individuals landing patterns creating the more upright trunk landing pattern (Griffin, Agel et al. 2000), where by a reduced degrees of freedom is suggested to increase ACL injury risk (Griffin, Agel et al. 2000, Shimokochi, Ambegaonkar et al. 2013). In addition to associations between lumbopelvic instability and injury risk factors, significantly increased trunk displacement following perturbation have been identified among athletes who sustained a knee injury within a three-year period, further increasing speculation that neuromuscular impairment of the core region may increase an athlete’s susceptibility to a knee injury (Zazulak, Hewett et al. 2007).
Consequently, recent research has turned its attention to enhancing the stability of the lumbopelvic region in relation to reducing lower limb injuries among the sporting population (Myer, Chu et al. 2008).

Many of these intervention programs however, have been implemented within a late adolescent or adult population (Chappell and Limpisvasti 2008, Herman, Weinhold et al. 2008, McCurdy, Walker et al. 2012) despite research suggesting that early to mid-adolescence is a key development phase for implementation of landing retraining injury prevention strategies (Myer, Faigenbaum et al. 2011). During this critical phase, cognitive and motor capabilities are more amenable to age appropriate training interventions (Myer, Faigenbaum et al. 2011), compared to children younger than 12 years. These younger children, who despite targeted paediatric programs, have been shown to be unable to alter lower limb biomechanics with training (DiStefano, Blackburn et al. 2011). Dynamic neuromuscular training has been reported to be effective for improving lower limb movement biomechanics among adolescent females and in turn, decreasing injury risk (Myer, Ford et al. 2005). These findings suggest that this population can be successfully re-trained to improve lower limb landing mechanics during dynamic landing tasks. Improvements in their performance and stability during motion are thought to occur mainly through general neuromuscular adaptations such as more comprehensive and synchronous firing of the muscular unit (Sale 1988), rather than specific responses to the program.

For interventions to be successful in this population, equipment must be readily available and elements of the program suited to junior sporting organisations. With the exception of a small number of programs such as the FIFA11+ (Bizzini, Junge et al. 2013) and FootyFirst (NoGAPS
intervention programs that require minimal equipment, many of the other current neuromuscular retraining programs are performed in controlled environments such as supervised gyms with specialised equipment and/or supervision required (Hewett, Lindenfeld et al. 1999, Myklebust, Engebretsen et al. 2003). This can create accessibility issues, especially in rural regions where the provision of formal sporting structures and support mechanisms is limited (Finch, Mahoney et al. 2003). Limited access to facilities may affect adherence rates (Tappe, Duda et al. 1989), which is negatively associated with injury risk (Soligard, Nilstad et al. 2010). Therefore, to have the greatest effect on youth sporting injury rates, it is essential that an accessible, easily implemented field-based program is developed to aid injury prevention among pre-elite youth athletes.

1.1.5 **Lumbopelvic link to risk factors and performance**

Literature has shown lumbopelvic stability to be influential in various acute and overuse lower limb injuries. For example, the overuse groin injury is commonly sustained among Australian rules football athletes (Orchard and Seward 2002) and has been linked with altered lumbopelvic control (Cowan, Schache et al. 2004, Edwards, Brooke et al. 2017). Athlete’s with a history of groin pain have displayed greater variation in their lumbo-pelvic and hip joint motor control during a R-COD task compared to those without a history (Edwards, Brooke et al. 2017). It remains unknown if this poor lumbopelvic control during a R-COD task is the underlying mechanism of the injury or the resultant symptom of groin injury. Furthermore, abdominal muscle recruitment strength has also been identified as a possible risk factor for groin strains in Australian football league athletes with chronic groin pain (Cowan, Schache et al. 2004). This finding supports previous research that identifies the feed-forward mechanistic role of the transverse abdominus prior to movement of the extremities (Cresswell, Oddsson et al. 1994, Hodges and Richardson 1997). In these athletes with chronic groin pain however, this
activation of the transverse abdominus is delayed (Cowan, Schache et al. 2004), corresponding with previous research that demonstrated that this muscle activation is altered with the onset of acute experimentally induced pain (Hodges, Moseley et al. 2003).

Another injury thought to be associated with lumbopelvic control is hamstring strain injuries, which typically occur during a forced eccentric muscle action during late swing phase in gait, to control or decelerate a high velocity movement of the thigh segment (Whiting and Zernicke 2008). With 69% of muscle strain injuries in Australian football involving the hamstrings and a history of previous injury being a significant risk factor for re-injury (Orchard 2001), the identification of mechanistic risk factors is of high importance for prevention of this injury. One possible risk factor identified for hamstring strain injuries is a lack of lumbopelvic stability (Devlin 2000), as their anatomical attachment location of the hamstrings to the ischial tuberosities suggests that they may play an important role in stabilisation of this region (Van Wingerden, Vleeming et al. 1997). Chumanov et al. (1994) demonstrated this link through the use of musculoskeletal modelling techniques, showing an increase in speed of movement significantly increased the eccentric load placed on the hamstring muscles. This increase in speed is said to vary with stride length based on fluctuations in the neuromuscular control. Specifically lumbopelvic pelvic muscles, such as the iliopsoas, have a major influence on the stretch of the hamstring muscle, suggesting that the increased lumbopelvic control is critical for the control of the hamstring stretch during high speed movements. Stiffness of the hamstring muscles, is measured as the ratio of change in the muscle length (passive knee extension in supine test) to the force value causing the change in muscle length (hand held tensometer). This stiffness is suggested to compensate for the lack of stabilisation when lumbopelvic control is compromised, and may be a reflection of the faulty neural control of the lumbopelvic region (Kuszewski, Gnat et al. 2009). This proposed notion provides a possible
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explanation as to why purely mechanical stretching is not effective in reducing hamstring muscle stiffness, as a lack of lumbopelvic control has not been addressed (Kuszewski, Gnat et al. 2009). As a lack of hamstring flexibility is implicated as a risk factor in hamstring injuries (Witvrouw, Danneels et al. 2003), and with a lack of lumbopelvic control implicated in muscle stiffness (Kuszewski, Gnat et al. 2009, Schuermans, Van Tiggelen et al. 2017), this suggests that lumbopelvic control is potentially an underlying risk factor for hamstring strain injuries. Furthermore, this relationship between lumbopelvic control and hamstring injuries is supported by Sherry and Best (2004) who showed a reduction in hamstring strain re-injury rates when rehabilitation consisted of a program of progressive agility and core stability exercises.

Anterior cruciate ligament (ACL) injuries are predominantly non-contact injuries with approximately 30% due to contact and 70% occurring due to non-contact situations (Boden, Dean et al. 2000). With knee valgus (adduction) (McLean, Huang et al. 2004, Dempsey, Lloyd et al. 2009), external or internal tibial rotation (Krosshaug, Nakamae et al. 2007), reduced knee flexion (Boden, Dean et al. 2000) and lateral trunk movements (Hewett, Ford et al. 2006) as noted as key injury risk factors for ACL injuries during COD tasks, much of the research has focused on the effects of changing these knee joint dynamics (Hewett, Lindenfeld et al. 1999, Myklebust, Engebretsen et al. 2003, Mandelbaum, Silvers et al. 2005). With key core stabilising muscles such as the erector spinae and quadratus lumborum responsible for the lateral flexion of the trunk segment (Saladin 2007), the lumbopelvic region can be suggested to also play a vital role in the incidence of this injury. A significantly increased trunk displacement following perturbation was seen among athletes who sustained a knee injury within a three year period, suggesting that neuromuscular impairment of the core region may increase an athlete’s susceptibility to a knee injury (Zazulak, Hewett et al. 2007). Hewett et al., (2011) proposed that this lack of neuromuscular control of the trunk region may lead to
increased knee loading. This increasing in knee loading was identified by Dempsey et al. (2009) in which a lateral ground reaction force vector in respect to the femur head increases hip adduction moments, ultimately leading to injury. Consequently recent research has turned its attention to enhancing the stability of the lumbopelvic region in relation to reducing the ACL injuries among the sporting population (Myer, Chu et al. 2008). This change in the forces around the knee joint may also be influential in the development of patellofemoral pain (Edwards, Steele et al. 2010).

Repetitive loading (Ferretti 1986) and an altered landing technique (Richards, Ajemian et al. 1996, Bisseling, Hof et al. 2007, Edwards, Steele et al. 2010) are primary risk factors for patellar tendinopathy (PT). This overuse knee joint injury is characterised by the progressive degeneration of the patellar tendon (Peers and Lysens 2005) that is thought to be due to adaptation to a change in the type and direction of tendon loading sustained by the patellar tendon during repetitive loading (Hamilton and Purdam 2004). Athletes with PT have been shown in the literature to land with alternative landing strategies (Richards, Ajemian et al. 1996, Bisseling, Hof et al. 2007). Another key risk factor in the development of PT is the identification of a patellar tendon abnormality on diagnostic imaging. For example, asymptomatic junior athletes with a patellar tendon abnormality have a 4.2 times greater risk of developing PT (Cook, Khan et al. 2000). Asymptomatic athletes with a patellar tendon abnormality where found to, utilise an altered hip landing strategy during the horizontal landing phase. This involved the athletes extending their hips during landing as opposed to the hip flexion displayed by athletes with a normal patellar tendon in adult athletes (Edwards, Steele et al. 2010) and youth basketball players (Mann, Edwards et al. 2013). This altered hip joint strategy suggest a potential deficit in lumbopelvic control during landing.
A major predisposing factor in the incidence of an ankle sprain is a history of a previous ankle sprain with 85% of ankle sprains represented a reoccurrence injury that occurs up to 12 months following injury and in either ankle, suggesting insufficient rehabilitation (Watson 1999). Increased postural sway has been noted in studies of athletes following an ankle injury (Beckman and Buchanan 1995), and has also been noted as a potential risk factor for ankle injuries in athletes (Beynnon, Murphy et al. 2002). With lumbopelvic or core musculature responsible for the control and stabilisation of the trunk region (Brown, Vera-Garcia et al. 2006), it is plausible that a neuromuscular or strength deficiency within this region may increase the risk of an ankle ligament injury.

Despite this, paradoxical evidence exists relating to lumbopelvic control and the implications with injury and performance. Previous research has indicated that increased trunk lateral flexion and rotation away from the COD direction, increases the risk of ACL injury risk (Dempsey, Lloyd et al. 2007). Yet on the contrary, decreased trunk range of motion summed across all three planes of motion has been associated with reduced performance in an agility task and a countermovement jump (Edwards, Austin et al. 2017). Given this apparently conflicting evidence, it is possible that there may exist an optimal trunk segment motion range during dynamic jump-landing tasks that allows optimal performance without increased injury risk. It should be noted however, that there is a lack of research surrounding the ideal biomechanical parameters for the stop-jump and unanticipated cutting task movement and whether a specific threshold exists for each risk factor within this population of youth athletes. While previous research exists for adult populations, youth athletes’ research is significantly lacking.
1.2 Statement of the Problem
Sporting injuries among the adolescent and early adult population are considerably higher than that of any other age group (Medibank Private 2003). This development phase group is susceptible to dynamic neuromuscular landing and core training strategies (Myer, Faigenbaum et al. 2011) and display decreased lumbopelvic control (Myer, Chu et al. 2008). Conversely these high sporting injury rates and risks among this population, identify the crucial need for injury identification via movement screening and prevention strategies to be validated and implemented to aid in the reduction of lower limb injuries within these athletes. While there is some research that has identified a link between lumbopelvic control injuries (See section 1.15), this area still requires additional research.

1.3 Research Aims
The primary aim of this research is to determine the reliability of a field-based movement competency screening, and the effect of different types of neuromuscular training intervention programs when examining jump-landing technique and lumbopelvic stability in pre-elite youth athletes. This will be achieved through a series of studies that aim to;

- **Manuscript 1:** The aim of this study was to (i) determine the inter- and intra-rater reliability of a field-based movement screen in novice and expert raters using different viewing methods; and (ii) evaluate the presence of a learning and familiarisation effect for both raters and participants, respectively.

- **Manuscript 2:** The purpose of this study is to compare the effects of three different 12-week intervention programs on the results of a full biomechanical analysis during a stop-jump landing task in pre-elite youth athletes.
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- **Manuscript 3:** The purpose of this study is to compare the effects of three different 12-week intervention programs on the results of a full biomechanical analysis during an R-COD in pre-elite youth athletes.

- **Manuscript 4:** This study aimed to identify which, if any, lower limb injury risk factors are associated with increased trunk ROM during R-COD in pre-elite youth athletes.

1.4 Research Hypotheses

It is hypothesised that lumbopelvic stability will be identified as a key factor that substantially influence pre-elite youth athlete’s ability perform fundamental dynamic movement patterns. The respective hypotheses are:

- **Manuscript 1:** It is hypothesised that the field-based movement dysfunction screen (MDS) criteria for each movement and total score will display high inter- and intra-rater reliability for both novice and expert raters, and that inter- and intra-rater reliability will improve with repeated exposure to the MDS due to a rater learning effect.

- **Manuscript 2:** While both core stability and landing re-training intervention programs are suggested to improve lumbopelvic stability and lower limb alignment, we hypothesise that the combination of both the core stability and landing re-training programs will result in the greatest improvement (e.g. less trunk range of motion) during the stop-jump with the strength and condition only program not altering their stop-jump technique.

- **Manuscript 3:** While both core stability and landing re-training intervention programs are suggested to improve lumbopelvic stability and lower limb alignment, we hypothesise that a combination of both the core stability and
landing re-training programs will result in the greatest improvement in lumbopelvic stability (e.g. less trunk range of motion) and lower limb alignment during the R-COD than the other intervention programs.

- **Manuscript 4:** With lumbopelvic control shown to be highly influential in numerous lower limb injuries, it is hypothesized that athletes with moderate magnitude of trunk-ab-pelvis range of motion during the R-COD will employ a strategy that is associated with lower limb injury risk compared to those with higher and lower trunk-ab-pelvis range of motion.

### 1.5 Limitations

The following assumptions and limitations apply to this study:

1. A participant cohort of pre-elite youth athletes (current scholarship holders) within the Western Region Academy of Sport in netball, softball, hockey, basketball or triathletes aged between 11 to 18 years restricts results being applied to other athletic populations and ages;

2. Field-based movement screening procedures are purely qualitative assessments; to help reduce inter-rater error, specific criteria have been designed for each assessed movement although this does not remove this limitation;

3. Biomechanical analysis requires athletes to perform two dynamic experimental tasks in a laboratory environment, both commonly performed in the sports these athletes compete in, and this study assumes the athlete will perform these tasks the same as they would in a field-based setting;

4. Athletes will be required to adhere to the intervention program; however, while athletes who lived in close proximity to Academy of Sport (Bathurst) completed their sessions with the supervision of their strength and conditioning coach, those athletes...
who lived in more remote locations were expected to compete some of their sessions via satellite or individually with supplemented by supervised sessions only every three weeks. Compliance is therefore difficult to control and report accurately; and

5. Although athletes are specifically told to perform their group training program and no other program, contamination of training programs due to athletes performing additional training cannot be entirely controlled.

1.6 Delimitations

The following delimitations apply to these studies:

1. The study population is restricted to include only pre-elite junior athletes that were used in these investigations, therefore results are a true representation of only this population;

2. Data collection throughout the study will be conducted using standardised protocols within a controlled laboratory environment;

3. Intervention training programs are encouraged by the squad’s strength and conditioning coaches to increase compliance rates in completing the training programs; however, adherence data was not collected during this study; and

4. All movement screening and biomechanical analysis sessions will be supervised by the primary investigator, using the same equipment to maintain consistency within the measures.

1.7 References

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Context of Manuscript in Relation to the Thesis

The manuscript below is an investigation into the first step of injury prevention, injury risk identification through movement screening. This manuscript will provide an analysis of the inter- and intra-rater reliability of a field-based movement screen and the learning and familiarisation effect of raters and athletes. Results and issues identified within this study may offer valuable insight into movement screening procedure requirements and current limitations of these procedures.
Chapter 2. The inter- and intra-rater reliability and learning effect of a movement dysfunction screen for pre-elite youth athletes in novice and expert raters

This chapter is an amended version of the manuscript: Mann K, O’Dwyer N, Bruton M, Edwards S. The inter- and intra-rater reliability and learning effect of a movement dysfunction screen for pre-elite youth athletes in novice and expert raters. To be submitted to the *Sports Medicine*.

**Abstract**

**Purpose:** Field-based movement screens (MSs) are frequently used by coaches and clinicians to assess risk of lower limb injury, but there is conflicting evidence for their reliability. These MSs are also limited in that often they do not assess lumbopelvic stability, despite its strong association with lower limb injuries. This study aimed to determine the reliability of a field-based movement dysfunction screen (MDS) in novice and expert raters, and to ascertain whether there was a familiarisation effect of the athletes performing or the assessors rating the MDS.

**Methods:** Fifty-five pre-elite youth athletes performed the MDS on three separate occasions and videos of their performance were rated three times in randomised order by 18 raters. Kappa score, percentage agreement and intra-class correlation (ICC) were calculated both for each movement and for the MDS composite score. Reliability was established using inter- and intra-rater reliability of novice and expert raters, with learning and familiarisation effects measured across repeated exposure of raters and athletes, respectively.
Chapter 2: Reliability of Movement Screen

**Results:** For individual movements, inter- and intra-rater reliability varied across novice and expert raters based on Kappa score and percentage agreement, but reliability increased between sessions in both novices and experts, from moderate to excellent based on the MDS composite score. The ICC exhibited excellent reliability in both expert and novice raters.

**Conclusions:** Both novice and expert raters demonstrated high variability to rate any single movement reliably. Yet when the individual movements were summed (MDS total score), excellent reliability was observed, providing preliminary evidence that the MDS can be reliably used to assess overall movement competency. This study also highlights that the specific movement tasks within a MDC are a learned skill and require participant familiarisation before data are collected.

**Key points**

- A familiarisation session is required prior to recording MDS performance because a ‘familiarisation effect’ is present in pre-elite youth athletes performing these novel tasks.

- Individual movements of the MDS are not reliable with the current three-point grading system. Future research should examine grading systems containing seven or more categories.

- Total MDS composite score rather than individual movement scores should be utilised to reliably determine an athlete’s overall movement competency.

**2.1 Introduction**

Due to the substantial financial and social benefits of reducing injury prevalence, simple and accessible movement screens (MSs) have been popular tools across all levels of the sporting community (Mottram and Comerford 2008). With injury risk management the
primary aim of most MSs, screening aims to quantify movement dysfunction in an athlete using procedures that may include identification of biomechanical symptoms in dynamic landing tasks (Myer, Ford et al. 2008, Padua, Marshall et al. 2009), dynamic postural stability exercises (Cook, Burton et al. 2006, Cook, Burton et al. 2006), range of motion (Bradley and Portas 2007) or joint proprioception deficiencies (Ebenbichler, Oddsson et al. 2001). Early identification of movement dysfunction via screening (Mann, Edwards et al. 2013), may in turn allow implementation of training programs for injury reduction and therefore lead to lower injury rates among youth sporting populations (Parkkari, Kujala et al. 2001).

For the implementation of MS within the sporting communities, MS protocols must attempt to meet a number of requirements, such as being simple, validated, reliable, cost effective, easily implemented and relevant to sport-specific injuries. Unfortunately, many of the current reliable injury risk identification protocols (Hewett, Myer et al. 2005, Edwards, Steele et al. 2010, Mann, Edwards et al. 2013) are not cost effective or easily implemented because they require gold-standard three-dimensional biomechanical motion analysis. One screening tool that has been widely adopted by coaches and clinicians is the Functional Movement Screen (FMS) (Cook, Burton et al. 2006, Cook, Burton et al. 2006). The FMS comprises seven dynamic movement tasks: the deep squat, hurdle step, inline lunge, shoulder mobility test, active straight leg raise, trunk stability push-up and rotary stability test. These movements are each scored on an ordinal scale from one to three, with four categories, and these categorical scores are then summed for a total score out of 21 (Cook, Burton et al. 2006, Cook, Burton et al. 2006). Whilst research has suggested if this total composite score falls below 14, increased injury risk is present (Kiesel, Plisky et al. 2007, Chorba, Chorba et al. 2010), yet recent research has
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refuted this demonstrating that the FMS is unable to predict injury risk (Bardenett, Micca et al. 2015, Bushman, Grier et al. 2016).

A substantial limitation of the FMS and other currently available movement screens is their lack of assessment of the lumbopelvic region (Myer, Chu et al. 2008), despite the importance of this region for trunk stability during force transfer during motion. Since the lumbopelvic region attaches the trunk to the lower extremities, it is a key area associated with performance enhancement (Hibbs, Thompson et al. 2008) and is thought to be critical in the etiology, rehabilitation and reduction of lower limb injuries (Hewett and Myer 2011). Poor lumbopelvic stability has been linked to many lower limb injuries (Beckman and Buchanan 1995, Cowan, Schache et al. 2004, Zazulak, Hewett et al. 2007, Kuszewski, Gnat et al. 2009, Edwards, Steele et al. 2010, Hewett and Myer 2011, Mann, Edwards et al. 2013) and low back pain (Akuthota, Ferreiro et al. 2008). It is thought that athletes who display delayed or poor neuromuscular control of this region during dynamic jump-landing tasks may be predisposed to lower limb injury through poor stability, excess motion and increased forces experienced by joints (Myer, Chu et al. 2008). Therefore, a major consideration for all movement screening is the inclusion of lumbopelvic assessment, with the single leg squat and/or dip test shown to be a reliable measure of lumbopelvic control (Perrott, Pizzari et al. 2011).

A key requirement of any MS is that it must exhibit high inter- and intra-rater reliability; that is to say, a high level of agreement between different raters (McHugh 2012) and high test-retest reliability of individual raters (Teyhen, Shaffer et al. 2012). These factors are critical for movement screening because of the observational variance that can occur within subjective rating (Tinsley and Weiss 1975). Since movement screening requires the ability of expert raters to observe and identify movement errors (Cook, Burton et al.
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2006, Cook, Burton et al. 2006, Myer, Ford et al. 2008, Padua, Boling et al. 2011), the test protocol must be specific enough to provide a reproducible result between raters and across sessions. Although studies have demonstrated good reliability within some field-based movement screens (Chorba, Chorba et al. 2010, Minick, Kiesel et al. 2010), there are methodological limitations. Many studies (Chorba, Chorba et al. 2010, Gribble, Brigle et al. 2013, Gribble, Brigle et al. 2013, Smith, Chimera et al. 2013) have employed the intra-class correlation coefficient (ICC) to assess reliability. This statistical procedure however, should only be applied to continuous scalar data, not ordinal data (Sim and Wright 2005) such as used in the FMS. More appropriate statistical methodology for reliability in ordinal data is the Kappa score (Sim and Wright 2005) or weighted Kappa, which places more importance on large rather than small differences in ratings between conditions (Sim and Wright 2005). Some studies (Minick, Kiesel et al. 2010, Onate, Dewey et al. 2012, Teyhen, Shaffer et al. 2012) have utilised Kappa to determine inter- and intra-rater reliability, but high reliability has been reported despite low Kappa scores for some movements (i.e. rotary final score k=0.43 (Minick, Kiesel et al. 2010), inline lunge k=0.45 (Teyhen, Shaffer et al. 2012), hurdle step total score k=0.31 (Onate, Dewey et al. 2012)). While these low Kappa scores have been suggested to result from poor scoring descriptions (Minick, Kiesel et al. 2010), the FMS may not be as reliable as previously implied because of incorrect statistical analysis and poor interpretation of previous findings.

Often when an athlete performs a movement screen, they have never performed some of the movements within the screening tool previously (e.g. a tuck jump (Myer, Ford et al. 2008)) and so it is likely that familiarisation occurs when first performing these tasks. A familiarisation effect can be identified via a comparison of repeated sessions of the same task (Hopkins 2000). If a change in performance occurs between sessions because of
practice or experience (Schmidt and Wrisberg 2008), then a familiarisation session(s), must be provided first in order to establish a reliable measure. It is currently unknown whether athletes require familiarisation with procedures prior to rating their movement competency for novel screening instruments.

The viewing methods are an additional component of the MS protocol, which may influence the reliability of the tool, and to the authors’ knowledge, this has not been previously investigated. Many sporting teams and clinicians have adopted simple, real-time, single-viewing, field-based procedures utilising manual grading methods (Cook, Burton et al. 2006, Cook, Burton et al. 2006, Myer, Ford et al. 2008). Whiteside, Deneweth et al. (2016) have highlighted that there may be an inability of the human brain to perform manual rating of multiple error cues simultaneously in a real-time setting. The limit on the capacity of the brain to perform dual tasks was originally described as a ‘bottleneck’, whereby only one of multiple high-speed tasks can be performed at the one time (Craik 1947). Yet more recent multiple resources theory suggests that the human brain can utilise a time-sharing strategy to complete multiple tasks at once (Wickens 2002), although the level of skill of the performer and the bandwidth of information processed are important determinants of performance. It is however, suggested that when multiple visual tasks are required, performance is reduced due to interference between tasks (Wickens 2002). Since manual grading of movement performance requires multiple visual cues to be detected over a short time, the cognitive demands of movement assessment may be reduced by viewing a video of the performance multiple times, focusing on different error cues each time, thereby reducing the attentional demands (Whiteside, Deneweth et al. 2016) and leading to an increase in reliability of the MS tool.
Chapter 2: Reliability of Movement Screen

Therefore, the aim of this study was to (i) determine the inter- and intra-rater reliability of a field-based movement screen in novice and expert raters using different viewing methods; and (ii) evaluate the presence of a learning and familiarisation effect for both raters and participants, respectively. It is hypothesised that the field-based MDS criteria for each movement and total score will display high inter- and intra-rater reliability for both novice and expert raters, and that inter- and intra-rater reliability will improve with repeated exposure to the MDS due to a learning effect.

2.2 Methods

2.2.1 Participants

Fifty-five pre-elite youth athletes (15.0±1.6 years; n=33 athletics, n=10 BMX and n=8 surfing) who had never previously performed movement screening were recruited from the Hunter Academy of Sport (New South Wales, Australia). The Hunter Academy of Sport is one of eleven regional academies across New South Wales, Australia who aim to assist regional pre-elite youth athletes in athletic development. Informed consent was obtained from all participants prior to data collection and all methods were approved by the local Human Research Ethics Committee (2012/157, Appendix 1).

Each athlete performed the MDS that comprised six dynamic movements on three separate occasions (data collection session 1, 2, 3), with a minimum four-week washout period between each data collection session. The dynamic movements were: Tuck Jump, Overhead Squat, Single Leg Squat, Dip Test, Forward Lunge and Prone Hold (details of the task requirements are outlined in Appendix 2). The performance of each movement was videoed in the sagittal and lateral planes at 240 Hz (ZR-200, Casio Computer Co., Ltd, Tokyo, Japan).
2.2.2 Video data analysis

Eighteen individuals \((n = 6\) expert; \(n = 12\) novice) rated the performance of the 55 athletes. The raters were divided into six groups based on three variables (Figure 2-1). First, there were novice and expert raters. An expert (E) rater was defined as an exercise science professional with a minimum of one year of experience completing greater than 150 movement screens, while a novice (N) rater was defined as an individual with less than one year of movement screening experience. Second, the viewing method was either single or multiple views of each movement. A single (Single) video viewing of a movement involved the rater watching the sagittal and lateral plane videos of a movement task once only, and assessing all the movement criteria at once. A multiple (Multiple) video viewing of a movement involved the rater watching the sagittal and lateral plane videos of a movement and assessing only two criteria, then re-watching the videos and assessing two different criteria, and repeating this procedure until all criteria were assessed for that movement. Third, the video data that was viewed was either data collection from session 1 viewed three times, in separate rating sessions (Session 1), or data collection from sessions 1, 2 and 3, each viewed once in separate rating sessions (Session 1, 2, 3).
Chapter 2: Reliability of Movement Screen

The six rating groups that were formed based on these variables were as follows (Figure 1). Expert (E-1-Single; \(n = 3\)) and novice raters (N-1-Single; \(n = 3\)) undertook single video viewings for each movement from data collection session 1 only, on three separate occasions. Different expert (E-123-Single; \(n = 3\)) and novice (N-123-Single; \(n = 3\)) raters undertook single video viewings, on separate occasions, for each movement from data collection sessions 1, 2 and 3. Novices (N-1-Multiple; \(n = 3\)) rated each movements, with multiple video viewings, from data collection session 1 only, on three separate occasions. Different novices (N-123-Multiple; \(n = 3\)) rated movements, with multiple viewings, from data collection sessions 1, 2 and 3 on separate occasions.

The purpose of these six groups was as follows. Ratings of data collection sessions 1, 2 and 3 were compared in order to determine the effect of familiarisation by the athletes performing the movements. All raters, regardless of rating condition, carried out ratings on three separate occasions in order to evaluate any effect of learning by the raters. Experts and novices were compared in order to determine the effect of rating experience on the reliability of the ratings. Single and multiple viewings of the movement videos

Figure 2-1  Raters divided into groups based on MDS viewing method.
were compared in order to determine the effect of simplifying the task for the rater by reducing the number of criteria that were assessed on each viewing.

Each rater scored each movement based on the presence or absence of errors (see Appendix 1) and counted the errors to yield a score (1, 2 or 3) for that movement (a zero for pain was not applicable in this study). Then, they summed the scores for all six movements to determine a composite score out of 27 (total score).

2.2.3 Statistical analysis

Kappa, intra-class correlation (ICC; 2,1) and percentage agreement for each of the six movements were calculated to determine intra- and inter-rater reliability as a pairwise comparison between each rater and analysis method. Kappa was defined as slight (0.00-0.20), fair (0.21-0.40), moderate (0.41-0.60), substantial (0.61-0.80) and almost perfect (0.81-1.00) (Landis and Koch 1977). Intra-class correlations are used to indicate the relationship between scalar data (Baumgartner, Strong et al. 2006) and were defined as poor (<0.40), fair/good (0.40-0.75) and excellent (>0.75) (Fleiss 1986). Percentage agreement was calculated to determine the ratio of the number of occasions that both observers agree the behaviour occurred to the number of all occasions (i.e. the sum of the occasions that the observers agree plus the occasions on which they disagree). This ratio was then converted to a percentage (Birkimer and Brown 1979). To define percentage agreement, the following categories were used, poor (<50%), moderate (51-79%) and excellent (>80%) (Landis and Koch 1977). Statistical analyses were performed using SPSS statistical package (Version 17.0.1, SPSS Inc, Chicago, IL).
2.3 Results

2.3.1 Movement Reliability

2.3.1.1 Intra-rater reliability

As seen in Table 2-1 for the novice single rater reliability when comparing session 1 vs 2 in the single view of the performance of the movement, was shown to have slight to fair Kappa scores across all movements, except for the moderate score in the right lunge (0.43). Whereas the moderate percentage agreement was observed for all movements with the right single leg squat scoring excellent agreement (80%). Inter-class correlations for the total composite score indicated excellent reliability (0.85) with a 95% confidence interval of 0.81.

2.3.1.2 Inter-rater reliability

Inter-rater reliability of multiple novice raters is depicted in Table 2-5 (Session 1, Session 2 and Session 3, Single View Session). When comparing sessions 1, 2 & 3 Kappa reliability was found to be slight to fair across all movements. Percentage agreement displayed moderate reliability in all movements, yet both the right and left dip tests and the prone hold indicated poor reliability, and the tuck jump agreement decreased from moderate to poor from session 1 to session 2 and 3 respectively. Total composite score for the inter-class correlations obtained a fair/good reliability in session 1 that increased to excellent in session 2 and 3 with a 95% confidence interval of 0.68, 0.64 and 0.55 across session 1, 2 and 3, respectively.

2.3.2 Athlete Repeatability

Athlete repeatability, as seen in Table 2-6 (Session 1, Session 2 and Session 3, Single View Session). Kappa scores fluctuated between slight to fair across the 3 sessions across
most movements, apart from the prone hold and the right dip test that displayed moderate reliability in session 1 and substantial reliability in session 2, respectively. Percentage agreement saw an increase in the reliability in all movements from session 1 to session 3, with the exception of the overhead squat and the prone hold that maintained moderate percentage agreement reliability across all sessions. Excellent reliability of the total composite score that steadily increased from 0.85 to 0.92 and 0.95 from session 1 to session 3.

2.3.3 Rater Learning Effect

Rater repeatability, as seen in Table 2-2 (Session 1v2, Session 2v3, Single View Session), identified an increase in Kappa across most movements excluding the overhead and single leg squats. Percentage agreement however increased from session 1v2 to session 2v3 in most movements, except for the right and left single leg squat, and the prone hold that displayed a negligible decrease or remained unchanged. Intra-class correlations identified a substantial increase from fair/good (0.51) to excellent (0.82) reliability in the total composite scores, with a 95% confidence interval of 0.44 and 0.77, respectively.

2.3.4 Single View Screening versus Multiple Views Screening

Tables 2-1, 2-2, 2-5 and 2-6 identify the results of a rater performing a single view screening versus multiple views screening of the movement. Kappa, percentage agreement and inter-class correlations identify minimal variation in the reliability across all conditions when comparing the Single View and Multiple Views.
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2.3.5 Influence of Experience

Inter- and intra-rater reliability of expert raters is identified in Table 2-3 & 2-4. Similarly to the change in analysis condition (Single View versus Multiple Views), there were negligible differences identified when comparing the novice versus expert raters across kappa, percentage agreement and inter-class correlations.

Table 2-1 Intra-rater Reliability of Session 1 Only - Novice Raters.

<table>
<thead>
<tr>
<th>Movement</th>
<th>Single View</th>
<th></th>
<th>Multiple View</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Session 1 v 2</td>
<td>Session 2 v 3</td>
<td>Session 1 v 2</td>
<td>Session 2 v 3</td>
</tr>
<tr>
<td></td>
<td>ICC 95% CI  k</td>
<td>%</td>
<td>ICC 95% CI  k</td>
<td>%</td>
</tr>
<tr>
<td>Tuck Jump</td>
<td>0.48 0.42 0.18 67</td>
<td>0.40 0.30 0.22 78</td>
<td>0.72 0.67 0.45 71</td>
<td>0.51 0.43 0.33 66</td>
</tr>
<tr>
<td>Overhead Squat</td>
<td>0.71 0.65 0.33 73</td>
<td>0.80 0.77 0.50 81</td>
<td>0.72 0.67 0.45 71</td>
<td>0.66 0.59 0.37 68</td>
</tr>
<tr>
<td>Single leg squat left</td>
<td>0.29 0.18 0.22 77</td>
<td>-1 -1 0.27 83</td>
<td>0.56 0.47 0.38 77</td>
<td>0.48 0.42 0.39 82</td>
</tr>
<tr>
<td>Single leg squat right</td>
<td>0.27 0.16 0.25 80</td>
<td>-1 -1 0.25 83</td>
<td>0.62 0.44 0.37 78</td>
<td>0.46 0.38 0.36 80</td>
</tr>
<tr>
<td>Dip test left</td>
<td>0.50 0.42 0.30 62</td>
<td>0.65 0.59 0.39 68</td>
<td>0.44 0.36 0.23 64</td>
<td>0.52 0.44 0.25 62</td>
</tr>
<tr>
<td>Dip test right</td>
<td>0.59 0.51 0.33 63</td>
<td>0.63 0.57 0.39 67</td>
<td>0.62 0.56 0.36 69</td>
<td>0.53 0.46 0.31 64</td>
</tr>
<tr>
<td>Lunge left</td>
<td>0.54 0.47 0.26 73</td>
<td>0.73 0.68 0.52 78</td>
<td>0.72 0.68 0.48 76</td>
<td>0.65 0.60 0.44 73</td>
</tr>
<tr>
<td>Lunge right</td>
<td>0.59 0.51 0.43 76</td>
<td>0.70 0.65 0.51 79</td>
<td>0.74 0.70 0.51 79</td>
<td>0.71 0.65 0.49 76</td>
</tr>
<tr>
<td>Prone hold</td>
<td>0.57 0.53 0.32 52</td>
<td>0.80 0.75 0.45 65</td>
<td>0.83 0.78 0.45 63</td>
<td>0.77 0.72 0.48 64</td>
</tr>
<tr>
<td>Total Score</td>
<td>0.85 0.81 - -</td>
<td>0.89 0.87 - -</td>
<td>0.95 0.94 - -</td>
<td>0.88 0.76 - -</td>
</tr>
</tbody>
</table>

1 A rater within this analysis had zero variance within their screening of this movement and thus no ICC or 95% CI could be calculated.
Table 2-2  Intra-rater Reliability of Session 1,2,3 - Novice Raters.

<table>
<thead>
<tr>
<th>Movement</th>
<th>Single View</th>
<th></th>
<th></th>
<th>Multiple View</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Session 1 v 2</td>
<td>Session 2 v 3</td>
<td>Session 1 v 2</td>
<td>Session 2 v 3</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>ICC 95% CI</td>
<td>k</td>
<td>%</td>
<td>ICC 95% CI</td>
<td>k</td>
<td>%</td>
</tr>
<tr>
<td>Tuck Jump</td>
<td>0.12</td>
<td>-0.05</td>
<td>0.02</td>
<td>-0.02</td>
<td>0.04</td>
<td>-0.04</td>
</tr>
<tr>
<td>Overhead Squat</td>
<td>0.59</td>
<td>0.52</td>
<td>0.31</td>
<td>0.62</td>
<td>0.48</td>
<td>0.36</td>
</tr>
<tr>
<td>Single leg squat left</td>
<td>0.46</td>
<td>0.36</td>
<td>0.16</td>
<td>0.62</td>
<td>0.34</td>
<td>0.20</td>
</tr>
<tr>
<td>Single leg squat right</td>
<td>0.41</td>
<td>0.37</td>
<td>0.20</td>
<td>0.61</td>
<td>0.47</td>
<td>0.36</td>
</tr>
<tr>
<td>Dip test left</td>
<td>0.35</td>
<td>0.24</td>
<td>0.11</td>
<td>0.57</td>
<td>0.54</td>
<td>0.47</td>
</tr>
<tr>
<td>Dip test right</td>
<td>0.01</td>
<td>-0.19</td>
<td>-0.07</td>
<td>0.50</td>
<td>0.41</td>
<td>0.27</td>
</tr>
<tr>
<td>Lunge left</td>
<td>0.36</td>
<td>0.18</td>
<td>0.23</td>
<td>0.63</td>
<td>0.63</td>
<td>0.54</td>
</tr>
<tr>
<td>Lunge right</td>
<td>0.22</td>
<td>0.07</td>
<td>0.06</td>
<td>0.59</td>
<td>0.58</td>
<td>0.50</td>
</tr>
<tr>
<td>Prone hold</td>
<td>0.44</td>
<td>0.35</td>
<td>0.21</td>
<td>0.68</td>
<td>0.65</td>
<td>0.51</td>
</tr>
<tr>
<td>Total score</td>
<td>0.51</td>
<td>0.44</td>
<td>-</td>
<td>0.82</td>
<td>0.77</td>
<td>-</td>
</tr>
</tbody>
</table>
### Table 2-3 Inter- and Intra-rater Reliability of Session 1 Only - Expert Raters.

| Movement             | Session 1 v 2 |         |         | Session 2 v 3 |         |         | Session 1 Only | k   | %    |         | k   | %    |         | k   | %    |         | k   | %    |         | k   | %    |         | k   | %    |         | k   | %    |         | k   | %    |         | k   | %    |         | k   | %    |         |
|----------------------|---------------|---------|---------|---------------|---------|---------|---------------|------|--------|---------|------|--------|---------|------|--------|---------|------|--------|---------|------|--------|---------|------|--------|---------|------|--------|---------|------|--------|---------|------|--------|---------|------|--------|---------|------|--------|---------|------|--------|---------|------|--------|---------|------|--------|---------|
|                      | ICC  | 95% CI | k    | %    | ICC  | 95% CI | k    | %    | ICC  | 95% CI | k    | %    | ICC  | 95% CI | k    | %    | ICC  | 95% CI | k    | %    | ICC  | 95% CI | k    | %    | ICC  | 95% CI | k    | %    |
| Tuck Jump            | 0.43 | -0.05  | 0.41  | 77   | 0.34 | 0.23  | 0.22  | 77   | 0.26 | 0.20  | 0.18  | 63   | 0.48 | 0.42  | 0.36  | 72   | 0.28 | 0.19  | 0.20  | 71   |
| Overhead Squat       | 0.70 | 0.52   | 0.58  | 78   | 0.61 | 0.55  | 0.45  | 82   | 0.65 | 0.56  | 0.32  | 67   | 0.58 | 0.50  | 0.40  | 73   | 0.69 | 0.60  | 0.43  | 73   |
| Single leg squat left| 0.18 | 0.36   | 0.49  | 85   | 0.03 | -0.11  | 0.06  | 83   | 0.42 | 0.35  | 0.24  | 81   | 0.29 | 0.18  | 0.20  | 89   | 0.57 | 0.51  | 0.29  | 87   |
| Single leg squat right| 0.17 | 0.37   | 0.46  | 85   | 0.09 | -0.09  | 0.03  | 87   | 0.34 | 0.25  | 0.17  | 80   | 0.15 | 0.03  | 0.30  | 93   | 0.59 | 0.53  | 0.31  | 87   |
| Dip test left        | 0.32 | 0.24   | 0.04  | 53   | 0.43 | 0.34  | 0.22  | 55   | 0.33 | 0.26  | 0.07  | 39   | 0.51 | 0.43  | 0.39  | 70   | 0.37 | 0.26  | 0.24  | 55   |
| Dip test right       | 0.36 | -0.19  | 0.25  | 43   | 0.49 | 0.41  | 0.17  | 58   | 0.26 | 0.20  | 0.06  | 39   | 0.39 | 0.30  | 0.26  | 66   | 0.61 | 0.54  | 0.35  | 62   |
| Lunge left           | 0.23 | 0.18   | 0.07  | 55   | 0.57 | 0.50  | 0.35  | 63   | 0.10 | 0.06  | 0.07  | 36   | 0.56 | 0.49  | 0.35  | 65   | 0.54 | 0.45  | 0.33  | 64   |
| Lunge right          | 0.34 | 0.07   | -0.10 | 58   | 0.53 | 0.46  | 0.28  | 68   | 0.19 | 0.15  | 0.05  | 35   | 0.39 | 0.32  | 0.25  | 62   | 0.52 | 0.44  | 0.31  | 63   |
| Prone hold           | 0.46 | 0.35   | 0.24  | 45   | 0.50 | 0.43  | 0.23  | 57   | 0.25 | 0.15  | -0.01 | 24   | 0.03 | -0.05 | 0.10  | 31   | 0.39 | 0.34  | 0.17  | 30   |
| Total Score          | 0.81 | 0.44   | -     | -    | 0.83 | 0.83  | -     | -    | 0.71 | 0.49  | -     | -    | 0.88 | 0.86  | -     | -    | 0.85 | 0.81  | -     | -    |
Inter- and Intra-rater Reliability of Session 1,2,3 - Expert Raters.

<table>
<thead>
<tr>
<th>Movement</th>
<th>Session 1 v 2</th>
<th>Session 2 v 3</th>
<th>Session 1</th>
<th>Session 2</th>
<th>Session 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ICC 95% CI k%</td>
<td>ICC 95% CI k%</td>
<td>ICC 95% CI k%</td>
<td>ICC 95% CI k%</td>
<td>ICC 95% CI k%</td>
</tr>
<tr>
<td>Tuck Jump</td>
<td>0.14 -0.04 0.2 64</td>
<td>0.29 0.25 -0.01 62</td>
<td>0.18 0.13 0.08 46</td>
<td>0.37 0.27 0.12 52</td>
<td>0.5 0.28 0.24 52</td>
</tr>
<tr>
<td>Overhead Squat</td>
<td>0.61 0.52 0.37 66</td>
<td>0.58 0.48 0.38 73</td>
<td>0.56 0.48 0.34 61</td>
<td>0.4 0.28 0.17 48</td>
<td>0.59 0.48 0.32 64</td>
</tr>
<tr>
<td>Single leg squat left</td>
<td>0.38 0.25 0.28 73</td>
<td>0.61 0.52 0.31 77</td>
<td>0.4 0.31 0.19 61</td>
<td>0.1 0.1 -0.01 31</td>
<td>0.22 0.17 0.08 39</td>
</tr>
<tr>
<td>Single leg squat right</td>
<td>0.27 0.14 0.32 77</td>
<td>0.26 0.12 0.23 73</td>
<td>0.41 0.36 0.14 65</td>
<td>0 0.01 - 36</td>
<td>0.18 0.14 0.1 42</td>
</tr>
<tr>
<td>Dip test left</td>
<td>0.54 0.43 0.28 57</td>
<td>0.72 0.65 0.5 73</td>
<td>0.49 0.38 0.11 44</td>
<td>0.26 0.2 -0.21 20</td>
<td>0.25 0.19 0.01 23</td>
</tr>
<tr>
<td>Dip test right</td>
<td>0.49 0.37 0.22 58</td>
<td>0.57 0.48 0.38 67</td>
<td>0.53 0.4 0.14 50</td>
<td>0.26 0.21 -0.07 14</td>
<td>0.24 0.18 0.07 33</td>
</tr>
<tr>
<td>Lunge left</td>
<td>0.32 0.27 0.15 55</td>
<td>0.66 0.58 0.43 72</td>
<td>0.47 0.37 0.01 63</td>
<td>0.42 0.26 -0.07 29</td>
<td>0.41 0.26 -0.03 28</td>
</tr>
<tr>
<td>Lunge right</td>
<td>0.42 0.37 0.18 58</td>
<td>0.51 0.4 0.33 69</td>
<td>0.4 0.3 0.09 63</td>
<td>0.33 0.23 -0.1 31</td>
<td>0.41 0.29 -0.15 19</td>
</tr>
<tr>
<td>Prone hold</td>
<td>0.58 0.49 0.18 50</td>
<td>0.73 0.66 0.32 65</td>
<td>0.12 0.1 0.12 28</td>
<td>0.19 0.17 0.03 17</td>
<td>0.12 0.13 0.02 11</td>
</tr>
<tr>
<td>Total Score</td>
<td>0.53 0.42 - - 82 8</td>
<td>0.72 0.44 - - 76 39 - - 0.8 0.53 - -</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

A rater within this analysis had zero variance within their screening of this movement and thus no Kappa value could be calculated.
### Table 2-5  Inter-rater Reliability of Session 1 Only - Novice Raters.

| Movement            | Single View | | | | | | Multiple View | | | |
|---------------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|
|                     | Session 1   | Session 2   | Session 3   | Session 1   | Session 2   | Session 3   | Session 1   | Session 2   | Session 3   | Session 1   | Session 2   | Session 3   | Session 1   | Session 2   | Session 3   |
|                     | ICC 95% CI k | %           | ICC 95% CI  k | %           | ICC 95% CI  k | %           | ICC 95% CI  k | %           | ICC 95% CI  k | %           | ICC 95% CI  k | %           | ICC 95% CI  k | %           |
| Tuck Jump           | 0.50 0.43 0.28 56 | 0.29 0.27 0.16 45 | 0.39 0.34 0.12 49 | 0.30 0.22 0.11 49 | 0.27 0.17 0.12 49 | 0.19 0.13 0.09 47 | 0.50 0.43 0.28 56 | 0.29 0.27 0.16 45 | 0.39 0.34 0.12 49 | 0.30 0.22 0.11 49 | 0.27 0.17 0.12 49 | 0.19 0.13 0.09 47 |
| Overhead Squat      | 0.69 0.57 0.38 64 | 0.56 0.47 0.34 59 | 0.60 0.49 0.31 61 | 0.67 0.59 0.38 65 | 0.61 0.53 0.29 59 | 0.42 0.32 0.10 45 | 0.69 0.57 0.38 64 | 0.56 0.47 0.34 59 | 0.60 0.49 0.31 61 | 0.67 0.59 0.38 65 | 0.61 0.53 0.29 59 | 0.42 0.32 0.10 45 |
| Single leg squat left | 0.30 0.25 0.13 60 | 0.06 0.00 0.06 63 | 0.12 0.04 0.06 72 | 0.37 0.30 0.18 62 | 0.60 0.54 0.43 76 | 0.07 -0.01 0.05 71 | 0.30 0.25 0.13 60 | 0.06 0.00 0.06 63 | 0.12 0.04 0.06 72 | 0.37 0.30 0.18 62 | 0.60 0.54 0.43 76 | 0.07 -0.01 0.05 71 |
| Single leg squat right | 0.32 0.22 0.08 61 | 0.08 0.02 0.14 65 | 0.17 0.10 0.32 71 | 0.37 0.33 0.29 63 | 0.52 0.43 0.25 70 | 0.19 0.12 0.13 68 | 0.32 0.22 0.08 61 | 0.08 0.02 0.14 65 | 0.17 0.10 0.32 71 | 0.37 0.33 0.29 63 | 0.52 0.43 0.25 70 | 0.19 0.12 0.13 68 |
| Dip test left       | 0.33 0.25 0.03 40 | 0.34 0.26 0.09 33 | 0.32 0.25 0.06 40 | 0.43 0.33 0.08 50 | 0.44 0.36 0.14 61 | 0.38 0.27 -0.04 36 | 0.33 0.25 0.03 40 | 0.34 0.26 0.09 33 | 0.32 0.25 0.06 40 | 0.43 0.33 0.08 50 | 0.44 0.36 0.14 61 | 0.38 0.27 -0.04 36 |
| Dip test right      | 0.35 0.26 0.07 44 | 0.50 0.36 0.11 41 | 0.44 0.36 0.16 49 | 0.45 0.35 0.09 49 | 0.59 0.49 0.24 62 | 0.28 0.21 -0.03 45 | 0.35 0.26 0.07 44 | 0.50 0.36 0.11 41 | 0.44 0.36 0.16 49 | 0.45 0.35 0.09 49 | 0.59 0.49 0.24 62 | 0.28 0.21 -0.03 45 |
| Lunge left          | 0.16 0.04 0.08 62 | 0.30 0.20 0.03 58 | 0.28 0.18 0.11 52 | 0.47 0.38 0.16 53 | 0.55 0.46 0.21 63 | 0.09 0.04 0.04 45 | 0.16 0.04 0.08 62 | 0.30 0.20 0.03 58 | 0.28 0.18 0.11 52 | 0.47 0.38 0.16 53 | 0.55 0.46 0.21 63 | 0.09 0.04 0.04 45 |
| Lunge right         | 0.36 0.19 0.20 65 | 0.51 0.42 0.23 68 | 0.25 0.17 0.07 51 | 0.46 0.38 0.16 64 | 0.48 0.40 0.14 63 | 0.19 0.13 0.06 48 | 0.36 0.19 0.20 65 | 0.51 0.42 0.23 68 | 0.25 0.17 0.07 51 | 0.46 0.38 0.16 64 | 0.48 0.40 0.14 63 | 0.19 0.13 0.06 48 |
| Prone hold          | 0.12 0.09 0.06 17 | 0.39 0.28 0.06 21 | 0.50 0.40 0.19 37 | 0.70 0.60 0.19 40 | 0.60 0.48 1.25 45 | 0.53 0.41 0.28 47 | 0.12 0.09 0.06 17 | 0.39 0.28 0.06 21 | 0.50 0.40 0.19 37 | 0.70 0.60 0.19 40 | 0.60 0.48 1.25 45 | 0.53 0.41 0.28 47 |
| Total Score         | 0.79 0.68 - - 0.85 0.64 - - 0.73 0.55 - - 0.84 0.57 - - 0.91 0.77 - - 0.70 0.48 - - |
Table 2-6  Inter-rater Reliability of Session 1,2,3 - Novice Raters.

<table>
<thead>
<tr>
<th>Movement</th>
<th>Single View</th>
<th>Multiple View</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Session 1</td>
<td>Session 2</td>
</tr>
<tr>
<td></td>
<td>ICC 95% CI</td>
<td>k</td>
</tr>
<tr>
<td>Tuck Jump</td>
<td>0.35</td>
<td>0.30</td>
</tr>
<tr>
<td>Overhead Squat</td>
<td>0.53</td>
<td>0.43</td>
</tr>
<tr>
<td>Single leg squat left</td>
<td>0.31</td>
<td>0.23</td>
</tr>
<tr>
<td>Single leg squat right</td>
<td>0.26</td>
<td>0.28</td>
</tr>
<tr>
<td>Dip test left</td>
<td>0.41</td>
<td>0.33</td>
</tr>
<tr>
<td>Dip test right</td>
<td>0.24</td>
<td>0.19</td>
</tr>
<tr>
<td>Lunge left</td>
<td>0.27</td>
<td>0.18</td>
</tr>
<tr>
<td>Lunge right</td>
<td>0.18</td>
<td>0.13</td>
</tr>
<tr>
<td>Prone hold</td>
<td>0.28</td>
<td>0.21</td>
</tr>
<tr>
<td>Total score</td>
<td>0.85</td>
<td>0.64</td>
</tr>
</tbody>
</table>
Chapter 2: Reliability of Movement Screen

2.4 Discussion

The ability to determine movement dysfunction in order to intervene to an individual to potentially reduce their prevalence of musculoskeletal injuries has enormous appeal due to the detrimental social and economic effects of sporting injuries on athletes (Caine, Maffulli et al. 2008). A more feasible solution to identify altered movement strategies than the costly and time-consuming process of three-dimensional biomechanical motion analysis (McLean, Walker et al. 2005) is to develop a reliable field-based movement screen that can be easily implemented by coaches and clinicians alike. For any movement screen to be implemented it must be reliable (Padua, Boling et al. 2011). This study is the first to demonstrate that pre-elite youth athletes display a familiarisation effect when performing novel movement screen tasks, which was not observed on further exposure to performing the tasks. The results also demonstrate a lack of reliability in individual screen tasks, however excellent reliability was observed when using the total composite score.

Previous research has inappropriately employed ICCs to determine the reliability of screening tools for ordinal data (Chorba, Chorba et al. 2010, Gribble, Brigle et al. 2013), which is an incorrect statistical procedure for categorical data, as ICCs are only appropriate for scalar data (Sim and Wright 2005). Within this study, ICCs were employed only for purposes of comparison with previous research of individual movement tasks (ordinal data), and to assess reliability for the total composite score (scalar data). This study employed the kappa score as it is an appropriate statistical measure of reliability of categorical data to assess “true” agreement (Sim and Wright 2005), in addition to the percentage agreement (Mitchell 1979) for individual movements of the MDS.

Novice and expert raters within this study were deemed too variable to reliably rate any of the individual movements within the MDS between rating sessions. This variability has been suggested to be due to the complex nature of viewing multiple identifiable
features at once, thought to interfere with information processing (Whiteside, Deneweth et al. 2016). The results of this study however, indicate that repeated viewing of the movement screen (N-Multiple-1 and N-Multiple-123), to allow reduced number of identifiable features at once, does not result in a learning effect or improve reliability of the rater. The reduced rater reliability observed in the individual movements may be attributed to the small scale on which the movement is scored (Preston and Colman 2000).

The current individual movement scoring system requires each of the movement errors observed to counted up and placed into a category (1, 2 or 3). Research has suggested that scoring criterion of only three categories results in reduced reliability, validity and discrimination, whereas scales between 7-10 categories are most reliable (Preston and Colman 2000). Furthermore, research has shown increased sensitivity when utilising error count as opposed to the three point category method (Perrott, Pizzari et al. 2017). It is therefore suggested that the criterion composing of a summation of the number of errors for each movement (total composite score) be utilised for scoring the individual movements of the MDS instead of the typical three categories used within this study and the FMS.

The categorical limits applied to movement screening are often arbitrary with data lost due to their categorical nature (Sim and Wright 2005). This choice of categorical limit and loss of data can often result in a reduction of statistical power, leaving the kappa score meaningless (Sim and Wright 2005). This reduction in statistical power was likely to be confounded by skewed data distribution of the data for each individual movement task (Sim and Wright 2005) (Table 2-7). That is, most athletes displayed numerous movement errors, leading to majority of participants being rated as a one or two for individual movements (Percentage of participants in category 1 and 2: tuck jump 96%; overhead squat 86%; single leg squat left 95% and right 95%; dip test left 84% and right 83%;
Chapter 2: Reliability of Movement Screen

Lunge left 78% and right 81%; prone hold 42%). This skewed data, which is reflective of the movement competency of this study’s adolescent athletes, contributed to the poor Kappa scores observed, due to Kappa’s inability to differentiate between random and systematic agreements (Sim and Wright 2005). For example, the single leg squat displayed unequal distributed data that contributed to its low Kappa score (Table 2-7) despite its high percentage agreement. As seen in the table below, rater 1 and rater 2 both gave a score of 1 for 48 of the athletes, with only three athletes having a scoring discrepancy. It is therefore critical that future research ensure normal distribution of the data when establishing the reliability of a MS.

Table 2-7 Kappa Analysis: Crosstabulation of two raters scores for a Left Single Leg Squat.

<table>
<thead>
<tr>
<th></th>
<th>Rater 1</th>
<th>Rater 2</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.00</td>
<td>2.00</td>
<td>Total</td>
</tr>
<tr>
<td>Rater 2</td>
<td>48</td>
<td>1</td>
<td>49</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>Total</td>
<td>50</td>
<td>1</td>
<td>51</td>
</tr>
</tbody>
</table>

Measure of Agreement Kappa = -0.027

Regardless of the overall poor reliability observed in individual movements, when scores of the six individual movements were summed together to obtain a total MDC score, excellent reliability, as indicated by its ICCs, was observed in both novice and expert raters. This discrepancy between reliability for individual and total composite score is likely due to the total score utilising a larger scale of 0-27 compared to scale of 0-3 of the individual rating (Preston and Colman 2000). Preston and Colman (2000) identify category scales of less than six categories have reduced reliability and discriminatory power compared with those of six or more. It is therefore suggested that the current MDS is reliable when utilising the total MDS score, however that an increase in scale is required to increase reliability in individual movements.
Despite a learning effect previously demonstrated in novel dynamic movement tasks (Hansen, Dieckmann et al. 2000), the familiarisation effect within movement screening has not previously been determined. This study identifies a familiarisation effect in athletes during initial performance of the MDS, as seen with the total composite score during ‘session 123’ video viewing (N-123-Single, N-123-Multiple and E-123-Single) increasing from moderate to excellent reliability from session1v2 to 2v3. This highlights that this MDS requires at least one familiarisation session in which the athlete performs the MDS prior to rating. It is plausible that more than one familiarisation sessions may be required but the exact number cannot be ascertain within this current study. Without familiarisation of the MDS, the recorded scores of the individual MDS movements cannot be considered a true representation of the athlete’s movement competency. Conversely, no learning effect was present among either novice nor expert raters for the total MDS score during ‘single’ video viewing (N-1-Single and E-1-Single) of the movement. The excellent reliability of the total composite score as a single viewing highlights that this MDS can be reliably replicated in real-time field-based environments which the MDS would be typically employed.

The authors acknowledge potential limitations within this study. Raters within this study were volunteers and had extensive volumes of movement screens to rate. This could have led to reduced attention span during some screening due to the tedious nature of the sessions. The movement screening was recorded on two video cameras (lateral and sagittal views). When watching these videos, it was only possible to watch one view at a time, which therefore increased the time required to view each MDS.
Chapter 2: Reliability of Movement Screen

2.5 Conclusions
The results of this study indicate that a rater’s movement screening experience does not affect their reliability and for raters scoring the MDS. Results also indicate that the total composite score can be reliably used to determine movement competency; however, the individual movements scores should not be relied on. The requirement of athlete familiarisation prior to MDS rating has also been identified. Therefore, it is suggested that MDS classification be based on the total composite score, following a familiarisation session, and that future research increase the scale for individual movement screening scores to obtain more reliable individual movement scores.

2.6 Acknowledgements
The authors gratefully acknowledge the Hunter Academy of Sport for providing the participants for this study and all the contribution of the raters who generously gave their time to complete the movement screening for this study.

2.7 References


Chapter 2: Reliability of Movement Screen


Context of Manuscript in Relation to the Thesis

This manuscript is an investigation into the effectiveness of whether a 12-week intervention program can modify jump-landing strategies in pre-elite youth athletes. The stop-jump task was chosen as the experimental task as many lower limb injuries and intervention programs are associate with landing mechanics during a stop-jump movement. However, many of these investigations have been conducted within an adult population despite the adolescents population being identified as a key population at risk of lower limb injury. With specialised equipment required for many of these intervention programs, it creates accessibility issues in rural and remote communities that often do not have access to these resources. This manuscript addresses these limitations in previous research by providing a 3D biomechanical motion analysis of a stop-jump task and evaluates the effectiveness of four intervention programs (core, landing, core and landing and control) to modify jump-landing strategies and variables associated with lower limb injury risk during landing. Results of this manuscript will provide coaches and clinicians valuable information on the pre-elite youth athlete population and their understanding of training program adaptations of these athletes with limited access to facilities and practical recommendations for injury prevention training.
Chapter 3. Stop-jump landing technique is modified by neuromuscular training programs in pre-elite youth athletes

This chapter is an amended version of the manuscript: Mann K, O’Dwyer N, Bruton M, Edwards S. Stop-jump landing technique is modified by neuromuscular training programs in pre-elite youth athletes. To be submitted to the Medicine and Science in Sports and Exercise.

ABSTRACT

**Purpose:** Neuromuscular training interventions for the reduction of lower limb injuries have been widespread; however, the current local focus on injury prevention at specific joints, when compared to a focus on the global kinetic chain, is less effective, as evidenced by high rates of re-injury. Research suggests that lumbopelvic stability may be critical in the prevention of lower limb injuries in athletes as a global focus in injury prevention. This study’s purpose was to compare the effects of three different 12-week intervention programs on the results of a full biomechanical analysis during a stop-jump landing tasks in pre-elite youth athletes.

**Methods:** Eighty-Nine junior pre-elite athletes with no current signs or symptoms of injury were recruited from the Western Region Academy of Sport. Five successful stop-jump tasks were completed both before and after exposure to one of three different 12-week training programs, or the control program, in conjunction with a strength and conditioning program for each participant. Mixed design factorial analysis of variance (ANOVA) was used to determine statistically significant between-group differences ($P \leq 0.05$).
**Chapter 3: Intervention programs alters stop-jump technique**

**Results:** There was no main effect of intervention type for any kinematic or kinetic variables; however, athletes used a straight trunk posture as shown via increased L5-S1 extension, thoracic-abdominal flexion identified across the landing phase \(\text{pre} = 7.2 \pm 1.0^\circ; \text{post}=4.2\pm0.9^\circ\) in post- than pre-intervention testing. Post-intervention testing showed significantly reduced hip flexion; T12-L1 rotation; hip external rotation, and increased L5-S1 flexion with a decrease in L5-S1 rotation range of motion (ROM), an increase in peak L5-S1 angles and a decrease in L5-S1 peak extension angles within the landing phase than pre-intervention testing. Significantly decreased medial ground reaction force (GRF)s and increased lateral GRFs accompanied by a significant decrease in duration from initial contact (IC) to peak anterior force and a decrease in IC-\(F_{V1}\) loading rate was also identified in post- compared to pre-intervention testing.

**Conclusions:** Results of this study demonstrate that regardless of intervention program, all athletes displayed similar changes pre- vs post-intervention results. It is therefore recommended that a single strength and conditioning program can be implemented in pre-elite youth athletes with poor movement competency as an injury reduction strategy. Interventions with alternate feedback or implemented within athletes with increased movement competency may provide more effective results than the current programs investigated.

**Keywords:** Injury, biomechanics, movement screening, prevention through prediction, dynamic landing

### 3.1 Introduction

The cost of sports injuries in Australia is increasing with an estimated cost of AUS$1.5 billion dollars in 2003 (Medibank Private 2003), rising to AUS$2 billion dollars in 2006 (Medibank Private 2006); however, a lack of population-wide data has limited more
Chapter 3: Intervention programs alters stop-jump technique

recent figures of the exact extent of injury cost in Australia (Finch 2011). Previous research has identified a relationship between growth, maturation and age that may predispose young athletes to injury (Emery 2003, Myer, Chu et al. 2008), specifically lower limb injuries that are more prevalent following adolescence (Finch, Valuri et al. 1998). The adolescent population has a higher incident of sporting injury (Medibank Private 2003), increased adaptability of the tendon to load and stress (Tuite, Renström et al. 1997), and following the pre-pubertal stage of maturation, high risk landing techniques begin to emerge (Hewett, Myer et al. 2004, Sigward, Pollard et al. 2012, Sigward, Pollard et al. 2012). Due to the substantial cost and potentially devastating effect of sporting injuries, injury reduction programs are becoming increasingly popular with the aim of reducing injury risk factors.

Landing technique is considered a key modifiable risk factor in lower limb injury, specifically the eccentric loading phase of a landing movement that is highly influential in the incidence of lower limb injuries (Boden, Dean et al. 2000, Myer, Ford et al. 2008, Edwards, Steele et al. 2010, Mann, Edwards et al. 2013). Landing risk factors such as increased (Richards, Ajemian et al. 1996, Edwards, Steele et al. 2010, Mann, Edwards et al. 2013) or decreased (Boden, Dean et al. 2000) knee joint flexion, incorrect hip movement strategies (Edwards, Steele et al. 2010, Mann, Edwards et al. 2013), increased knee internal rotation (Hewett, Myer et al. 2005) and increase hip adduction angles (Edwards, Steele et al. 2010) have been identified as biomechanical injury risk factors during a jump landing task. Dynamic neuromuscular landing re-training programs in adolescent female volleyball athletes has been shown to decrease forces and modify critical biomechanical injury risk factors during landing. For risk factors such as peak GRF’s and peak knee moments within the eccentric loading phase (Hewett, Stroupe et al. 1996), landing retraining is a commonly used intervention for the reduction of lower limb
injuries (Hewett, Lindenfeld et al. 1999, Myklebust, Engebretsen et al. 2003, Mandelbaum, Silvers et al. 2005). Many of these programs however, have been implemented within a late adolescent or adult population (Chappell and Limpisvasti 2008, Herman, Weinhold et al. 2008, McCurdy, Walker et al. 2012). This is despite research suggesting that early adolescence population are at a key development phase for implementation of landing retraining injury prevention strategies (Myer, Faigenbaum et al. 2011). During the critical early adolescence phase, cognitive and motor capabilities are highly susceptible to age appropriate training interventions (Myer, Faigenbaum et al. 2011). Before early adolescence (children younger than 12 years) is not the most appropriate time to implement interventions as they are unable to alter lower limb biomechanics with training (DiStefano, Blackburn et al. 2011). Dynamic neuromuscular training programs in adolescent females has been reported to be effective for improving their lower limb movement mechanics during landing and in turn, decreasing injury risk (Myer, Ford et al. 2005). Large gains in performance and stability within the novice populations are thought to occur mainly through neuromuscular adaptations such as more comprehensive and synchronous firing of the muscular unit. These neuromuscular adaptations can result in improved skill and coordination (Rutherford and Jones 1986), which supports the notion that the novice adolescent population as at a key time for intervention strategies to be implemented aimed at reducing their injury risk (Myer, Faigenbaum et al. 2011).

For interventions to be successful within this population, equipment must be readily available and strategies suited to junior sporting organisations. Many of the current neuromuscular retraining programs are performed in controlled environments such as supervised gyms and require specialised equipment (Hewett, Lindenfeld et al. 1999, Myklebust, Engebretsen et al. 2003). This can create access issues, especially in rural
regions where access to formal sporting structures and support mechanisms is limited (Finch, Mahoney et al. 2003). Reduced access may affect adherence rates (Tappe, Duda et al. 1989), which is negatively associated with injury risk (Soligard, Nilstad et al. 2010). Therefore, to have the greatest effect on adolescent sporting injury rates, it is essential that an accessible, easily implemented field based program is developed to aid injury prevention among pre-elite youth athletes.

A key focus of neuromuscular prevention strategies has been to improve an individual’s landing technique (Hewett, Stroupe et al. 1996, Myer, Ford et al. 2005). Yet focusing on a specific joint (e.g. the knee joint for ACL injuries) and its symptoms (e.g. increased knee abduction in ACL injuries) to prevent lower limb injuries is ineffective, as high rates of injury and re-injury remain (Motttram and Comerford 2008) despite advanced in sports medicine and rehabilitation (Hewett, Ford et al. 2006). A broader focus on the entire kinetic chain might therefore be warranted that incorporates the lumbopelvic region. An athlete who displays delayed or poor neuromuscular control in the lumbopelvic region during dynamic landing tasks may be predisposed to a lower limb injury through poor stability, motion and increased forces experienced by the lower limb joints (Myer, Chu et al. 2008). Not only is the lumbopelvic region considered to play a critical role in the aetiology, rehabilitation and prevention of lower limb injuries (Beckman and Buchanan 1995, Beynnon, Murphy et al. 2002, Cowan, Schache et al. 2004, Sherry and Best 2004, Willson, Dougherty et al. 2005, Chumanov, Heiderscheit et al. 2007, Edwards, Steele et al. 2010, Hewett and Myer 2011, Mann, Edwards et al. 2013, Edwards, Brooke et al. 2017) such as lower back (Akuthota, Ferreiro et al. 2008) and groin pain (Edwards, Brooke et al. 2017), it has also been associated with performance enhancement during R-COD (Edwards, Austin et al. 2017). Furthermore, trunk stabilisation during dynamic tasks is of particular concern during the adolescent phase, when athletes undergo rapid
Chapter 3: Intervention programs alters stop-jump technique

Increases in height and body mass due to puberty (Myer, Chu et al. 2008). This is largely a result of an increase in the length of the long bones, which will increase the height of centre of gravity (Myer, Chu et al. 2008) and challenge trunk stabilisation (Myer, Chu et al. 2008) of the adolescent athlete. Therefore, the purpose of this study is to compare the effects of three different 12-week intervention programs on the results of a full biomechanical analysis during a stop-jump landing task in pre-elite youth athletes.

3.2 Methods

3.2.1.1 Participants

Eighty-nine junior pre-elite athletes (age = 15.2 ± 2.2 years, height = 171.1 ± 9.4 cm; mass = 61.9 ± 12.3 kg) with no current signs or symptoms of injury were recruited from the Western Region Academy of Sports Basketball, Hockey, Netball, Triathlon and Softball teams (Table 3-1). A total of 67 athletes completed both pre- and post-intervention testing, and were included within the analysis. Written informed consent was obtained from each participant prior to data collection, with parental/guardian consent obtained for minors. All methods were approved by the institution’s Human Research Ethics Committee (2012/157, Appendix 2).
**Chapter 3: Intervention programs alters stop-jump technique**

Table 3-1  Descriptive characteristics of pre-elite youth athletes (n- no additional training; C-Core; L-Landing; C&L-Core & Landing).

<table>
<thead>
<tr>
<th>Variable</th>
<th>Pre-Intervention</th>
<th>Post-Intervention</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>n</td>
<td>C</td>
</tr>
<tr>
<td><strong>Sport</strong></td>
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<tr>
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</tr>
<tr>
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<td>23</td>
</tr>
<tr>
<td><strong>Sex</strong></td>
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<td>6</td>
</tr>
<tr>
<td>Female</td>
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<tr>
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<td>23</td>
</tr>
<tr>
<td><strong>Movement</strong></td>
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</tr>
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<td>Very Low</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>Low</td>
<td>16</td>
<td>20</td>
</tr>
<tr>
<td>Moderate</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>High</td>
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<td>0</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
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<td><strong>Tanner Scale</strong></td>
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<tr>
<td><strong>TOTAL</strong></td>
<td>22</td>
<td>23</td>
</tr>
</tbody>
</table>
3.2.2 Experimental Task

Since eccentric control during a landing task is commonly implicated in altered landing patterns during a stop-jump task (Edwards, Steele et al. 2010, Mann, Edwards et al. 2013), each participant performed five successful stop-jump tasks before and after the completion of a 12-week intervention program. A successful stop–jump was defined as a participant: obtaining an adequate approach speed of between 3.5 and 4.5 m·s⁻¹, measured using infrared timing lights (Smart Speed, Fusion Sport, Queensland, Australia); placing a foot wholly on the force platform during the horizontal landing phase; and contacting the ball suspended from the ceiling with both hands. The approach speed was based on 10 m sprint times from the Western Region Academy of Sports previous years (4.0 ± 0.1 m·s⁻¹), as these are considered typical values within this cohort. During task familiarisation, the jump height effort was standardized for each participant by positioning the ball at the maximum height each participant could touch the ball with both hands after performing the horizontal landing phase of the stop-jump task.

3.2.3 Experimental Procedure

Preceding biomechanical testing, a familiarisation session of the movement screening protocol was conducted. During biomechanical testing, a static trial was performed prior to completing a 5-minute self-paced warm-up on a cycle ergometer (Monark 828E, Varburg, Sweden) and a movement dysfunction screen (Appendix 2). Each movement within this screening tool (tuck jump, overhead squat, single leg squat, dip test, forward lunge, prone hold) was scored based on the presence or absence of errors observed by a single rater in single view of the sagittal and frontal plane videos (see Appendix 2). After viewing the videos, the rater and counted the errors for the individual movement to allocate a categorical score (1, 2 or 3) for that movement (a zero for pain was not
Chapter 3: Intervention programs alters stop-jump technique

applicable in this study). The categorical scores of each of the six individual movements were summed to determine a total composite score out of 27 (total score).

The participant performed five successful dynamic stop-jump trials after being familiarised with the movement. During each trial, the three-dimensional ground reaction forces generated at landing were recorded (2,500 Hz) using two multichannel force platforms with built-in charge amplifiers (Type 9281CA, Kistler, Winterthur, Switzerland; Type 9821EA, Kistler, Winterthur, Switzerland) embedded in the floor and each connected to control units (Type 5233A, Kistler, Winterthur, Switzerland). The participant’s three-dimensional lower limb and trunk motion was recorded (250 Hz) using 12 Qualisys Oqus 300+ camera system (Qualisys AB, Göteborg, Sweden). Passive reflective markers were placed on each participant’s lower limbs, pelvis and torso, on the shoe at the first and fifth metatarsal head, mid anterior foot and calcaneus, lateral and medial malleolus, lateral and medial femoral epicondyle, four-marker cluster placed on the leg and thigh, greater trochanter, anterior superior iliac spine, posterior superior iliac spine, iliac crest, sternal notch, xiphoid process, acromion, lumbo-sacral (L5-S1) intervertebral joint space, thoraco-lumbar (T12-L1) intervertebral joint space, bilaterally on the ribcage at the level of the T12-L1 intervertebral joint space and immediately superior to the iliac crest marker, and five tracking markers placed on the lumbar region. To avoid losing view of the passive reflective markers, the participants wore minimal clothing (shorts), and their athletic running shoes and socks.

3.2.4 Intervention Program

Each participant was randomised into one of four intervention programs: core; landing retraining, core and landing retraining; or control. Appendix 3 details the four specific exercises within each intervention program and their associated competency criteria that
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had to be met by the participant at each level before moving on to the next stage of the specific intervention program. Each athlete was provided with a compact disk (CD) that included videos of all the exercises for each phase of their program. In addition to their program, all athletes also performed a standard strength and conditioning program provided by the Western Region Academy of Sport (Appendix 5), consisting of four key exercises (push, pull, squat and lunge). Strength and Conditioning interns (undergraduate exercise and sports science students) monitored the athletes progress throughout the program and performed movement competency testing of these athletes every three weeks. The protocol for each intervention was as follows:

Common strength and conditioning program: This program was designed and implemented by the Western Region Academy of Sport and encompassed a dynamic warm up, a push, pull, squat and lunge resistance exercise and cool down stretches, performed by all athletes (Appendix 5).

Program 1 – Core program: This program implemented a range of functional balance and postural stability core exercises designed to improve lumbopelvic stability. Athlete’s undertaking this program progressed through the four levels of core stabilisation training; stabilisation, stabilisation and strength, integrated stabilisation strength and explosive stabilisation using the core stabilisation guidelines outlined by Clarke (2004).

Program 2 – Landing retraining program: The landing re-training program included basic strength, stability and plyometric exercises in attempt to re-train the landing technique of the athletes included within this program. Athletes progressed from basic strength and stability to the six stages of plyometric training outlined by Chu (1999).

Program 3 – Core program and landing retraining program: This program combined both the core stability and landing re-training programs together by incorporating a half load of each training program. The design of this program was to provide a core stability and
landing re-training exercises that also followed the guidelines outlined by Clark (2004) and Chu (1999).

Program 4 – Control program: This program did not perform any additional intervention training on top of their strength and conditioning program provided by the Western Region Academy of Sport.

3.2.5 Data Reduction and Analysis

Analysis of the three-dimensional kinematic and kinetic data was performed using Visual 3D software (Version 5, C-Motion, Germantown, MD), and GRF data analysed in a custom built LabView program (Lab-View 2014, National Instruments, Austin, TX, USA). Fourth-order zero-phase Butterworth low-pass digital filters were used to filter all raw kinematic coordinates; GRF’s; free moments and centre of pressure data prior to calculating individual joint kinematics and net internal joint moments \(f_c = 18 \text{ Hz}\), whereas the raw GRFs were filtered separately to calculate GRF variables \(f_c = 50 \text{ Hz}\). Segment masses were defined from Zatsiorsky, Seluyanov et al. (1990) for the foot, shank and thigh segments, and Pearsall, Reid et al. (1996) for the pelvis, lumbar, thorax and trunk segments. Segmental inertial properties of each segment were modelled using geometric primitives (Hanavan 1964) with the foot, shank and thigh defined as a frusta of a right cone, and the pelvis, lumbar, thorax and trunk defined as elliptical cylinders (Seay, Selbie et al. 2008). To support Cartesian local coordinate system sign conventions, all segments were defined as follows: x-axis as medio-lateral, y-axis as anterior-posterior and z-axis as the vertical direction. Loads applied to each joint were defined as net internal joint moments that were normalised to each individual participant’s body mass and height, and ground reaction forces were normalised to body weight to account for variations between participants. Using the 18 Hz filtered kinetic data, the horizontal
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landing phase was defined from initial contact (IC) when the vertical GRF exceeded 10 N to the first peak ($F_{V1}$) and local minimum ($F_{V2}$), to the second vertical GRF peak ($F_{V3}$) and then to take-off (TO) when the vertical GRF fell below 10 N. For each trial, intersegment joint angles of the ankle, knee, hip, L5-S1 (lumbar segment relative to the pelvis), T12-L1 (lumbar segment relative to the thoracic segment), Thoracic_Ab-Pelvis (trunk segment relative to the pelvis segment) at the time of IC, $F_{V1}$, $F_{V2}$, $F_{V3}$, and TO were calculated. Peak ankle, knee, hip, L5-S1, and T12-L1 joint angles and net internal moments, and peak GRF and impulses, were identified during the phase from IC to TO. While both the left and right lower limb data were analysed, only the left lower limb was included in statistical analysis, as lower limb were show to be symmetrical (Appendix 4).

3.2.6 Statistical Analysis

A G*Power calculation of the required sample size was performed for an actual power of 0.96. This calculation showed a total sample size of 56 athletes was required, suggesting that this study is adequately powered. A series of mixed-design factorial analyses of variance (ANOVA) were performed on the outcome variables that consisted of joint angles at specific time events, peak joint angles, ranges of motions (ROMs), ground reaction forces (GRFs) and joint moments during the stop-jump task. The primary effect of interest was the independent factor of intervention (core, landing, core-landing and control), and the secondary repeated measures factor was that of time (pre- and post-intervention). There were four factors for analyses of joint angles (intervention*pre/post*events*angles). Time events comprised five levels; the discrete GRF time-points within the stance phase of the R-COD (IC, $F_{V1}$, $F_{V2}$, $F_{V3}$, TO), while angles comprised of 18 levels; six joints (ankle, knee hip, L5-S1, T12-L1, TrunkAB_Pelvis ) in three respective planes (x,y,z). There were three factors for the other kinematic analyses of ROM (intervention*pre/post*ROM) and peak angles
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(intervention*pre/post*peak angles). Three factors were also used for each of the kinetic variable analyses of joint moments (intervention*pre/post*moments), GRF peaks (pre/post*GRF peaks), GRF impulse (pre/post*GRF impulse) and GRF timing (intervention*pre/post*GRF timing). It was to be expected that the outcome variables (joint angles, segment alignments, joint moments, ROMs and GRFs) would vary significantly across the stages of the stop-jump landing phase. Similarly, significant differences were to be expected between the variables within each category of outcome variable. For example, differences would be expected between joint angles and between segment alignments. Such differences, however, were not relevant to the primary hypotheses concerning the effects of the interventions or pre/post testing. Therefore, only main effects or interactions that involved the factors of intervention and/or pre/post testing were reported here.

All tests were conducted using Statistica (v.13, StatSoft Inc., Tulsa, OK, USA), with significant results reported where \( p<0.05 \); Tukey Post hoc tests were used to identify where the significant effect occurred. Assumptions of constant variance and normality were examined for all data through their residuals and distribution Kolmogorov Smirnov test with Lilliefors correction, respectively, and both were satisfied and accepted. If Tukey post hoc did not reveal the significant effect where a significant interaction was indicated in the ANOVA results, univariate and independent t-tests were employed to assess which variable was responsible for the interaction and effect size analyses, respectively. Effects sizes \( \eta^2 \) were defined as trivial \((<0.0099)\), small \((0.0099-0.0588)\), moderate \((0.0588-0.1379)\), and large \((>0.1379)\) sizes (Richardson 2011).
3.3 Results

3.3.1 Kinematics

Joint angles showed no significant main effect of intervention ($F_{3,62}=0.23$, $p=0.88$, $\eta^2=0.0109$) or pre/post ($F_{1,62}=0.18$, $p=0.67$, $\eta^2=0.0029$); however, significant interactions between pre/post*events ($F_{4,248}=4.10$, $p=0.003$, $\eta^2=0.0620$), pre/post*angles ($F_{17,1054}=3.71$, $p<0.001$, $\eta^2=0.0565$) and pre/post*events*angles ($F_{68,4216}=2.04$, $p<0.001$, $\eta^2=0.0318$; Table 3-2) were present. *Post hoc* tests failed to identify the source of the significance in pre/post*events yet revealed that from pre- to post-intervention, the grand mean across all events was greater for L5-S1 extension (pre= 11.8±1.1°; post= 1.3±0.9°; $p<0.01$) and thoracic-abdominal (pre= 7.2±1.0°; post= 4.2±0.9°; $p<0.05$) joint angles pre- compared to post-intervention. Comparing pre- to post-intervention, a significant reduction in hip flexion at IC ($p<0.001$), $F_{V1}$ ($p<0.001$); thoracic abdominal flexion at all events ($p<0.001$); T12-L1 rotation at $F_{V1}$ ($p<0.05$); hip external rotation at $F_{V3}$ ($p<0.01$) and increased L5-S1/L5-S1 flexion at all events ($p<0.001$) was identified. Whilst joint ROM showed no main effect of intervention ($F_{3,62}=0.11$, $p=0.95$, $\eta^2=0.0053$) or pre/post ($F_{1,62}=3.81$, $p=0.06$, $\eta^2=0.0578$) for peak joint angles, but a significant pre/post*peak angle interaction ($F_{29,1798}=2.77$, $p<0.001$, $\eta^2=0.0428$) were observed. *Post hoc* analysis identified an increase in peak L5-S1 flexion angles ($p<0.05$), and a decrease in L5-S1 peak extension angles ($p<0.05$) from pre- to post-intervention. No main effects of intervention ($F_{3,62}=0.11$, $p=0.95$, $\eta^2=0.0053$) or pre/post ($F_{1,62}=0.86$, $p=0.35$, $\eta^2=0.0138$) for segment angles were observed. There was a significant pre/post*events*segment interaction ($F_{80,4960}=2.00$, $p<0.001$, $\eta^2=0.0312$; Table 3-2) which *post hoc* revealed the
Chapter 3: Intervention programs alters stop-jump technique

stance foot was in a more dorsiflexed position at IC, plantarflexion position at \( F_{V2} \) and \( F_{V3} \) and TO, reduced lumbar rotation at \( F_{V1} \), and the thigh segment to be less internally rotated at \( F_{V3} \) and TO post- versus pre-intervention \((p<0.001)\).
### Chapter 3: Intervention programs alters stop-jump technique

**Table 3-2** Kinematic changes between pre- and post-intervention in a stop-jump movement.

<table>
<thead>
<tr>
<th>Outcome Variable</th>
<th>Change</th>
<th>Event</th>
<th>PRE Mean ± SD</th>
<th>POST Mean ± SD</th>
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<tr>
<td><strong>Joint Angles</strong></td>
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<tr>
<td>L5S1 Flexion</td>
<td>↓</td>
<td>IC</td>
<td>-1.7° ± 1.1°</td>
<td>1.3° ± 1.0°</td>
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<td>Hip Flexion</td>
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<td>IC</td>
<td>61.5° ± 1.1°</td>
<td>58.4° ± 1.1°</td>
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<td>Thoracic Abdominal flexion</td>
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<td>IC</td>
<td>4.2° ± 1.0°</td>
<td>1.1° ± 0.9°</td>
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<tr>
<td>Hip Flexion</td>
<td>↓</td>
<td>Fv1</td>
<td>64.2° ± 1.1°</td>
<td>61.3° ± 1.2°</td>
</tr>
<tr>
<td>L5S1 Flexion</td>
<td>↑</td>
<td>Fv1</td>
<td>-0.9° ± 1.1°</td>
<td>2.3° ± 1.0°</td>
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<tr>
<td>T12L1 Rotation</td>
<td>↓</td>
<td>Fv1</td>
<td>2.0° ± 1.0°</td>
<td>-0.1° ± 0.3°</td>
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<td>Thoracic Abdominal flexion</td>
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<td>Fv2</td>
<td>5.3° ± 1.1°</td>
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<td>L5S1 Flexion</td>
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<td>Fv2</td>
<td>0.9° ± 1.2°</td>
<td>4.0° ± 1.0°</td>
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<td>Fv3</td>
<td>3.4° ± 1.1°</td>
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<td>Hip External Rotation</td>
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<td>Fv3</td>
<td>8.0° ± 1.2°</td>
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<td>L5S1 Flexion</td>
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<td>Fv3</td>
<td>0.6° ± 1.2°</td>
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<tr>
<td>Thoracic Abdominal flexion</td>
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<td>Fv4</td>
<td>3.3° ± 1.1°</td>
<td>0.5° ± 1.0°</td>
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<tr>
<td>L5S1 Extension</td>
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<td>TO</td>
<td>8.0° ± 1.1°</td>
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<td>Thoracic Abdominal flexion</td>
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<td>3.2° ± 0.2°</td>
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<tr>
<td>L5S1 flexion</td>
<td>↑</td>
<td>-</td>
<td>3.5° ± 1.0°</td>
<td>7.1° ± 1.0°</td>
</tr>
<tr>
<td>L5S1 extension</td>
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<td>9.2° ± 1.0°</td>
<td>5.6° ± 0.9°</td>
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<tr>
<td><strong>Segment Angles</strong></td>
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<tr>
<td>Foot Dorsiflexion</td>
<td>↑</td>
<td>IC</td>
<td>24.0° ± 1.6°</td>
<td>26.7° ± 1.4°</td>
</tr>
<tr>
<td>Lumbar Rotation</td>
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<td>Fv1</td>
<td>2.6° ± 1.2°</td>
<td>0.1° ± 0.6°</td>
</tr>
<tr>
<td>Foot Dorsiflexion</td>
<td>↓</td>
<td>Fv2</td>
<td>1.2° ± 2.7°</td>
<td>-2.1° ± 0.3°</td>
</tr>
<tr>
<td>Foot Plantarflexion</td>
<td>↑</td>
<td>Fv3</td>
<td>3.3° ± 2.7°</td>
<td>6.5° ± 0.3°</td>
</tr>
<tr>
<td>Thigh External Rotation</td>
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<td>Fv4</td>
<td>8.6° ± 1.1°</td>
<td>6.2° ± 1.0°</td>
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<tr>
<td>Foot Plantarflexion</td>
<td>↑</td>
<td>TO</td>
<td>32.5° ± 2.9°</td>
<td>35.1° ± 0.5°</td>
</tr>
<tr>
<td>Thigh External Rotation</td>
<td>↓</td>
<td>TO</td>
<td>7.7° ± 1.4°</td>
<td>5.2° ± 1.2°</td>
</tr>
</tbody>
</table>
### Table 3-3

Kinetic changes between pre- and post-intervention in a stop-jump movement.

<table>
<thead>
<tr>
<th>Outcome Variable</th>
<th>Change</th>
<th>PRE Mean ± SD</th>
<th>POST Mean ± SD</th>
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<td><strong>Peak GRF</strong></td>
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<td>Medial GRF</td>
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<td>0.1 ± 0.0</td>
<td>0.1 ± 0.1</td>
</tr>
<tr>
<td>Lateral GRF</td>
<td>↑</td>
<td>-0.3 ± 0.0</td>
<td>-0.3 ± 0.2</td>
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<tr>
<td><strong>GRF Timing</strong></td>
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<tr>
<td>IC-F&lt;sub&gt;max&lt;/sub&gt;</td>
<td>↓</td>
<td>0.2 ± 0.0</td>
<td>0.2 ± 0.2</td>
</tr>
<tr>
<td><strong>Loading Rate</strong></td>
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<td></td>
</tr>
<tr>
<td>IC-F&lt;sub&gt;v1&lt;/sub&gt;</td>
<td>↓</td>
<td>7.6 ± 0.3</td>
<td>6.8 ± 0.3</td>
</tr>
</tbody>
</table>
3.3.2 Kinetics

No significant main effects of intervention for joint moments (F_{3,62}=0.98, p=0.41, \eta^2=0.0452) or any interactions were observed. Peak GRF showed a significant main effect for pre/post (F_{1,84}=51.72, p=0.00, \eta^2=0.9368) yet not for intervention (F_{3,244}=0.42, p=0.79, \eta^2=0.7985), and a significant pre/post*peak GRF interaction was observed (F_{4,336}=11.53, p<0.001, \eta^2=0.0666; Table 3-3). When comparing pre- to post-intervention, post hoc analysis identified a significant decrease in medial GRFs (p<0.001) but an increase in lateral GRFs (p<0.001). Although no main effect of intervention was identified in GRF timing (F_{3,84}=0.82, p=0.49, \eta^2=0.0334), a pre/post*GRF timing interaction was also evident (F_{7,588}=3.74, p<0.001, \eta^2=0.2067; Table 3-3). Post hoc analysis identified a significant pre/post-intervention difference, with a significant decrease in the duration from IC to F_{ANT} displayed (p<0.05). There was no main effect of intervention identified in LR F_{V1} (F_{1,62}=7.50, p=0.01, \eta^2=0.1079); however, a significant interaction of pre/post revealed it decrease from pre- to post-intervention identified by post hoc analysis.

3.4 Discussion

With injury prevalence rates high and the cost of sports injuries increasing (Medibank Private 2003, Medibank Private 2006), injury reduction programs are an appealing option for coaches and clinicians to reduce injury risk in their athletes. The current study is the first to compare the effects of three different field-based injury reduction programs on the stop-jump landing mechanics among pre-elite youth athletes. Results revealed no significant differences between the interventions; however, a significant change in landing mechanics were identified between pre/post 12-week intervention. Specifically,
all youth athletes, regardless of training intervention group, landed in a more upright trunk relative to pelvis position in post-intervention than pre-intervention testing. Youth athletes generally lack previous exposure to age appropriate strength and conditioning training, due to policies outlining the requirement for supervision by qualified professionals prior to the age of 16 (Parker 2003). Within this study, screening revealed that the athletes displayed poor movement competency total scores, which may be indicative of a lack of training. Neuromuscular training often elicits a training effect that is commonly identified in strength interventions programs, whereby the neuromuscular activation patterns become more succinct leading to an improved performance (Sale 1988). Thus, the altered movement pattern between pre- and post-intervention is likely related to an increase in neuromuscular control as a result of general training rather than any specific intervention program.

Research has identified adolescent athletes as an ideal target population to retrain (DiStefano, Padua et al. 2009). Older populations have a reduced ability for tissues to adapt in response to internal and external loads (Tuite, Renström et al. 1997); highlighted in an older cohort of 18-30 years old who failed to alter their stop-jump mechanics after a 9-week strength program (Herman, Weinhold et al. 2008). Younger athletes (<13 years) have also been identified as displaying no training benefits, suggested to be due to alternate requirement for early adolescent athletes. This early adolescent population are suggested to require internal feedback, such as bend your knees, in contrast to the external feedback required for older populations (DiStefano, Padua et al. 2009). The middle period of adolescence phase appears to be the optimal period for neuromuscular intervention to elicit a positive effect. The present study supports this notion as strength training for youth athletes (15.2±2.2 years) was able to alter jump-landing mechanics after a 12-week intervention program. It is likely that differences in training age for strength training may
contribute to the different findings between this and other studies. Therefore, strength training can successfully alter jump-landing mechanics in those adolescent athletes who self-report no or little strength training experience.

Irrespective of the type of intervention program, this study identified significant pre/post program differences in landing mechanics, with all athletes landing in a more upright trunk relative to pelvis position. While this upright trunk landing posture in itself has been suggested to be an ACL injury risk factor (Griffin, Agel et al. 2000, Shimokochi, Ambegaonkar et al. 2013), the present study did not observe any ACL landing risk factors associated with this landing strategy. That is, no indications of higher posterior GRF, lower knee flexion at IC or greater peak knee abduction during landing were observed, all of which have been defined as key injury factors (Shimokochi, Ambegaonkar et al. 2013). It is possible that the youth athletes here, most of whom commenced the program with poor movement competency, were attempting to modify their landing strategy by adopting a ‘guarding’ (van der Hulst, Vollenbroek-Hutten et al. 2010) or ‘splinting’ (Arendt-Nielsen, Graven-Nielsen et al. 1996) technique. While a universal definition of this phenomenon does not exist in the literature (van der Hulst, Vollenbroek-Hutten et al. 2010), it has been characterised by a general increase in muscular tension, specifically increased activation of the superficial core musculature, and has also been related to low back pain (Ahern, Follick et al. 1988, Arendt-Nielsen, Graven-Nielsen et al. 1996). Strength and Conditioning training often enforces a similar protective strategy with control, good posture and bracing as correct technique (Baechle and Earle 2004) as a strategy to protect athletes from injuries during training (Faigenbaum, Kraemer et al. 2009). We postulate that the splinting strategy for maintaining a upright trunk posture may have been a transfer training effect from the strength and conditioning training that all athletes undertook, which influenced this modification of the dynamic stop-jump movement performance. It is unknown however, whether this altered movement strategy
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has been adopted by these athletes due to their novice status of training, whether it is attributed to the early learning stage in which athletes typically display stiff looking movements (Schmidt and Wrisberg 2008), and/or if these altered patterns are beneficial or detrimental to lower limb injury risk.

Adopting a ‘guarding’ technique, landing in a more upright position by reducing trunk relative to pelvis flexion and rotation, may have been an attempt by the participants to control their body segment stability during the task in a strategy to reduced their degrees of freedom, i.e the complexity of the task (Wang, O’Dwyer et al. 2013). Increased trunk movement has been shown to be indicative of increased risk of knee injury due to the influence on dynamic stability of the knee joint and low back injury (Zazulak, Hewett et al. 2007). With both lower trunk motion (Griffin, Agel et al. 2000, Shimokochi, Ambegaonkar et al. 2013) and greater trunk motion (Zazulak, Hewett et al. 2007) both associated with knee injuries, it is plausible that there is an optimal middle range of trunk motion that is ideal for reducing injury risk. This would be similar to findings at the knee, where decreased and increased knee flexion has been associated with ACL injuries (Boden, Dean et al. 2000) and patellar tendinopathy (Edwards, Steele et al. 2010), respectively. However, further research is required to determine if this this notion is so. McGill (2010) suggested a necessary balance between increased stability and mobility for injury prevention and optimal performance. This notion supports recent research that highlighted the need for athletes to possess some trunk motion when performing a R-COD movement, to effectively utilise the stretch shortening cycle for optimal force production (Edwards, Austin et al. 2017). This is supported by additional research that found that those with chronic low back pain who employed a ‘splinted’ movement strategy displayed decreased movement speed and power (Arendt-Nielsen, Graven-Nielsen et al. 1996). It is therefore suggested that employing the splinting or guarding
mechanism could potentially reduce the reactive athletic capability of these pre-elite youth athletes, yet the effect on injury risk utilising this strategy remains unclear.

Results of this study did not identify any differences in ankle or knee mechanics between pre/post programs, which could be a result of the feedback strategies utilised during the intervention programs. Research has determined that externally focused feedback (implicit), focusing on the result of the movement such as a ‘landing softly’, is increasingly beneficial for learning. This is as opposed to internally focused feedback (explicit) such as ‘increase your knee flexion’ during landing, focusing on the performance of the movement, as it develops automatic motor control resulting in more effective and faster learning (Wulf, Shea et al. 2010). With females suggested to be less responsive to explicit feedback (Benjaminse, Otten et al. 2017), the proportionately greater numbers of female subjects in the present study may have had bearing on this study’s results. It is unknown whether increased time in the intervention program can elicit a response in female athletes. The use of explicit instructions for the desired landing and the provision of internal feedback, has previously been common in landing retraining programs (Donnelly, Elliott et al. 2012). The results of this study suggests explicit learning intervention programs in novice skill adolescent athletes was ineffective in altering the ankle and knee mechanics, and thus altering landing technique.

A significant decrease in hip flexion at IC during the stop-jump post- versus pre-intervention in this current study concurs with the findings of Chappell et al., (2008) neuromuscular intervention program in late adolescent female basketball and soccer players. It is likely that this decrease in hip flexion along with less trunk relative to their pelvis flexion (upright trunk position) enable the participants to return their centre of mass
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over their base of support to maintain their equilibrium control of their landing technique.

This more upright trunk position is further explained by the decrease in T12-L1 flexion moment identified within this study, which is suggested to be due to a reduction in the moment arm of the trunk segment moving closer to the location of the centre of mass.

Landing in a more upright trunk position, is postulated to be due to an increase in core musculature control reducing the requirement of the hip flexors to assist in stabilising the lumbopelvic region, though this notion requires verification.

A decrease in hip external rotation to a more anatomical hip position at $F_{v3}$, was also identified post-intervention compared to pre-intervention in this current study and in previous research (Chappell and Limpisvasti 2008). The splinting or guarding hypothesis (van der Hulst, Vollenbroek-Hutten et al. 2010) is postulated to also explain this decrease, with athletes suggested to reduce the degrees of freedom in their movements order to increase hip joint stability. Hip internal rotation position has been associated with a more anatomical position in athlete with a history of groin injury (Edwards, Brooke et al. 2017) but also greater rotation in ACL injuries during the weight acceptance phase (Koga, Nakamae et al. 2018). Yet here in this study this decrease in internal hip rotation occurred within the propulsion phase as opposed to the weight acceptance phase reported in either groin (Edwards, Brooke et al. 2017) or ACL injuries (Koga, Nakamae et al. 2018). Therefore, this decrease in hip internal rotation was not deemed as an increase in injury risk.

An increased posterior GRF is indicative of ACL injury risk (Dai, Herman et al. 2012). This study identified an increase in posterior impulse and a decrease in GRF loading rate when comparing post- versus pre-intervention. It is suggested that these kinetics variables
in conjunction with hip and knee kinematics during a stop-jump movement, play a vital role in ACL injury mechanics. Without a significant increase in peak posterior GRF, the increase in loading rate (IC-$F_{V1}$), and increase in time from IC to anterior and lateral peak GRF’s present within the current study was not deemed as an increased risk for ACL injury.

The authors acknowledge the potential limitations of the current study. The 12-week intervention was designed for implementation in a non-gymnasium setting to alleviate the common problem of access and supervision for the rural and remote athletes. While this intervention allowed a real-world situational approach, a more controlled environment may have produced altered adherence that may have affected this study’s findings. It should be noted that compliance rates for injury prevention programs are closely related to success (Benjaminse, Otten et al. 2017). This current study did not record adherence data as athletes who lived in close proximity to Bathurst completed their sessions with the supervision of their strength and conditioning coach. Athletes who lived in more remote locations were expected to compete some of their sessions via satellite or individually. The precise adherence rate is therefore unknown. A major unavoidable limitation within this study is the lack of a genuine control group as it is virtually impossible to obtain a sporting group that receives no training at all, due to the nature of this study’s population.

3.5 Conclusions

Results indicated that regardless of the intervention, all athletes displayed similar post-intervention changes. This suggests that a single strength and conditioning program, as opposed to a more complex intervention program, may be implemented in pre-elite youth
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athletes with poor movement competency to provide changes in landing patterns, however a learning effect cannot be eliminated. While it is unknown whether the splinting or guarding strategy implemented by athletes is beneficial or detrimental to performance or alter injury risk, longitudinal research is required to determine whether this landing strategy is maintained after this study or is just the first step in learning to land in a more controlled manner.

3.6 Acknowledgements
The authors gratefully acknowledge the Western Region Academy of Sport for providing the participant pool from which participants were recruited for this study.

3.7 References


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**Chapter 3: Intervention programs alters stop-jump technique**


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Context of Manuscript in Relation to the Thesis

This manuscript builds on this thesis investigation into the effectiveness of whether a 12-week intervention program can modify reactive change-of-direction (R-COD) strategies in pre-elite youth athletes, specifically this manuscript focuses on a R-COD movement strategy. The R-COD was chosen as the experimental task as this is a task used to investigate key lower limb injuries, such as the anterior cruciate ligament injury and groin pain, and are repetitively performed within a game and/or training environment. Much of the previous literature on COD and injury prevention studies have been completed within an adult population; however, it is unknown whether we can modify the landing strategies within a youth population. This manuscript addresses these limitations in previous research by providing a 3D biomechanical analysis of a R-COD task and examines the effectiveness of four intervention programs (core, landing, core and landing and control) to modify R-COD strategy and variables associated with lower limb injury risk within a youth population. Results of this manuscript will provide coaches and clinicians valuable information on how pre-elite youth athletes move, improve their understanding of how an intervention leads to training adaptations and provide practical recommendations for coaches and clinicians.
Chapter 4. Any type of neuromuscular training program can modify pre-elite youth athletes reactive change-of-direction technique

This chapter is an amended version of the manuscript: Mann K, O’Dwyer N, Bruton M, Edwards S. Any type of neuromuscular training program can modify pre-elite youth athletes reactive change-of-direction technique. To be submitted to the American Journal of Sports Medicine.

**Background:** Neuromuscular training is commonly used in anterior cruciate ligament (ACL) injury prevention programs, yet current intervention strategies are not delivering the desired reduction in injury rates. It is likely these interventions programs are limited in their effectiveness as they often target specific joints, not including the entire kinetic chain such as the lumbopelvic region, and are very unlikely to be implemented in rural regions with limited access to facilities.

**Purpose:** This study’s purpose was to determine the most effective 12-week intervention program to reduce lower limb injury risk during a reactive change-of-direction (R-COD) maneuver in pre-elite youth athletes.

**Study Design:** Controlled laboratory study.

**Methods:** Eighty-nine pre-elite youth athletes with no current signs or symptoms of injury were recruited from a regional Academy of Sport. Five successful R-COD on each leg were performed by four groups, both before and after completing 12-week training program. Every group completed a standard strength and conditioning program, with three of four groups completing either an additional core, landing or core-landing component. Mixed model factorial analysis of variance (ANOVA) was used to determine statistically significant between-group differences ($P \leq 0.05$).

**Results:** While no main effect of intervention type for any kinematic or kinetic variables were identified, all athletes displayed a guarding or splinting trunk posture during their R-COD,
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exemplified by reduced L5-S1 flexion, and trunk-ab-pelvis extension post- compared to pre-intervention. This strategy contributed to a significant decrease in T12-L1 flexion moment and increased posterior impulse was also identified between pre- and post-intervention testing.

Conclusions: Results of this study showed no differences between intervention programs to modify R-COD, suggesting that a single strength and conditioning program can be utilised to modify landing patterns within pre-elite youth athletes. This general strength and conditioning program is postulated to have led to all groups increasing their trunk control via utilising a trunk splinting strategy post-compared to pre-intervention

Clinical Relevance: Athletes R-COD technique can be altered using a simple strength and conditioning program in youth athletes as opposed to a specialised program.

Key Terms: Injury, biomechanics, movement screening, prevention through prediction, dynamic landing

4.1 INTRODUCTION

The knee is the most commonly injured joint in Australia, (Medibank Private 2006) with a marked increase in knee injuries between ages 10-14 and 15-17 years (Kreisfeld, Harrison et al. 2017). The anterior cruciate ligament (ACL) resides within the internal capsule of the knee joint and acts to prevent anterior translation of the tibia with respect to the femur (Palastanga, Field et al. 2006), and was injured in approximately 3,125 Australian individuals in 2012-13 (Kreisfeld, Harrison et al. 2017). The cost of knee injuries however, is substantial with major injuries that require surgical intervention costing on average between AUS $11,000 and $16,500 (Medibank Private 2006). While ACL injury occurs in both contact and non-contact situations, it is estimated that approximately 70% of injuries are a result of a non-contact scenario (Boden, Dean et al. 2000). The detrimental effects of ACL injury persist long term after the injury, with an increased risk of early-onset osteoarthritis (Lohmander, Östenberg et al. 2004).
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The high prevalence (Kreisfeld, Harrison et al. 2017), substantial costs (Medibank Private 2006) and detrimental long term effects (Lohmander, Östenberg et al. 2004) of ACL injury make injury reduction a worthwhile pursuit. Injury reduction programs have been implemented across a range of age groups (Hewett, Lindenfeld et al. 1999, Wedderkopp, Kaltoft et al. 1999, Myklebust, Engebretsen et al. 2003, Mandelbaum, Silvers et al. 2005). Targeting an adolescent population with injury reduction programs is critical as early adolescence injury rates begin to increase (Kreisfeld, Harrison et al. 2017) and the rapid increases in height and body mass increase the height of the location of centre of mass (Myer, Chu et al. 2008) that can cause the trunk segment to become harder to stabilise during motion. This difficulty in stabilising the trunk during motion can be further compounded by an absence of sufficient neuromuscular control and strength (Myer, Chu et al. 2008) and is suggested to cause increased knee joint moments (Hewett and Myer 2011), making the adolescence population a key population for intervention training strategies.

ACL injuries are multifactorial, having a combination of both modifiable and non-modifiable risk factors (van Mechelen, Hlobil et al. 1992). Modifiable risk factors such as landing technique are often the focus of injury prevention programs; the eccentric loading phase is critical phase associated with many lower limb injuries (Boden, Dean et al. 2000, Myer, Ford et al. 2008, Edwards, Steele et al. 2010, Mann, Edwards et al. 2012). Within the eccentric loading phase, biomechanical variables such as knee abduction angles (McLean, Huang et al. 2005), net external knee abduction moment (Dempsey, Lloyd et al. 2009), external or internal tibial rotation (Krosshaug, Nakamae et al. 2007), reduced knee flexion (Boden, Dean et al. 2000) and lateral trunk movements away from the direction of travel (Dempsey, Lloyd et al. 2007) have been associated with ACL injury during a COD task. Dynamic neuromuscular landing re-training in adolescent female volleyball athletes has been shown to successfully decrease joint forces and modify critical ACL biomechanical risk factors within this deceleration phase (Hewett, Stroupe et al. 1996). As such, landing retraining programs is a popular intervention for preventing ACL injury (Hewett, Lindenfeld et al. 1999, Myklebust, Engebretsen et
Chapter 4: Intervention programs alters R-COD technique

al. 2003, Mandelbaum, Silvers et al. 2005). However, the need for controlled environments or specialised equipment in the aforementioned programs may affect adherence rates, due to the challenges in accessing appropriate facilities (Tappe, Duda et al. 1989), especially among rural and remote athletes (Finch, Mahoney et al. 2003). As greater adherence rates are associated with a decrease in injury risk (Soligard, Nilstad et al. 2010), providing a field based injury reduction program that is easy to implement and access for athletes is essential for any injury reduction program.

Injury reduction strategies that aim to correct or modify lower limb patterns of movement during landing, are often the focus of ACL injury prevention programs (Hewett, Stroupe et al. 1996, Myer, Ford et al. 2005). However, high rates of injury and re-injury (Mottram and Comerford 2008) suggest that this joint specific approach (e.g. the knee joint for ACL injuries), targeting underlying mechanics associated with the specific joint are not effective as opposed to a global kinetic chain focus that also incorporate the lumbopelvic region. Delayed or poor neuromuscular control of the lumbopelvic region during dynamic landing tasks may predispose athletes to a lower limb injury through poor stability, motion and increased forces experienced by the lower limb joints (Myer, Chu et al. 2008). As lumbopelvic instability has been linked to groin (Cowan, Schache et al. 2004, Edwards, Brooke et al. 2017), hamstring strain (Sherry and Best 2004, Chumanov, Heiderscheit et al. 2007), knee joint (Edwards, Steele et al. 2010, Hewett and Myer 2011, Mann, Edwards et al. 2012) and ankle joint injuries (Beckman and Buchanan 1995, Beynnon, Murphy et al. 2002), lumbopelvic instability may be a key area in relation to the prevention of lower limb injuries in athletes.

Dynamic neuromuscular training has been shown to be an effective intervention for improving biomechanical injury risk factors among adolescents during drop jump landing (DiStefano, Padua et al. 2009) and in turn, decreasing injury risk (Myer, Ford et al. 2005). This suggests that this population can be successfully re-trained, in a more complex sport specific movement such as the R-COD task. These changes in landing technique within this population are thought to occur mainly
Chapter 4: Intervention programs alters R-COD technique

through increased neuromuscular adaptations, such as more comprehensive and synchronous firing of the muscular unit (Sale 1988). Therefore, the purpose of this study is to compare the effectiveness of three different 12-week intervention programs to modify the R-COD technique in pre-elite youth athletes.

4.2 MATERIAL AND METHODS

4.2.1 Participants

Eighty-nine junior pre-elite athletes (age = 15.2 ± 2.2 years, height = 171.1 ± 9.4 cm; mass = 61.9 ± 12.3 kg) with no current signs or symptoms of injury were recruited from the Western Region Academy of Sports Basketball, Hockey, Netball, Triathlon and Softball teams (Error! Reference source not found.). A total of 67 athletes completed both baseline (pre) and post-intervention testing, and were included in the analysis. Written informed consent was obtained from each participant prior to data collection, with parental/guardian consent obtained for minors. All methods were approved by the institution’s Human Research Ethics Committee (2012/157, Appendix 1).
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Table 4-1 Descriptive characteristics of pre-elite youth athletes (n- no additional training; C- Core; L-Landing; C&L-Core & Landing).

<table>
<thead>
<tr>
<th>Variable</th>
<th>Pre-Intervention</th>
<th>Post-Intervention</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>n</td>
<td>C</td>
</tr>
<tr>
<td><strong>Sport</strong></td>
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<tr>
<td>Netball</td>
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<td>5</td>
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<tr>
<td>Basketball</td>
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<td>2</td>
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<tr>
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<tr>
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<tr>
<td>Female</td>
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<td>23</td>
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<tr>
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<tr>
<td><strong>TOTAL</strong></td>
<td>22</td>
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</table>
4.2.2 Experimental Task

A movement screening familiarisation was performed followed by a data collection session before and after completion of a 12-week intervention program. Each data collection session involved participants to perform five R-COD on each leg and the movement screening protocol.

The movement screening protocol, outlined in detail in Appendix 2, was videoed and involved each participant performing six movements (tuck jump, overhead squat, single leg squat, dip test, forward lunge and prone hold). Each movement was scored based on the presence or absence of errors by a single rater (KM) who counted the errors to yield a score of either 1, 2 or 3 for that movement. Then, the rater summed the scores for all six movements to determine a total composite score out of 27.

The R-COD involved the participant accelerating forward (mean approach speed 4.0±0.1 m·s⁻¹) for 7 metres in a straight line towards two force platforms. It was followed by a plant-and-cut manoeuvre at an angle between 30° to 60° originating at the centre of the force plates (mean exit speed 4.3±0.1 m·s⁻¹). Line markings were made on the floor using duct tape outlining the angle of cut. A skeleton placed 2.8 m from the base of the force platforms to simulate a defensive opponent in a game environment (Besier, Lloyd et al. 2001). An automatic light-emitting timing gates protocol (4-gate-cut protocol; Smart Speed, Fusion Sport, Queensland, Australia) signalled the participant a right or left COD when they reached a two-metre distance from the force platforms. A successful trial was defined as the: participants’ whole foot being in contact with the force platforms during the plant-and-cut (opposite foot to the direction of the cut task (i.e. right foot for left R-COD); the participants cut direction matching the light-emitting diode; and the approach speed was between 3.5 and 4.5 m·s⁻¹. To ensure sufficient recovery between trials and to minimise effects of fatigue, participants were given a 30 second rest between each trial, and a minimum of 5-minute following every 20 trials.
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4.2.3 Experimental Procedure

A static trial and movement competency screen (Appendix 2) was performing prior to completing a 5-minute self-paced warm-up on a cycle ergometer (Monark 828E, Varburg, Sweden). The participant was then familiarised with the COD before performing the experimental task. Ground reaction forces generated at landing were recorded (2400 Hz) using two multichannel force platforms with built-in charge amplifiers (Type 9281CA, Kistler, Winterthur, Switzerland; Type9821EA, Kistler, Winterthur, Switzerland) embedded in the floor and connected to control units (Type 5233A, Kistler, Winterthur, Switzerland) for each trial. Using a 12 Qualisys Oqus 300+ camera system (Qualisys AB, Göteborg, Sweden), three-dimensional lower limb and trunk motion was recorded (250 Hz) for each participant. Passive reflective markers were placed on each participant’s lower limbs, pelvis and torso, on the shoe at the first and fifth metatarsal head, mid anterior foot and calcaneus, lateral and medial malleolus, lateral and medial femoral epicondyle, a four-marker cluster placed on the leg and thigh, greater trochanter, anterior superior iliac spine, posterior superior iliac spine, iliac crest, sternal notch, xiphoid process, acromion, lumbo-sacral (L5-S1) intervertebral joint space, thoraco-lumbar (T12-L1) intervertebral joint space, bilaterally on the ribcage at the level of the T12-L1 intervertebral joint space and immediately superior to the iliac crest marker, and five tracking markers placed on the lumbar region. The participants wore minimal clothing (shorts) to avoid interference with the passive reflective markers, and their athletic running shoes and socks.

4.2.4 Intervention Program

Participants were randomly allocated into one of four intervention programs: core plus standard strength and conditioning; landing retraining plus standard strength and conditioning, core and landing retraining plus standard strength and conditioning; or only standard strength and conditioning (control; Appendix 3). Every participant performed a standard strength and conditioning program consisting of four key exercises (push, pull, squat and lunge). To aid participants in adhering to the
program, they were provided with a compact-disk (CD) that had videos of all exercises for each phase of their program. At the beginning and every three weeks after the commencement of the program, Strength and Conditioning interns completed the movement competency testing to record each athlete’s progression in the intervention program and assessed their execution of their selected exercises. Each intervention program required participants to meet a competency criterion before advancing to the next level of the program (Appendix 3). Below outlines the rationale for each intervention.

**Strength and conditioning program:** Designed and implemented by the Academy of Sport, this program incorporated a dynamic warm up, a push, pull, squat and lunge resistance exercise and cool-down stretches (Appendix 5).

**Program 1 – Core program:** This program was designed to include a range of functional balance and postural stability core exercises to improve lumbopelvic stability. Athlete’s in this program progressed through the four levels of core stabilisation training; stabilisation, stabilisation and strength, integrated stabilisation strength and explosive stabilisation using the core stabilisation guidelines outlined by Clarke (2004).

**Program 2 – Landing retraining program:** This landing re-training program included basic strength, stability and plyometric concepts to re-train landing technique. Athletes progressed from basic strength and stability to the six stages of plyometric training outlined by Chu (1999).

**Program 3 – Core program and landing retraining program:** This program was designed to combine both the core stability and landing re-training programs together by incorporating a half load of each training program to provide a core stability and landing re-training exercises that also followed the guidelines outlined by Clark (2004) and Chu (1999).

**Program 4 – Control program:** This program did not perform any additional intervention training in conjunction with their strength and conditioning program provided by the Academy of Sport.
4.2.5 Data Reduction and Analysis

Visual 3D software (Version 5, C-Motion, Germantown, MD) was used for analysis of the three-dimensional kinematic and kinetic data for angles and joint moments, with a custom built LabView program (Lab-View 2010, National Instruments, Austin, TX, USA) for GRF data analysis. All raw kinematic coordinates, GRF’s, free moments and centre of pressure data were filtered through a fourth-order zero-phase Butterworth low-pass digital filter prior to calculating individual joint kinematics and net internal joint moments ($f_c = 18$ Hz), and raw GRFs to calculate GRF variables ($f_c = 50$ Hz).

Segment masses were defined from Zatsiorsky et al. (1990) for the foot, shank and thigh segments, and from Pearsall et al. (1996) for the pelvis, lumbar, thorax, and trunk segments. Segmental inertial properties of each segment were modelled using geometric primitives (Hanavan 1964) with the foot, shank, and thigh defined as a frusta of a right cone, and the pelvis, lumbar, thorax, and trunk defined as elliptical cylinders (Seay, Selbie et al. 2008). To support Cartesian local coordinate system sign conventions, all segments were defined as follows: x-axis as medio-lateral, y-axis as anterior-posterior and z-axis as the vertical direction. Loads applied to each joint were defined as internal net joint moments that were normalised to each individual participant’s body mass multiplied by height, and ground reaction forces were normalised to body weight to account for variations between participants. Using the 18 Hz filtered kinetic data, the horizontal landing phase was defined from initial contact (IC) when the vertical ground reaction force exceeded 10 N to the first peak ($F_{V1}$) and local minimum ($F_{V2}$), to the second GRF$_V$ peak ($F_{V3}$) and then to take-off (TO) when the vertical GRF fell below 10 N. For each trial, intersegment joint angles of the ankle, knee, hip, L5-S1 (lumbar segment relative to the pelvis), T12-L1 (lumbar segment relative to the thoracic segment), Thoracic_Ab-Pelvis (trunk segment relative to the pelvis segment) at the time of IC, $F_{V1}$, $F_{V2}$, $F_{V3}$, and TO were calculated. Peak net internal ankle, knee, hip, L5-S1, and T12-L1 joint moments, and peak anteroposterior, mediolateral and vertical GRF were identified during the ground contact period.
from IC to TO. While both the left and right lower limb data were analysed, only the left lower limb was included in statistical analysis, as lower limb were show to be symmetrical (Appendix 4).

4.2.6 Statistical Analysis

A G*Power calculation of the required sample size was performed for an actual power of 0.96. This calculation showed a total sample size of 56 athletes was required, suggesting that this study is adequately powered. A series of mixed-design factorial analyses of variance (ANOVA) were performed on the outcome variables that consisted of joint angles, peak joint angles, ranges of motions (ROMs), GRFs and joint moments during performance of the R-COD. The primary effect of interest was the independent factor of intervention (core, landing, core-landing and control), and the secondary repeated measures factor was that of time (pre- and post-intervention). There were four factors for analyses of joint angles (intervention*pre/post*events*angles). Events comprised of five levels; the discrete GRF time-points within the stance phase of the COD (IC, $F_{V1}$, $F_{V2}$, $F_{V3}$, TO), while angles comprised of 18 levels; six joints (ankle, knee, hip, L5-S1, T12-L1, thoracic abdominal pelvis) in three respective planes ($x,y,z$). There were three factors for the other kinematic analyses of ROM (intervention*pre/post*ROM) and peak angles (intervention*pre/post*peak angles). There were also three factors for each of the kinetic variable analyses of joint moments (intervention*pre/post*moments), GRF peaks (pre/post*GRF peaks), GRF impulse (pre/post*GRF impulse) and GRF timing (intervention*pre/post*GRF timing. It was to be expected that the outcomes variables (joint angles, segment alignments, joint moments, ROMs and GRFs) would vary significantly across the stages of the horizontal landing phase. Similarly, significant differences were to be expected between the variables within each category of outcome variable. For example, differences would be expected between joint angles and between segment alignments. Such differences, however, were not relevant to the primary hypotheses concerning the effects of the interventions or pre/post testing. Therefore, only main effects or interactions that involved the factors of intervention and/or pre/post testing were reported here.
Chapter 4: Intervention programs alters R-COD technique

All tests were conducted using Statistica (v.13, StatSoft Inc., Tulsa, OK, USA), with significant results reported for \( p<0.05 \) and Tukey Post hoc tests used to identify where the significant effect occurred. All data were tested for the assumptions of normality of distribution and sphericity, with multivariate ANOVA considered when sphericity was not satisfied. Assumptions of constant variance and normality were examined through residuals and were both satisfied and accepted. Where the Tukey post hoc did not reveal the significant effect when a significant interaction was indicated in the ANOVA results, univariate and independent \( t \)-tests were employed to assess which variable was responsible for the interaction and effect size analyses, respectively. Effects sizes (\( \eta^2 \)) were defined as trivial (<0.0099), small (0.0099-0.0588), moderate (0.0588-0.1379), and large (>0.1379) sizes (Richardson 2011).

4.3 RESULTS

4.3.1 Kinematics

Joint angles showed no significant main effect of intervention group (\( F_{3,62}=0.46, p=0.71, \eta^2=0.0219 \)), or pre/post time point (\( F_{1,62}=0.006, p=0.94, \eta^2=0.0001 \)); however, significant interactions between pre/post*angles (\( F_{17,1054}=295.4, p<0.001, \eta^2=0.0383 \)) and pre/post*events*angles (\( F_{68,4216}=1.42, p=0.02, \eta^2=0.0225 \), Table 4-2) were present. Post hoc tests failed to determine the source of the effect in the pre/post*angles interaction. It was revealed that pre- compared to post-intervention, in the pre/post*events*angles interaction, that there was significantly reduced L5-S1 flexion at IC (\( p<0.001 \), \( F_{V1} \) (\( p<0.001 \), \( F_{V2} \) (\( p<0.001 \), \( F_{V3} \) (\( p<0.001 \), TO (\( p<0.041 \), thoracic abdominal extension at IC (\( p<0.05 \), T12-L1 extension at TO (\( p<0.001 \), increased forefoot abduction at \( F_{V1} \) (\( p<0.05 \) and hip external rotation at \( F_{V3} \) (\( p<0.05 \)). There were no main effects of intervention (\( F_{3,62}=2.59, p=0.06, \eta^2=0.1112 \)) or pre/post (\( F_{1,62}=1.05, p=0.31, \eta^2=0.0167 \), and no significant interactions for joint range of motion were observed. Nor were there any main effects of intervention
(F_{3,62}=0.49, \ p=0.69, \ \eta^2=0.0230), \text{ or } \text{pre/post (F}_{1,62}=0.02 \ p=0.89, \ \eta^2=0.0003), \text{ nor significant interactions for peak joint angles or joint segments displayed.}

\textbf{4.3.2 Kinetics}

For joint moments, there were no main effects of intervention \ ((F_{3,62}=1.64, \ p=0.19, \ \eta^2=0.0734), \text{ or pre/post (F}_{1,62}=1.94 \ p=0.17, \ \eta^2=0.0303; \text{ Table 4-3) observed. However, a significant interaction was identified between pre/post*moments (F}_{29,1798}=1.98 \ p=0.001, \ \eta^2=0.0309; \text{ Table 4-3). Post hoc analysis identified a significant decrease in T12-L1 flexion moment (p<0.05) between pre- and post-intervention were observed. A significant main effect of pre- post-intervention was reported for peak GRF (F}_{4,248}=2.61, \ p=0.04, \ \eta^2=0.0404); however, post hoc analysis failed to identify the source of the significant interaction. No main effect of intervention group (F_{3,62}=0.47, \ p=0.70, \ \eta^2=0.0223), \text{ or pre/post (F}_{1,62}=4.57, \ p=0.37, \ \eta^2=0.0686), \text{ or any interactions were identified in GRF timing.}
**Table 4-2**  Kinematic changes between pre- and post-intervention in a RCOD task.

<table>
<thead>
<tr>
<th>Outcome Variable</th>
<th>Change</th>
<th>Event</th>
<th>PRE Mean ± SD</th>
<th>POST Mean ± SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint Angles</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L5S1 Extension</td>
<td>↓</td>
<td>IC</td>
<td>-1.5° ± 1.2°</td>
<td>2.0° ± 1.1°</td>
</tr>
<tr>
<td>Thoracic Abdominal Extension</td>
<td>↑</td>
<td>IC</td>
<td>3.2° ± 1.2°</td>
<td>5.7° ± 1.1°</td>
</tr>
<tr>
<td>Forefoot Abduction</td>
<td>↓</td>
<td>Fv1</td>
<td>17.1° ± 0.9°</td>
<td>14.6° ± 1.2°</td>
</tr>
<tr>
<td>L5S1 Extension</td>
<td>↓</td>
<td>Fv1</td>
<td>-0.4° ± 1.2°</td>
<td>2.9° ± 1.1°</td>
</tr>
<tr>
<td>L5S1 Flexion</td>
<td>↑</td>
<td>Fv2</td>
<td>1.1° ± 1.2°</td>
<td>4.6° ± 1.1°</td>
</tr>
<tr>
<td>Hip External Rotation</td>
<td>↓</td>
<td>Fv3</td>
<td>5.1° ± 1.4°</td>
<td>2.7° ± 1.1°</td>
</tr>
<tr>
<td>L5S1 Flexion</td>
<td>↑</td>
<td>Fv3</td>
<td>2.5° ± 1.2°</td>
<td>5.6° ± 1.1°</td>
</tr>
<tr>
<td>L5S1 Extension</td>
<td>↓</td>
<td>TO</td>
<td>-2.4° ± 1.2°</td>
<td>0.2° ± 0.1°</td>
</tr>
<tr>
<td>T12L1 Extension</td>
<td>↑</td>
<td>TO</td>
<td>2.8° ± 1.1°</td>
<td>5.5° ± 1.0°</td>
</tr>
</tbody>
</table>

**Table 4-3**  Kinematic changes between pre- and post-intervention in RCOD task.

<table>
<thead>
<tr>
<th>Outcome Variable</th>
<th>Change</th>
<th>PRE Mean ± SD</th>
<th>POST Mean ± SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint Moments</td>
<td></td>
<td>1.5 ± 0.1</td>
<td>1.2 ± 0.1</td>
</tr>
</tbody>
</table>
4.4 DISCUSSION

Prevention programs for ACL injury are increasingly popular, with programs successfully shown to alter landing technique (Hewett, Lindenfeld et al. 1999, Wedderkopp, Kaltoft et al. 1999, Mandelbaum, Silvers et al. 2005). Yet the unchanged rate of injury observed (Medibank Private 2003, Medibank Private 2006) may be due to these programs not being adopted by the general population. A barrier to implementation of and adherence to these programs, that can directly impact the effectiveness of prevention program (Benjaminse, Otten et al. 2017) is that many programs require specific equipment or specialised trainers (Söderman, Werner et al. 2000, Myklebust, Engebretsen et al. 2003, Olsen, Myklebust et al. 2005, Petersen, Braun et al. 2005). This present study’s field-based neuromuscular training intervention programs were easily implemented without the need for specialised equipment or supervision and were shown they could alter youth athletes R-COD technique regardless of the type of intervention program. Irrespective of the type of intervention, athletes displayed a less flexed trunk-pelvis position during the R-COD post- compared to pre-intervention. Minimal differences displayed between the intervention programs is postulated to be attributed to the overall poor movement competency of all participants at commencement of the program along with their lack/minimum prior strength training exposure. A similar training effect has been identified in strength training of novice individuals, where an increase in performance is related to more succinct neuromuscular patterns (Sale 1988). Important to note is that previous research has identified that athletes displaying poor movement screening prior to intervention obtain a greater effect of training (DiStefano, Padua et al. 2009), an effect likely to contribute to this study’s results.

Early adolescent athletes are a key population for implementation of injury reduction programs. This population are key given the reduced resistance to internal and external
loads and reduction in adaptability seen in the developing tendon (Tuite, Renström et al. 1997), along with the increase in injuries identified within late adolescents and yearly adulthood (Kreisfeld, Harrison et al. 2017). This study strengthens previous research suggesting that successful training programs can be implemented within this adolescent population (DiStefano, Padua et al. 2009). However without a ‘real’ control group (i.e. no training), it remains questionable whether this was in fact a training or learning effect. It should be noted that the retention of the training adaption three months post-intervention may be poor (Prapavessis, McNair et al. 2003), and it remains unknown whether the participants in this current study maintained their altered R-COD strategy. The minimal pre/post-interventions differences identified in the lower limb mechanics in the current study may be associated with the participant age range, from 12 to 16 years, utilised in this study. Age has been shown to be a factor in which feedback strategies and phrasing of directions need to be utilised to produce a significant effect on motor learning (Benjaminse, Gokeler et al. 2015). It is possible that this lack of difference between the interventions may be due to the more traditional explicit feedback incorporated within the program (e.g. keep your trunk stable, don’t let your knee medially collapse), as opposed to implicit feedback that is reported to enhance autonomous learning and retention (Benjaminse, Otten et al. 2017). Children younger than 13 years of age require more simplistic feedback strategies to elicit a change in movement patterns, as proposed by previous research that suggests implicit feedback mechanisms are beneficial in speeding up the progression through the learning phases to enable automaticity (Benjaminse, Gokeler et al. 2015). However, with children younger than 13 responding to internal feedback, different age groups may respond to different feedback strategies depending on their learning phase. The use of internal feedback is common in prevention programs (Donnelly, Elliott et al. 2012); however, it may explain the limited success in changing
the ankle and knee landing biomechanics in the current study and previous research (Donnelly, Elliott et al. 2012).

Successfully altering high risk ACL movement patterns, such as knee flexion at IC, has been shown in dynamic singular plane movements such as the stop-jump (Chappell and Limpisvasti 2008) but not multi-planar movement such as the COD (Donnelly, Elliott et al. 2012). A COD task requires sagittal plane running followed by rapid deceleration, with an abrupt change direction through rotation of the body and subsequent re-acceleration (Kristianslund and Krosshaug 2013). In contrast, a stop-jump requires acceleration, deceleration and a vertical jump that are all primarily performed within the sagittal plane. This lack of training modification seen in R-COD, may be due to the high intensity, rapid and single leg supported nature of the R-COD that causes significantly higher knee joint moments that increases the risk of ACL injury (Kristianslund and Krosshaug 2013).

No significant pre-/post-intervention differences in the R-COD mechanics were found between interventions, suggesting a general, rather than a specific effect of the training is effective in adolescent athletes with no/minimal strength training experience. This study’s finding is in agreement with previous research that athletes with poor movement competency, such as observed in this study, receive the most benefit from training interventions (DiStefano, Padua et al. 2009). It is suggested that this may be due to a lack of previous structured training, initiated a training effect similar to that seen in strength training (Sale 1988), whereby an increase in the function of the neuromuscular pathways occurs to improve performance. It is plausible that this non-specific effect of core, landing and core and landing type of intervention program may not be observed in youth athletes.
One significant finding of this current study was the significant reduction in trunk-abdomen-pelvis flexion in post- compared to pre-intervention, a key aim in neuromuscular intervention program in adults (King, Franklyn-Miller et al. 2018). An upright trunk posture during landing has been associated with increased ACL injury risk (Griffin, Agel et al. 2000, Shimokochi, Ambegaonkar et al. 2013) and decrease performance (Edwards, Austin et al. 2017) during a R_COD. It is possible that this change in trunk-abdomen-pelvis flexion observed in this current study represents an increased ACL injury risk in these athletes and poorer athletic performance pre- versus post-intervention. The ‘guarded’ posture is suggested here to be related to the focus of the strength and conditioning programs on maintaining trunk control and posture throughout movements. A similar ‘guarding’ technique has been previously identified in chronic low back pain (Arendt-Nielsen, Graven-Nielsen et al. 1996); however, it is unknown whether this movement strategy is beneficial or detrimental to an athlete, or whether this is a permanent change or an early stage learning strategy to simplify the movement. Athletes employed this ‘guarding’ technique to effectively reduce their degrees of freedom and thus their movement complexity in a strategy to react to stimuli and increase their ability to control their movement. Given there was no concomitant increase in $F_{\text{POST}}$, decrease in knee flexion at IC, peak knee abduction nor peak knee adduction joint moment, we suggest that overall less flexed trunk-abdomen-pelvis posture did not result in an increased ACL injury risk. This is further confirmed by the reduced T12-L1 flexion moment identified within the landing phase, likely to be due to the reduction in T12-L1 moment arm, with the reduced flexion of the trunk-abdomen-pelvis.
Finally, a decrease in $F_V$ loading rate post-intervention was that only kinetic variable identified compared to pre-intervention, a finding considered to be a protective effect against lower limb injury. No other GRF variables indicative of ACL injury risk such as $F_{POST}$ (Dai, Herman et al. 2012) or peak net internal knee adduction joint moment (Hewett, Myer et al. 2005) (note different methodology: peak net external knee valgus moment is equivalent to peak net internal knee adduction moment) were observed in this study.

The authors acknowledge the potential limitations of the current study. To aid with adherence for the rural and remote athletes, the intervention program was designed as a field-based prevention program for a non-gymnasium setting. While a non-gymnasium setting permitted a more realistic approach, a more controlled setting may have presented different findings. Research has shown that adherence to injury prevention programs is closely associated to the success of the program (Benjaminse, Otten et al. 2017); however, adherence data was not collected as many athletes live up to 266 km away from the Academy of Sport. Additionally, supervision by the strength and conditioning coaches was provided to athletes who lived near the Academy of Sport, while athletes who lived more remotely were provided with satellite sessions or individual completed the sessions by themselves.

Results of this study showed minimal changes between the intervention programs, suggesting that a single strength and conditioning program may be utilised to modify landing patterns within pre-elite youth athletes, however a learning effect cannot be eliminated. Increased trunk control, as seen by a reduction in trunkab-pelvis flexion in
post- compared to pre-intervention is suggested to be a result of the general strength and conditioning program completed by all athletes within the study.

4.5 ACKNOWLEDGEMENTS
The authors gratefully acknowledge the Western Region Academy of Sport for providing the participant pool from which participants were recruited for this study.

4.6 REFERENCES


Chapter 4: Intervention programs alters R-COD technique


Chapter 4: Intervention programs alters R-COD technique


Chapter 4: Intervention programs alters R-COD technique


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Context of Manuscript in Relation to the Thesis

This manuscript was originally designed to compare the high risk of injury group, as defined by the field-based movement screen in Manuscript 1, to known injury risk variables. However, as we were unable to obtain evenly distributed data from Manuscript 1’s movement screening results, this Manuscript’s focus shifted from injury risk to trunk ROM during the R-COD task. Trunk ROM was utilised as an injury risk factor as previous research has identified increased trunk flexion as a key variable in injury mechanics, specifically in a COD task, while other research refutes this. Results of this manuscript will additional insight into the relationship between trunk ROM and injury mechanics providing practical recommendations for injury prevention training for athletes and their coaches.
Chapter 5. The effect of dynamic trunk-pelvis range of motion on lower limb injury risk factors in pre-elite youth athletes

This chapter is an amended version of the manuscript: Mann K, O’Dwyer N, Bruton M, Edwards S. The effect of dynamic trunk-pelvis range of motion on lower limb injury risk factors in pre-elite youth athletes. To be submitted to the Medicine and Science in Sports and Exercise.

Abstract

**Purpose:** Landing with a more upright trunk or increased trunk ROM, relative to the pelvis, has both been associated an increased risk of ACL injury risk; however, additional research has found reductions in knee forces which are suggested to decrease injury risk with this more upright trunk posture. With this contradictive research, the purpose of this study was to determine the effect of trunk ROM on known injury risk variables, such as net external peak adductor and internal/external knee and hip joint moments.

**Methods:** Eighty-nine junior pre-elite athletes with no current signs or symptoms of injury were recruited from the Western Region Academy of Sport. Five successful reactive change of direction (R-COD) tasks with a left stance leg were performed with three-dimensional biomechanical analysis of the lower limb and trunk. Participants were ranked in order based on their trunk ROM during R-COD and categorised into one of five groups. Only the LOW, MID and HIGH ROM groups were included within the statistical analysis using a mixed modelling factorial analysis of variance (ANOVA). All groups were used to undertake bivariate Pearson’s product-moment correlation ($p<0.05$) to determine statistically significant between-group differences ($P\leq0.05$).
Chapter 5: Trunk-Pelvis ROM & Injury Risk in R-COD

**Results:** The current study identified that the HIGH trunk-ROM-group exhibited a significantly more upright trunk movement strategy at take-off (TO), with a reduced hip flexion and more internally rotated hip during R-COD.

**Conclusions:** Results of this current study identify that athletes with increased trunk-ROM land with a more anatomical hip pattern. While previous research has suggested this to be indicative of increasing injury risk, the current study fail to identify significant links with trunk ROM, injury risk or performance.

**Keywords:** Injury, biomechanics, trunk kinematics, risk identification, dynamic landing

5.1 Introduction

Injury risk is multifactorial in nature, with both modifiable and non-modifiable factors playing a part in an individual’s likelihood of injury (Emery 2003). To identify injury risk, biomechanical research has traditionally focused on landing patterns during high impact dynamic movements such as the change-of-direction (COD) task (Dempsey, Lloyd et al. 2007, Cochrane, Lloyd et al. 2010, Edwards, Brooke et al. 2017). Change of direction tasks are chosen for investigation as these are sport specific movements with an eccentric deceleration phase that is commonly implicated in the injury mechanism (Boden, Dean et al. 2000, Myer, Ford et al. 2008, Edwards, Steele et al. 2010, Mann, Edwards et al. 2013). During this eccentric load absorption phase of the R-COD task, the extensor muscles of the lower limb and trunk act eccentrically to control the deceleration of the body prior to beginning the propulsion phase. Instability or a lack of control of the trunk region during this phase is suggested to predispose athletes to an increased injury risk (Edwards, Steele et al. 2010, Mann, Edwards et al. 2013), by increasing the moment arm of the trunk segment thus increasing the forces around the joints of the lower limb. Specific risk factors such as an increase (Dempsey, Lloyd et al. 2009) or decrease (Sheehan, Sipprell III et al. 2012) in trunk flexion during the eccentric loading phase and
Chapter 5: Trunk-Pelvis ROM & Injury Risk in R-COD

at initial contact respectively, increased lateral trunk flexion (Dempsey, Lloyd et al. 2007), trunk rotation (Dempsey, Lloyd et al. 2007) away from the direction of travel during the weight acceptance phase, and increased peak hip internal rotation and peak knee abduction angles (McLean, Huang et al. 2005) have been suggested to play a role in increasing an individual’s risk of injury.

A mechanistic connection between lower limb risk factors, performance and lumbopelvic or trunk control has been identified. Comparison of literature investigating the lumbopelvic region during landing is difficult due to the varied definitions (Panjabi 1992, Mills, Taunton et al. 2005, Kibler, Press et al. 2006). Based on previous research (Panjabi 1992, Mills, Taunton et al. 2005, Kibler, Press et al. 2006), this study has defined lumbopelvic stability as the ability of an individual to obtain and maintain the alignment of the body segments in a task dependant manner without substitution strategies, in both static positions and during dynamic movements. Associations between increased peak internal/external knee and hip adductor moments have been reported during COD (Dempsey, Lloyd et al. 2007). Increases in lateral trunk flexion increases the distance between the GRF vector and the knee joint centre and head of the femur thus increasing the knee moments and hip adduction muscle activation (Hewett and Myer 2011). Additionally, weak hip extensors have shown to increase the activation requirement of the hip flexors, specifically the iliopsoas, to control the lumbopelvic region and trunk region during landing (Chumanov, Heiderscheit et al. 2007), This landing strategy is suggested to ‘stiffen’ individuals landing patterns by creating a more upright trunk landing pattern (Griffin, Agel et al. 2000), where by a reduced degrees of freedom and is suggested to increase ACL injury risk (Griffin, Agel et al. 2000, Shimokochi, Ambegaonkar et al. 2013). Associations between significantly increased trunk displacement following perturbation and those athletes who sustained a knee injury within a three-year period further increases the speculation that neuromuscular
impairment of the core region may increase an athlete’s susceptibility to a knee injury (Zazulak, Hewett et al. 2007). Consequently, researchers have suggested turning their attention to enhancing the stability of the lumbopelvic region in relation to reducing lower limb injuries among the sporting population (Myer, Chu et al. 2008).

Intervention programs have been shown to successfully modify landing patterns in a supervised research setting (Hewett, Lindenfeld et al. 1999, Myklebust, Engebretsen et al. 2003, Mandelbaum, Silvers et al. 2005). Injury risk factors such as peak ground reaction forces (Hewett, Stroupe et al. 1996), knee flexion angles at initial contact (Cowling, Steele et al. 2003, Chappell and Limpisvasti 2008) and peak knee flexion (Cowling, Steele et al. 2003, Chappell and Limpisvasti 2008, Milner, Fairbrother et al. 2011, McCurdy, Walker et al. 2012), knee internal rotation (Cailliet 1988) and peak net external knee valgus knee moment (Dempsey, Lloyd et al. 2009) and lateral trunk flexion angles (Dempsey, Lloyd et al. 2009) effectively altered pre- versus post-intervention.

Traditionally interventions have largely focused on modifying resultant symptoms with a localised strategy whereby they focus on one specific joint (Myer, Chu et al. 2008), such as knee joint flexion and peak net internal knee adduction moment in ACL injury prevention research. Lumbopelvic instability and a lack of trunk control has also been suggested to be underlying cause of many lower limb injury risk variables (Hewett and Myer 2011). With links to groin (Cowan, Schache et al. 2004, Edwards, Brooke et al. 2017), hamstring strain (Sherry and Best 2004, Chumanov, Heiderscheit et al. 2007), knee joint (Edwards, Steele et al. 2010, Hewett and Myer 2011, Mann, Edwards et al. 2013), and ankle joint injuries (Beckman and Buchanan 1995, Beynnon, Murphy et al. 2002), it may be suggested that a global approach of focusing on the underlying lumbopelvic instability would be more effective. Although, previous research has identified that this is not the case in the adult (>18 years) population (Whyte, Richter et al. 2018), it remains
unknown in the adolescent population. Balance and core stability have been associated with a reduction in injury rates (Sherry and Best 2004, Myer, Ford et al. 2006), however there are conflicting results as to the effectiveness of plyometric jump training programs (Myer, Ford et al. 2006). It is postulated that purely plyometric programs might have neglected a critical component of the injury prevention re-training strategies, that being the basic development of lumbopelvic stability. Previous lumbopelvic intervention programs have elicited a training response in modifying an athletes COD technique following an intervention program (Bencke, Næsborg et al. 2000, Dempsey, Lloyd et al. 2009, DiStefano, Blackburn et al. 2011) by successfully altering high risk variables such as peak net external knee adduction moment (Dempsey, Lloyd et al. 2009, Cochrane, Lloyd et al. 2010) and trunk lateral flexion angle (Dempsey, Lloyd et al. 2009).

Previous prevention programs that have focused on lumbopelvic stability have displayed some conflicting results, with differing populations suggested to be a critical underlying cause of these discrepancies. When responding to internal and external loads, older individuals have less adaptable tissues (Tuite, Renström et al. 1997), while younger athletes (<13 years) have displayed no training adaptation to interventions (DiStefano, Padua et al. 2009). Therefore, training interventions within the middle range of adolescents (13-18 years old) are considered the primary target population. The adolescent period, involves rapid increases in height and body mass due to puberty. This increase in height is largely due to the increase in length of the long bones of the lower limbs that results in an increase in height of the location of centre of gravity (Myer, Chu, et al., 2008). A combination of this increase in centre of gravity and an absence of sufficient neuromuscular control and strength, is often observed in adolescents who may have difficulty in their trunk stabilisation (Myer, Chu, et al., 2008), thus identifying the importance of lumbopelvic stability within this population. Therefore, the current study
aimed to identify which, if any, lower limb injury risk factors are associated with increased trunk ROM in pre-elite youth athletes.

5.2 Methods

5.2.1 Participants

Eighty-nine junior pre-elite athletes (age: 15.2±2.2 years, height: 171.1±9.4 cm; mass: 61.9±12.3 kg) with no current signs or symptoms of injury were recruited from the Western Region Academy of Sports Basketball, Hockey, Netball, Triathlon and Softball teams (Table 1). Written informed participant and parental/guardian consents was obtained from each participant prior to data collection. All methods were approved by the institution’s Human Research Ethics Committee (2012/157, Appendix 1).

5.2.2 Experimental Task

Participants were required to perform five successful R-COD (left stance leg) on each leg that involved the participant accelerated forward (approach speed 4.0-5.0 m·s⁻¹) for 7 metres in a straight line towards two force platforms. The participant then performed a plant-and-cut manoeuvre at an angle between 30° to 60° originating at the centre of the force plates (mean exit speed 4.3 ± 0.1 m·s⁻¹). Line markings on the floor were made using duct tape outlining the cut direction. To simulate a defensive opponent in a game environment a skeleton was placed 2.8 m from the base of the force platforms (Besier, Lloyd et al. 2001). An automatic light-emitting timing gates protocol (4-gate-cut protocol; Smart Speed, Fusion Sport, Queensland, Australia) signalled as the participant reached a two-metre distance from the force platforms to indicate a right or left R-COD. In a successful trial, the participants’ foot wholly contacted the force platforms during the
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plant-and-cut (opposite foot to the direction of the cut task (i.e. right foot for left R-COD), the participants cut direction matched the light-emitting diode, and the approach speed was required to be between 3.5 and 4.5 m·s⁻¹. To minimise the effects of fatigue and ensure sufficient recovery between trials, participants were given a 30 second rest between each trial, and a minimum of 5-minutes following every 20 trials.

5.2.3 Experimental Procedure

Prior to five successful R-COD tasks, a static trial, familiarisation movement competency screen (see Appendix 2), and a 5-minute self-paced warm-up on a cycle ergometer (Monark 828E, Varburg, Sweden) was completed. The movement screening protocol, outlined in detail in Appendix 2, involved each participant performing six movements (tuck jump, overhead squat, single leg squat, dip test, forward lunge and prone hold). Each movement was scored based on the presence or absence of errors by a single rater (KM) who counted the errors to yield a score of either 1, 2 or 3 for that movement. Then, the rater summed the scores for all six individual movements to determine a total composite score out of 27.

Each R-COD trial, three-dimensional ground reaction forces generated at landing were recorded (2400 Hz) using two multichannel force platforms with built-in charge amplifiers (Type 9281CA, Kistler, Winterthur, Switzerland; Type9821EA, Kistler, Winterthur, Switzerland) embedded in the floor and connected to control units (Type 5233A, Kistler, Winterthur, Switzerland). Using a 12 Qualisys Oqus 300+ camera system (Qualisys AB, Göteborg, Sweden), 3D lower limb and trunk motion was recorded (250 Hz) for each participant. Passive reflective markers were placed on each participant’s lower limbs, pelvis and torso, on the shoe at the first and fifth metatarsal head, mid
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anterior foot and calcaneus, lateral and medial malleolus, lateral and medial femoral epicondyle, a four-marker cluster placed on the leg and thigh, greater trochanter, anterior superior iliac spine, posterior superior iliac spine, iliac crest, sternal notch, xiphoid process, acromion, lumbo-sacral (L5-S1) intervertebral joint space, thoraco-lumbar (T12-L1) intervertebral joint space, bilaterally on the ribcage at the level of the T12-L1 intervertebral joint space and immediately superior to the iliac crest marker, and five tracking markers placed on the lumbar region. To avoid losing view of the passive reflective markers placed on each participant’s lower limbs, pelvis and torso, on the shoe (Mann, Edwards et al. 2013) and wore minimal clothing (shorts) and their athletic running shoes and socks.

5.2.4 Data Reduction and Analysis

Visual 3D software (Version 5, C-Motion, Germantown, MD) was utilised for analysis of the three-dimensional kinematic and kinetic data, with a custom built LabView program (Lab-View 2010, National Instruments, Austin, TX, USA) for GRF data analysis. Prior to calculating individual joint kinematics and net internal joint moments ($f_c = 18$ Hz), and raw GRFs to calculate GRF variables ($f_c = 50$ Hz), all raw kinematic coordinates, GRF’s, free moments and centre of pressure data were filtered through a fourth-order zero-phase Butterworth low-pass digital filter. Segment masses were defined from Zatsiorsky et al. (1990) for the foot, shank and thigh segments, and Pearsall et al. (1996) for the pelvis, lumbar, thorax and trunk segments. Segmental inertial properties of each segment were modelled using geometric primitives (Hanavan 1964), with the foot, shank and thigh defined as a frusta of a right cone, and the pelvis, lumbar, thorax and trunk defined as elliptical cylinders (Seay, Selbie et al. 2008). To support Cartesian local coordinate system sign conventions, all segments were defined as follows: x-axis as medio-lateral, y-axis as anterior-posterior and z-axis as the vertical direction. Internal net
joint moments were normalised to each individual participant’s body mass, and ground reaction forces were normalised to body mass and height to account for variations between participants. Using the 18 Hz filtered kinetic data, the stance phase was defined from initial contact (IC) when the vertical ground reaction force exceeded 10 N to the first vertical GRF peak ($F_{V1}$), first local minimum ($F_{V2}$), to the second vertical GRF peak ($F_{V3}$) and then to take-off (TO) when the vertical GRF fell below 10N. For each trial, intersegmental joint angles of the ankle, knee, hip, L5-S1 (lumbar segment relative to the pelvis), and T12-L1 (lumbar segment relative to the thoracic segment) at the time of IC, $F_{V1}$, $F_{V2}$, $F_{V3}$, and TO were calculated. Peak ankle, knee, hip, L5-S1, and T12-L1 joint angles and moments, and peak GRF and impulses, were identified during the phase from IC to TO. Trunk control during the R-COD was assessed as the vector sum of the ROM of the trunk relative to the pelvis from IC to TO in all three planes.

5.2.5 Statistical Analysis

The participants were ranked in order based on their trunk-ROM during R-COD and categorised into one of five groups; <19.0° (LOW, n=23), 19.1°-20.0° (LOW-MID, n=14), 21.0°-24.9° (MID, n=23), 25.0°-26.9° (MID-HIGH, n=13) and >27.0° (HIGH; n=17). To ensure a clear differentiation in trunk ROM between groups only the LOW, MID, and HIGH ROM groups were included within a series of mixed-design factorial analyses of variance (ANOVA). These ANOVA were performed on the outcome variables that consisted of joint angles, peak joint angles, ranges of motions (ROMs), GRFs and joint moments during R-COD. The primary effect of interest was the independent factor of trunk ROM. There were two factors for analyses of risk factors (Trunk ROM*risk factors). Since the effects of interest for this study were any differences between Trunk ROM and risk factors, only main effects and interactions involving the trunk ROM will be reported. All tests were conducted using Statistica (v.13, StatSoft Inc.,
Tulsa, OK, USA), with significant results reported for \( p < 0.05 \). All data were tested for the assumptions of normality of distribution and sphericity, with multivariate ANOVA considered when sphericity was not satisfied. Assumptions of constant variance and normality were examined through residuals and were both satisfied and accepted. Bivariate Pearson’s product-moment correlation \( (p < 0.05) \) was calculated between the trunk ROM and the injury risk variables on all participants, and classified according to Hopkins (2000). Effects sizes \( (\eta^2_p) \) were defined as trivial \( (< 0.0099) \), small \( (0.0099 - 0.0588) \), moderate \( (0.0588 - 0.1379) \), and large \( (> 0.1379) \) sizes (Richardson 2011).

### 5.3 Results

Analyses of variance of joint angles showed no significant main effect of trunk-ROM-group \( (F_{2,57} = 0.05, \ p = 0.96, \ \eta^2 = 0.0016) \); however, significant interactions between angles*trunk-ROM-group \( (F_{34,969} = 1.47, \ p = 0.04, \ \eta^2 = 0.0492) \) and angles*events*trunk-ROM-group \( (F_{136,3876} = 1.63, \ p < 0.001, \ \eta^2 = 0.0542; \text{Figure 5-1}) \) were present. *Post hoc* tests failed to identify the source of significance in angles*trunk-ROM-group yet revealed that in angles*events*trunk-ROM-group significant differences were present with HIGH compared to MID trunk-ROM-group displaying significantly decreased hip flexion at \( F_{v3} \) \( (\text{MID} = 43.5 \pm 2.8^\circ, \text{HIGH} = 36.3 \pm 2.8^\circ; \ p < 0.01) \) and significantly increased hip internal rotation at \( F_{v1} \) \( (\text{MID} = 4.9 \pm 2.6^\circ, \text{HIGH} = 12.3 \pm 2.6^\circ; \ p < 0.01) \). Significant differences were also identified between LOW and HIGH trunk-ROM-groups with the HIGH group displaying significantly increased trunk-abdominal pelvis extension at \( TO \) \( (\text{LOW} = -1.7 \pm 2.1^\circ, \text{HIGH} = 5.4 \pm 2.1^\circ; \ p < 0.01) \), hip internal rotation at \( F_{v1} \) \( (\text{LOW} = 3.6 \pm 2.6^\circ, \text{HIGH} = 12.3 \pm 2.6^\circ; \ p < 0.001) \) and \( F_{v2} \) \( (\text{LOW} = 5.8 \pm 2.3^\circ, \text{HIGH} = 12.2 \pm 2.3^\circ; \ p < 0.05) \), and forefoot abduction at \( F_{v1} \) \( (\text{LOW} = -14.9 \pm 2.4^\circ, \text{HIGH} = -21.4 \pm 1.7^\circ; \ p < 0.05) \) than the LOW trunk-ROM-group. Significantly decreased hip flexion was observed at IC in the HIGH trunk-ROM-group when comparing to the LOW trunk-ROM-groups \( (\text{LOW} = 56.3 \pm 2.4^\circ, \ p < 0.05; \text{HIGH} = 43.5 \pm 2.8^\circ, \ p < 0.05) \).
HIGH = 47.9±2.4°; \( p<0.001 \), \( F_{V1} \) (LOW = 50.3±2.4°, HIGH = 43.4±2.4°; \( p<0.01 \)), \( F_{V2} \) (LOW = 53.2±2.7°, HIGH = 45.2±2.7°; \( p<0.001 \)) and \( F_{V3} \) (LOW = 44.1±2.8°, HIGH = 36.3±2.8°; \( p<0.001 \)).

Peak joints angles showed no significant main effect of ROM group (\( F_{2,57}=0.19, \ p=0.83, \ \eta^2=0.0067 \)). Although a significant peak*ROM group interaction was present (\( F_{58,1653}=1.44, \ p=0.02, \ \eta^2=0.0480 \)), post hoc analysis failed to identify the source of the significance. A significant main effect of ROM was not identified in joint ROM (\( F_{2,57}=1.49, \ p=0.23, \ \eta^2=0.0497 \)); however, a ROM*trunk-ROM-group effect was present (\( F_{16,456}=2.31, \ p=0.003, \ \eta^2=0.0750 \)) despite no source of this significance identified through post hoc analysis.

No main effect of ROM group was identified in joint moments (\( F_{2,57}=0.89, \ p=0.42, \ \eta^2=0.0303 \)), GRF (\( F_{2,57}=0.46, \ p=0.64, \ \eta^2=0.0158 \)), or GRF timing (\( F_{2,57}=0.57, \ p=0.57, \ \eta^2=0.0196 \)), nor was there a moments*ROM group (\( F_{58,1653}=1.18, \ p=0.16, \ \eta^2=0.0399 \)), GRF*ROM group (\( F_{14,399}=1.11, \ p=0.35, \ \eta^2=0.0375 \)), or timing*ROM group (\( F_{14,399}=0.51, \ p=0.93, \ \eta^2=0.0174 \)) interaction present.

Bivariate Pearson’s product-moment correlation determined a significant correlation between peak knee flexion and total trunk ROM (\( r^2=0.06; \ p=0.02 \)); however, the trivial effect size indicates that this is of no practical significance. No other correlations were significant (Table 5-1).
Table 5-1: Bivariate Pearson’s product-moment correlations between total trunk ROM groups and injury risk variables.

<table>
<thead>
<tr>
<th>Variables</th>
<th>$r^2$</th>
<th>$p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ankle Inversion/eversion IC</td>
<td>0.00</td>
<td>0.79</td>
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<tr>
<td>Peak Ankle Inversion</td>
<td>0.02</td>
<td>0.20</td>
</tr>
<tr>
<td>Knee Add/Abb IC</td>
<td>0.01</td>
<td>0.31</td>
</tr>
<tr>
<td>Peak Knee Adduction</td>
<td>0.01</td>
<td>0.48</td>
</tr>
<tr>
<td>Knee Flexion IC</td>
<td>0.01</td>
<td>0.29</td>
</tr>
<tr>
<td>Peak Knee Flexion</td>
<td>0.06</td>
<td>0.02</td>
</tr>
<tr>
<td>Hip Flexion IC</td>
<td>0.03</td>
<td>0.10</td>
</tr>
<tr>
<td>Peak Hip Flexion</td>
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<td>0.09</td>
</tr>
<tr>
<td>Hip internal rotation IC</td>
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<td>0.07</td>
</tr>
<tr>
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<td>0.07</td>
</tr>
<tr>
<td>Knee moment max_x</td>
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<td>0.52</td>
</tr>
<tr>
<td>Knee moment max_y</td>
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<td>0.93</td>
</tr>
<tr>
<td>Knee moment max_z</td>
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<td>0.06</td>
</tr>
<tr>
<td>Vertical GRF</td>
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</tr>
<tr>
<td>Posterior GRF</td>
<td>0.00</td>
<td>0.52</td>
</tr>
</tbody>
</table>
5.4 Discussion

Increased lateral trunk flexion during landing is implicated in lower limb injury risk in some research (Dempsey, Lloyd et al. 2007, Dempsey, Lloyd et al. 2009). While other research contests this notion by supporting the contrast notion of a more posterior trunk position within the base of support (Sheehan, Sipprell III et al. 2012). It is therefore important to establish if lower limb risk is mitigated during R-COD, via altering trunk ROM. This current study does not support the hypothesis that either increased or decreased trunk ROM utilised the stance phase of the R-COD is associated with key injury risk variables such as peak knee abduction angle or peak net internal knee adduction moment. This study observed that although the groups utilised different trunk ROM, no significant differences were observed in any trunk kinematics nor kinetics. This difference in trunk-ROM strategy during the stance phase lead to the HIGH compared to LOW and MID trunk-ROM-groups exhibiting reduced hip flexion with a more internally rotated hip during R-COD (Figure 5-1) but did not lead to any changes in joint moments.

Reduced hip flexion displayed by the HIGH trunk-ROM-group compared to MID and LOW trunk-ROM-groups, ranging from a 6.9° to 8.4° difference between ROM groups, was identified within the current study. This strategy has previously been associated with increased ACL injury risk during single leg drop landings (Shimokochi, Ambegaonkar et al. 2013); however, this increased risk occurs when combined with higher posterior GRF, lower knee flexion at IC and greater peak knee abduction during landing, none of which were identified during the current study. Additionally, increased hip flexion angles at IC, 56.8 ± 10.5°, during a stop-jump task have been associated with athletes at risk of patellar tendinopathy (Mann, Edwards et al. 2013), whereby they extend their hips during landing as opposed to flexing their hips (Edwards, Steele et al. 2010). Results of the current study identified athletes with increased trunk ROM as displaying reduced hip flexion at IC, 47.9 ± 2.4°, suggesting that the increase trunk ROM has not increased their risk of patellar
tendinopathy. Previous research has also identified increase internal hip abduction moment in athletes with increased trunk ROM while performing a wide stance R-COD (Dempsey, Lloyd et al. 2007). Although the current study’s analysis did not calculate foot stance width, results did not identify an association between hip abduction moments and increased trunk ROM.

An underlying reduced lumbopelvic control leading to forward pelvic tilt posture has been suggested to lead to increased hip internal rotation, 26-36°, which is associated with increased risk of ACL injury (Koga, Nakamae et al. 2018). This increased hip internal rotation may result in an inability to stabilise resultant knee valgus loads by way of reduced activation of the medial muscles of the lower limb (McLean, Huang et al. 2005). The current study identified increased hip internal rotation of 7.4° between the HIGH trunk ROM group compared to MID trunk ROM, with a difference between the HIGH trunk ROM group compared to the LOW trunk ROM group of 8.6° and 6.3° at $F_{V1}$ and $F_{V2}$, respectively. Despite this increase in hip internal rotation, it did not lead to any significant differences in any joint moments, which does not support previous findings of being associated with increased peak net internal knee adduction moment (McLean, Huang et al. 2005). Nor does the current study support other research that has associated high internal knee adduction moments with a greater lateral trunk flexion whereas a trunk planar angle (Jamison, Pan et al. (2012), which are significantly associated with ACL incidence (Hewett, Myer et al. 2005). Despite this, results of the current study do not support previous research with no association identified between trunk ROM and knee adduction moments, however different angle definitions of trunk posture may have resulted in these between-study differences.
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The current study identified that the HIGH trunk-ROM-group displayed an increase of 6.5° forefoot abduction compared to LOW-trunk-ROM; however, with limited research it is unknown whether this is a risk factor for increased injury risk. Despite the limited research on the effects of trunk-ROM on ankle mechanics, increased postural sway has been identified in athletes with a history of unilateral inversion ankle injury (Cornwall and Murrell 1991, Beckman and Buchanan 1995), and has also been noted as a potential risk factor for ankle injuries in athletes (Beynnon, Murphy et al. 2002). With lumbopelvic or core musculature responsible for the control and stabilisation of the trunk region (Brown, Vera-Garcia et al. 2006) and postural stability (Cornwall and Murrell 1991, Beckman and Buchanan 1995), it is possible that a neuromuscular or strength deficiency in this region could potentially contribute to this increase in injury risk. However, the results of the current study failed to identify a significant correlation between trunk ROM and ankle injury risk factors such as peak inversion moment (Richards, Ajemian et al. 2002) observed in previous research, and further research is required in this area.

While increased trunk ROM has not been associated with variables associated with injury risk during R-COD in the current study, previous research by Edwards, Austin et al. (2017) has associated this variable with superior agility performance. Specifically, athletes who utilised increased trunk range of motion (sum of all three planes) during a R-COD performed better in field-based performance tests, as evidence by a higher countermovement jump height and faster Illinois agility test. Although this study did not conduct field-based performance testing, this current study also did not identify a significant correlation with reaction time during R-COD and trunk-ROM-group.
5.5 Conclusions
The current study failed to identify links with trunk-pelvis ROM, or any key lower limb kinematic or kinetic variable associated with injury risk during the R-COD. It remains unknown if this relationship exists in an adult population and if athletes with differing skill level, and whether it affects athletic performance, suggesting further research is needed.

5.6 Acknowledgements
The authors gratefully acknowledge the Western Region Academy of Sport for providing the participant pool from which participants were recruited for this study.

5.7 References


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Chapter 6. Summary, Conclusions and Recommendation for Future Research

6.1 Summary of Conclusions
With the grave impacts sporting injuries have on the athletic community, it is increasingly important for the risk factors associated with sporting injuries to be mitigated. To reduce the prevalence of sporting injuries many simple qualitative movement screening tools to assess injury risk and reduction programs to reduce or moderate these injury risks have been used with limited success. Many of these screening tools and programs have fallen short in their effectiveness due to methodological reasons. In particular, the absence of lumbopelvic screening and training has been a crucial flaw in previous protocols despite research demonstrating the significant effect this region has on injury risk and injury mechanics. There has been the use of inappropriate statistical analysis and questionable interpretation of many studies that inappropriately claim high reliability within their movement screens such as the FMS. Nevertheless, many sporting teams and clinicians have adopted screening protocols without scientific evidence-based research to support their use. Therefore, there is a requirement for a new field-based movement screen that is simple, includes assessment of the lumbopelvic region, and is reliable.

The aims of the current studies were the following. Study a) To determine the inter- and intra-rater reliability of a field-based MS in novice and expert raters using different viewing methods and determine the presence of a familiarisation effect for both the rater and the participants. To compare the effect of four different 12-week intervention programs on modifying the jump-landing mechanics of a Study b) stop-jump and Study c) R-COD tasks in pre-elite youth athletes. Study d) To identify if trunk ROM during R-COD in pre-elite youth athletes is associated with lower limb injury risk factors.
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Respective hypotheses for each of these aims were as follows. a) The field-based MS criteria for each movement and total composite score will display high inter- and intra-rater reliability for both novice and expert raters, and inter- and intra-rater reliability will improve after repeated exposure to the MS due to a familiarisation effect. That a combination intervention program of core stability and landing re-training will result in the greatest improvement in lumbopelvic stability and lower limb alignment compared to the other programs, therefore reducing injury risk factors associated with the b) stop-jump landing and c) R-COD. d) Athletes utilising high and low trunk ROM during R-COD will display lower limb injury risk variables compared to those with moderate magnitude of trunk range of motion. To achieve the aim of Study a), 55 pre-elite youth athletes who had never previously performed movement screening were recruited from the Hunter Academy of Sport. While for the aims of Studies b) to d), 89 junior pre-elite athletes with no current signs or symptoms of injury were recruited from the Western Region Academy of Sports Basketball, Hockey, Netball, Triathlon and Softball teams.

Based on the findings of these studies results, there is only partial support of some of the studies hypotheses, it does not support other hypotheses but identifies future research areas and practical recommendation for coaches and clinicians. For Study a), the hypothesis was supported for high inter- and intra-rater reliability observed in both novice and expert raters for the total composite score, and the presence of a familiarisation effect in athletes who perform the movement screen for the first time. However, the hypothesis of high inter- and intra-rater reliability was not supported, likely to be due to the small categorical scale used to rate athlete’s movement quality. Additionally, a learning effect was not identified in either novice or expert raters in contrast to the hypothesis, suggesting the movement screening criteria is explicit and simple enough for a novice rater to utilise.
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Results of this thesis did not support the hypothesis of Study b) nor Study c) that a specific intervention program, core and landing retraining program, was superior to the other intervention programs as all athletes across the study population displayed a similar change in their landing technique as a result of the intervention. This change in landing technique is suggested to occur as a result of the strength and conditioning program that all athletes completed in conjunction with the study intervention programs. With a lack of ‘true’ control group (i.e. no training group) within the study design, there is a limitation that is ultimately unavoidable, as it is virtually impossible to study a cohort of pre-elite youth athletes who are not undergoing any kind of strength and conditioning training. While this limitation has been controlled as much as possible, it must be acknowledged that this group cannot be considered a ‘true’ control group. Both studies results did however, identify a change in lumbopelvic stability during the eccentric loading phase of the stop-jump movement (Study b) and R-COD (Study c), with athletes tending to land in a more upright trunk position; however, it is unknown whether this landing technique is beneficial or detrimental to injury risk.

For Study d), the results did not support previous research that propose that increased trunk range of motion during R-COD correlates with increase lower limb injury risk. Results of this study however, did indicate that athletes with a high trunk ROM employed supplementary strategies in order to control their trunk region during the eccentric loading phase of the R-COD when compared to moderate and low trunk ROM. Specifically, reduced hip flexion and increased internal hip rotation were identified in athletes with increase trunk ROM, suggested to be a more anatomical hip landing strategy to create a more anatomical position whereby reducing the degrees of freedom and thus reducing the complexity of the task.
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Results of this collection of studies within this thesis provide valuable insight into the issues, requirements and current limitations of attempting to identify athletes at increased injury risk using field-based movement screening. Further insight of the effectiveness of intervention programs such as, core, landing retraining programs and a combination of these programs, to modify landing mechanics of pre-elite youth athletes performing a stop-jump and R-COD, and the role that trunk ROM plays in injury risk. Study a) was the first to demonstrate that pre-elite youth athletes display a familiarisation effect when performing novel movement screen tasks. It is therefore recommended that athletes perform a familiarisation trial prior to rating in order to obtain a true representation of the athlete’s movement capability. Although it is beyond the design of this study, it should be acknowledged that athletes may require additional familiarisation sessions and this is an important future research area. This current study identified poor reliability when rating the individual movements which is thought to be confounded by the non-normative distributed data and a small rating scale. By increasing the rating scale of the individual movements within the movement screen, it is likely to improve the reliability of the rating of the individual movements. A higher reliability of the rating of the individual movements would allow coaches and/or clinicians to gain understanding of athlete’s movements. An addition, it would provide a more valid tool to reliably record longitudinally specific movement limitations or errors within an individual athlete’s movement patterns, making this data more practical in terms of usability. Whereas the total composite score displayed excellent reliability in both novice and expert raters. This suggests that this movement screening protocol is a reliable protocol when used to assess overall movement quality. An absence of a learning effect for both novice and expert raters observed in this study suggests that this movement screening tool is easily implemented by individuals regardless of screening experience, and eliminated the requirement for extensive training to implement the screening tool.
While the results of Study b) and c) revealed no significant differences between the types of interventions programs, all youth athletes, regardless of training intervention program, landing in a more upright trunk position in stop-jump and R-COD after their 12-week intervention program compared to before. It is suggested that an change in neuromuscular control as a result of general training occurred, thus supporting the use of strength training for modification of jump-landing mechanics in those athletes with no or little previous strength training experience. This more upright trunk relative to pelvis position post-intervention compared to pre-intervention was seen by increased L5-S1 extension and thoracic-abdominal flexion angles identified across the stop-jump landing phase and a decrease in hip flexion at IC and T12-L1 joint moment during the R-COD task. This movement strategy has previously been associated with ACL risk, however this study showed no associated increase in posterior GRF, decrease in knee flexion at IC or peak knee abduction angle. Therefore, we suggest that overall this change in landing posture as a result of the interventions did not alter ACL injury risk. It is postulated that the landing strategy employed by athletes following the intervention program may have been an attempt to correct their landing technique and/or increase their trunk stability through what is known as a ‘guarding’ or ‘splinting’ technique to reduce the frontal and transverse plane motion. It is unknown however, whether this strategy had been adopted by these athletes due to their novice status of training, and/or whether these movement patterns are beneficial or detrimental to lower limb injury risk. A decrease in hip external rotation to a more anatomical position, was also identified post- compared to pre-intervention within the current study. Despite this more anatomical hip internal rotation position being associated with athletes with a history of groin injury, here the increase observed occurred within the propulsion phase as opposed to the weight acceptance phase where the risk of injury occurs and therefore, was not deemed as an increase in groin injury risk.
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Intervention programs did not alter any of the ankle and knee kinematics nor kinetics, and it is suggested that the feedback strategies utilised during the prevention program were lacking external feedback. Although explicit feedback has commonly been utilised in previous training programs, results of the current study show that this focus did not produce a beneficial training effect to reduce injury risk. It is also questioned whether the training program was too advanced for the novice state of these athletes as seen by their low total composite score in the movement screening tool.

Despite previous research suggesting that increased trunk ROM during landing is implicated in lower limb injury risk, results of the Study d) do not support this notion. Trunk ROM was not correlated with any key lower limb injury risk factors during a R-COD. Increased trunk ROM was associated in this study with reduced hip flexion, increased hip internal rotation and increased forefoot abduction, yet none of these variables were determined to be associated with increased lower limb injury risk due to an absence of associated variables. That is, the reduced hip flexion identified in athletes with HIGH trunk ROM creates a more anatomical hip movement strategy, commonly associated with ACL injury risk; however, this increased risk occurs when combined with higher posterior GRF, lower knee flexion at IC and greater peak knee abduction during landing, none of which were identified in this current study. The increased hip internal rotation identified within this study, has previously been associated with increased peak internal knee adduction (external valgus) joint moment and ACL risk; however, no correlation between trunk ROM and peak internal knee adduction joint moment was observed in this study. The HIGH trunk ROM group displaying increased forefoot abduction in comparison to LOW trunk ROM. While increased trunk ROM has not been
associated with variables associated with injury risk during R-COD in the current study, it was questioned whether there was an association with performance variables as previously identified in research. Previous research has associated a higher countermovement jump height and faster Illinois agility test performance with increased trunk ROM; however, the current study did not identify any correlation with reaction time and trunk ROM.

6.2 Conclusions
Results of this study indicate that movement screening experience does not affect rater reliability; however, familiarisation is required for athletes performing the MS. Additionally, the MS total composite score can be reliably used to determine movement competency; however, individual movements scores should not be relied on. When implementing strength and conditioning programs in pre-elite youth athletes, the specific exercises included within the program is not of great importance as regardless of intervention, all athletes displayed similar changes in their landing mechanics. That is, a simple strength and conditioning program comprising of four exercises with limited equipment required, can be implemented in pre-elite youth athletes with poor movement competency to modify their landing patterns. As a result of these intervention programs athletes displayed a more upright trunk relative to pelvis position during landing that was not shown to alter the risk of lower limb injury; however, it is unknown whether this movement strategy is beneficial or detrimental to athletic performance. This current study failed to identify links between trunk ROM, injury risk and/or performance. It is recommended that further research is needed to determine how trunk ROM during landing tasks affects these factors that influence lower limb injury risk and athletic performance.
6.3 Recommendation for Future Research
Following are recommendations for future research based on the findings of the studies in this thesis:

- Determine if increasing the numerical scale for the rating of the individual movements will improve the reliability when assessing the quality of motion of an individual movement;
- Ensure a normal distribution of the MDS data in order to determine if this limitation in the dataset affected the reliability of this screening assessment tool;
- Investigate the effect of the intervention programs on populations that are trained and untrained in strength and conditioning to determine if prior training experience in an adult cohort alters their interventions effectiveness;
- Completion of a longitudinal study to determine the relationship between movement screening score and injury prevalence in pre-elite youth athletes in a larger cohort (>200 participants); and
- Investigation of the effect of lumbopelvic instability on lower limb risk factors, in particular dynamics jump-landing tasks.
Appendix 1 – Ethics

16 April 2013

Ms Kerry Mann
School of Human Movement Studies
Charles Sturt University
Panorama Avenue
Bathurst NSW 2795

Dear Ms Mann,

The CSU Human Research Ethics Committee (HRBC) operates in accordance with the National Health and Medical Research Council’s National Statement on Ethical Conduct in Research Involving Humans.

The HRBC has reviewed your report requesting a variation for your research project “Lumbo pelvic Stability: The primary cause of lower limb injuries in pre-elite youth athletes?”, protocol number 2012/157 and I am pleased to advise that this request for a variation meets the requirements of the National Statement; and variation for this research is granted for a twelve month period from 16 April 2013.

Please note the following conditions of approval:

- all Consent Forms and Information Sheets are to be printed on Charles Sturt University letterhead. Students should liaise with their Supervisor to arrange to have these documents printed;
- you must notify the Committee immediately in writing should your research differ in any way from that proposed. Forms are available at http://www.csu.edu.au/__data/assets/word_doc/0010/175683/ehrcc_annrep.doc
- you must notify the Committee immediately if any serious and or unexpected adverse events or outcomes occur associated with your research, that might affect the participants and therefore ethical acceptability of the project. An Adverse Incident form is available from the website as above;
- amendments to the research design must be reviewed and approved by the Human Research Ethics Committee before commencement. Forms are available at the website above;
- if an extension of the approval period is required, a request must be submitted to the Human Research Ethics Committee. Forms are available at the website above;

Variation.doc

Last updated: February 2013
Next review: February 2014

www.csu.edu.au

CRICOS Provider Numbers for Charles Sturt University: 00005F (NSW), 01067G (VIC) and 019966 (ACT). ABN: 81 078 309 551

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Appendices

- you are required to complete a Progress Report form, which can be downloaded as above, by 21 March 2014 if your research has not been completed by that date;
- you are required to submit a final report, the form is available from the website above.

You are reminded that an approval letter from the CSU HRREC constitutes ethical approval only.

If your research involves the use of radiation, biological materials or chemicals separate approval is required from the appropriate University Committee.

Please don't hesitate to contact the Executive Officer: telephone (02) 6338 4628 or email ethics@auu.edu.au if you have any queries about this matter.

Yours sincerely,

Julie Allen
Executive Officer
Human Research Ethics Committee
Direct Telephone: (02) 6338 4628
Email: ethics@auu.edu.au

On behalf of
Dr Stephen Nield

This HRREC is constituted and operates in accordance with the National Health and Medical Research Council's (NHMRC) National Statement on Ethical Conduct in Human Research (2007).

Varinder Jot

Last updated: February 2013
_next Review: February 2014

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Appendix 2 - Movement Screen Information

The Tuck Jump

The tuck jump requires the athletes to perform continuous maximal vertical jumping manoeuvres, in which the participant jumps vertically upwards off the ground, then tucks their legs up towards their chest during the up flight period, and then extends their legs to allow a safe upright landing for a ten second period.

<table>
<thead>
<tr>
<th>Table 1. Criterion of the Tuck Jump</th>
</tr>
</thead>
<tbody>
<tr>
<td>☑ Medial knee collapse during landing.</td>
</tr>
<tr>
<td>☑ Thighs not equal and parallel through flight and at top of jump.</td>
</tr>
<tr>
<td>☑ Deviation in flight motion (i.e., forward, backward, left or right).</td>
</tr>
<tr>
<td>☑ Foot contact time not simultaneous.</td>
</tr>
<tr>
<td>☑ Pause between repetitions.</td>
</tr>
<tr>
<td>☑ Technique declines prior to 10 seconds.</td>
</tr>
</tbody>
</table>

Scoring criteria: 0 = Pain; 1 = 3+ errors; 2 = 1-2 errors; 3 = no errors

“You need to jump up vertically as high as you can, tucking your knees to your chest, continuously for 10 seconds”. *Demonstration of two jumps.*
The Overhead Squat

The overhead squat is completed by the participant performing three repetitions of a squat movement while holding a 2 metre length of dowel above their head.

Table 2. Criterion of the Overhead Squat

| ✓ Bar not aligned directly over the head and feet throughout the movement. |
| ✓ Full squat range of motion not achieved. |
| ✓ Lumbar spine segment doesn’t remain neutral. |
| ✓ Knees not aligned over feet while squatting/medial knee collapse present. |
| ✓ Heels do not remain on the floor throughout the movement. |
| ✓ Uncontrolled movement. |

Scoring criteria: 0 = Pain; 1 = 3+ errors; 2 = 1-2 errors; 3 = no errors

“Hold the dowel above your head with your arms straight, about shoulder width apart, with your feet at hip width. Perform three deep, controlled squats”. 

Demonstration of one overhead squat.
The single leg squat involves the participant performing five repetitions of a squatting manoeuvre using single leg stance while lowering into a squat position. This movement is performed on both the right and left legs.

### Table 3. Criterion of the Single Leg Squat

<table>
<thead>
<tr>
<th>Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>☑ Jerky and uncontrolled trunk, pelvis or thigh movement.</td>
</tr>
<tr>
<td>☑ Trunk rotation or side flexion.</td>
</tr>
<tr>
<td>☑ Pelvic rotation.</td>
</tr>
<tr>
<td>☑ Medial knee collapse.</td>
</tr>
<tr>
<td>☑ Abduction of non-trial leg.</td>
</tr>
<tr>
<td>☑ Excessive hip flexion during movement.</td>
</tr>
</tbody>
</table>

Scoring criteria: 0 = Pain; 1 = 3+ errors; 2 = 1-2 errors; 3 = no errors

“Stand on one leg with your hands on your shoulders. Squat down and back up, keeping your trunk upright. 5 times each leg. Demonstrate one on each leg.
The Dip Test

The dip test is performed similar to the single leg squat. It involves the participant performing five repetitions of a squatting manoeuvre using single leg stance while resting the uninvolved foot on a step behind the participant. This movement is performed on both the right and left legs.

Table 4. Criterion of the Dip Test

| ✓ Jerky and uncontrolled trunk, pelvis or thigh movement. |
| ✓ Level pelvis not maintained during movement. |
| ✓ Medial knee collapse. |
| ✓ Abduction of non.-trial leg. |

Scoring criteria: 0 = Pain; 1 = 3+ errors; 2 = 1-2 errors; 3 = no errors

“Same as the single leg squat but your other leg is sitting with your toe resting on the top of a small step. Five times each leg”. Demonstrate one of each leg.
**Lunge**

Each participant will perform a forward lunge by stepping one leg a stride in front and lowering themselves till their front knee reaches a 90° angle and their back lower leg is parallel to the ground, and then returning to an upright position.

**Table 5. Criteria of the Lunge**

<table>
<thead>
<tr>
<th>Criteria</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Front knee not behind the line of the toes.</td>
<td>☑</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lateral flexion or rotation of the trunk or pelvis.</td>
<td>☑</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lumbar spine does not remain neutral (rotation, or excessive extension or flexion present)</td>
<td>☑</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Excessive feet turned in or out.</td>
<td>☑</td>
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</tbody>
</table>

Scoring criteria: 0 = Pain; 1 = 3+ errors; 2 = 1-2 errors; 3 = no errors

“Take a long stride out in front of you and lower yourself down and back up to a standing position. Perform three repetitions on each leg”. *Demonstration one on each leg.*
**Prone Hold**

The prone hold will require participants to extend their body into a straight line in a prone position propped up on their elbows and toes for two minutes.

**Table 6. Criterion of the Prone Hold**

| ☑️ Hips drop. |
| ☑️ Thoracic and lumbar region not neutral |
| ☑️ Head and shoulders not centred and stable. |
| ☑️ Hips knees, ankles and feet not aligned and unstable. |

Scoring criteria: **0** = < 30 seconds; **1** = 30-60 seconds; **2** = 60-90 seconds; **3** = 90-120 seconds

“Lay down in a plank position on your forearms and propped up on your toes. Maintain a stable and straight position, with your hands flat. Keep this position for 2 mins”. *Demonstration of position.*
### Appendices

<table>
<thead>
<tr>
<th>Tuck Jump</th>
<th>(10s max-hgt)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Key Components</strong></td>
<td><strong>Errors</strong></td>
</tr>
<tr>
<td>Medial knee collapse</td>
<td></td>
</tr>
<tr>
<td>Thighs not parallel at peak jump</td>
<td></td>
</tr>
<tr>
<td>Deviation in flight motion</td>
<td></td>
</tr>
<tr>
<td>Foot contact timing not equal</td>
<td></td>
</tr>
<tr>
<td>Pause between jumps</td>
<td></td>
</tr>
<tr>
<td>Technique declines prior to 10 s</td>
<td></td>
</tr>
<tr>
<td><strong>Score (0,1,2,3)</strong></td>
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</table>

<table>
<thead>
<tr>
<th>Overhead Squat</th>
<th>(3reps)</th>
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</thead>
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<tr>
<td><strong>Key Components</strong></td>
<td><strong>Errors</strong></td>
</tr>
<tr>
<td>Bar not aligned over head/feet</td>
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<tr>
<td>Squat depth not full ROM</td>
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<tr>
<td>Lumbar not neutral</td>
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<tr>
<td>Knees not aligned over feet</td>
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<tr>
<td>Uncontrolled movement</td>
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<tr>
<td>Heels not remaining on the floor</td>
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<tr>
<td><strong>Score (0,1,2,3)</strong></td>
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</table>

<table>
<thead>
<tr>
<th>Single Leg Squat</th>
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</thead>
<tbody>
<tr>
<td><strong>Key Components</strong></td>
<td><strong>Errors L</strong></td>
</tr>
<tr>
<td>Jerky mvt trunk pelvis &amp; thigh</td>
<td></td>
</tr>
<tr>
<td>Trunk rotation or side flexion</td>
<td></td>
</tr>
<tr>
<td>Pelvic rotation</td>
<td></td>
</tr>
<tr>
<td>Medial knee collapse</td>
<td></td>
</tr>
<tr>
<td>Abduction of non-trial leg</td>
<td></td>
</tr>
<tr>
<td>Excessive hip flexion during mvt</td>
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</tr>
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<td><strong>Score L</strong></td>
<td><strong>Score R</strong></td>
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<table>
<thead>
<tr>
<th>Dip Test</th>
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</tr>
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<td><strong>Key Components</strong></td>
<td><strong>Errors L</strong></td>
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<tr>
<td>Jerky mvt trunk pelvis &amp; thigh</td>
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</tr>
<tr>
<td>Pelvis does not remain level</td>
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<td></td>
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<tr>
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</tr>
<tr>
<td><strong>Score L</strong></td>
<td><strong>Score R</strong></td>
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<table>
<thead>
<tr>
<th>Lunge</th>
<th>(3 reps es)</th>
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<tbody>
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<td><strong>Key Components</strong></td>
<td><strong>Errors L</strong></td>
</tr>
<tr>
<td>Front knee not behind line of toes</td>
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<tr>
<td>Lateral flexion or rotation of the trunk or pelvis</td>
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</tr>
<tr>
<td>Lumbar not neutral/rotation</td>
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</tr>
<tr>
<td>Excessive feet turning in or out</td>
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</tr>
<tr>
<td><strong>Score L</strong></td>
<td><strong>Score R</strong></td>
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</table>

<table>
<thead>
<tr>
<th>Prone Hold</th>
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<td><strong>Key Components</strong></td>
<td><strong>Errors</strong></td>
</tr>
<tr>
<td>Hips drop</td>
<td></td>
</tr>
<tr>
<td>Thoracic&amp;Lumbar not neutral</td>
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<tr>
<td>Head/Shoulders not centred/stable</td>
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<tr>
<td>Hips/Knees/Ankes/Feet not aligned</td>
<td></td>
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<tr>
<td><strong>Score</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Movement Score</strong></td>
<td></td>
</tr>
</tbody>
</table>
Appendix 3 – Intervention Programs.

Core Exercise Set 1:

Arabesque (60°) - supported
• With arms outstretched at shoulder height, stand on one leg while balancing on a wall using the same side hand. Lean forward so your trunk is 60° from vertical and lift your other leg backwards keeping it in line with your trunk. Lower your other hand down towards the floor, rotating your trunk and pelvis over your hip. This movement will be limited by your hand position on the wall.
• 10 reps x 2 sets on each leg.

Arabesque (60°) - unsupported
• With your arms outstretched at shoulder height, stand on one leg. Lean forward so your trunk is 60° from vertical and lift your other leg backwards keeping it in line with your trunk. Lift one hand up in the air towards the ceiling while lowering your other hand down towards the floor, rotating your trunk and pelvis over your hip.
• 10 reps x 2 sets on each leg.

Arabesque (60°) - weight
• Perform as above with 0.5 kg weight in the hand you are lifting towards the ceiling. If the weight feels too light use 1.0 kg.
• 10 reps x 2 sets on each leg.

Arabesque (60°) - ball bounce
• Perform as above, when fully rotated bounce a ball against a wall while maintaining your position.
• 10 reps x 2 sets on each leg.

Exercise Competency Criteria
• Trunk, pelvis, thigh, ankle remains stable
• Controlled movements
• No stumbling, swaying or falling
• Maintain hip alignment (no drop)
Core Exercise Set 2:

**Single leg upright squats - supported**
- With one hand balancing on a wall and standing on the opposite leg, squat down as slowly as possible without losing balance.
- Repeat on the other leg and opposite hand.
- 10 reps x 2 sets on each leg.

**Single leg upright squats - unsupported**
- Perform exercise as above but without using the wall to balance.
- Repeat on the other leg.
- 10 reps x 2 sets on each leg.

**Running man arms**
- Stand on one leg with one arm raised above the head. Keep the heel on the ground; do not let the other foot touch the ground. Squat down as far as possible while keeping the heel on the ground. Lower the raised arm so both arms are down. Rise from the squat and raise the other arm over head. Squat down again as far as possible while keeping the heel on the ground. Repeat on the other leg.
- Exercise Tempo - 2-2-2 (2 seconds up - 2 seconds down). Continue squatting on the same leg while alternating arms for 10 repetitions.
- 15 reps x 2 sets on each leg. Rest for 10 seconds between each set.

**Upright single leg squat with rotating trunk and arms**
- Stand on one leg with hands forward at shoulder height. Squat down (Exercise Tempo - 2-2-2. 2 seconds down - 2 seconds up). When bending knee rotate arms to one side and to front when coming up, repeat to other side. One rep = 2 squats and arm rotations to each side.
- 15 reps x 2 sets on each leg. Rest for 10 seconds between each set.

**Exercise Competency Criteria**
- Full ROM
- Trunk, pelvis and thigh remain stable - minimal movement out of starting plane
- Heel remains on the floor
- Trunk remains upright - except during the "runner squat" and "running man arms" exercises
- Movement initiated at the hips
- Do not let the knee move sideways, or come over the line
Core Exercise Set 3:

**Side plank - with arm lift**
- Lie on the side with one leg on top of the other, distributing the body weight evenly over the forearm. Raise the hips and the top arm simultaneously to achieve a straight body. (If necessary, start with weight on bent knees rather than the feet, then progress to feet.) Lower arm and hips to floor simultaneously. Repeat on the other side.
- Exercise Tempo — 2-2-2 (i.e. 2 seconds to raise, 2 second hold, 2 seconds to lower).
- 5 reps each side.

**Side plank - Lift and lower hips**
- Lie on the side with one leg on top of the other, distributing the body weight evenly over the forearm. Slowly lift the hips to achieve a straight body. Slowly lower the hips to the ground. Repeat on the other side.
- Exercise Tempo — 2-2-2 (2 seconds to lift and 2 seconds to lower).
- 5 reps x 2 sets on each side, with a 5 second rest between sets.

**Side plank, plank, side plank**
- Start in a front plank position with the weight resting evenly on the forearms; hold for 1 second. Roll to the side position, hold for 1 second. Roll again back to the front; hold for 1 second. Roll to the other side; hold for 1 second.
- One repetition is when each of these four positions has been held for 1 second.
- 5 reps.

**Side plank with arm and leg lift**
- Lie on the side with one leg on top of the other, distributing the body weight evenly over the forearm. Lift the hips to achieve a straight body. Raise the arm at the same time. Raise the top leg about 1’st and hold for 5 seconds. Lower the top leg, hips and arm. Repeat on the other side.
- 5 reps.
- Rest for 3 seconds between repetitions.

**Exercise Competency Criteria**
- Try to be a 'plank'
- Keep head, shoulders, trunk, hips and knees in a straight line.
- Keep shoulders in line with the trunk.
- Do not drop the hips.
- Do not hold for longer than the correct bodyform can be maintained.
- Do not roll shoulders forward or back.
- Do not bend forward or backwards at the hips.
- Emphasize control — maintain a straight body when moving to a new position.
- Breathe normally.
Appendices

Core Exercise Set 4:

Prone Plank
- Rest on elbows with weight distributed on forearms. Lift hips to form a "plank" between the shoulders and feet (or knees if too difficult on feet - progress to feet).
- Exercise Tempo – 2-2-2 (i.e. 2 seconds to raise, 2 second hold, 2 seconds to lower). Hold raised position for 2 seconds.
- 6 reps

Prone plank elbows to hands - hands to elbows
- Lift up into plank position with feet and elbows on the floor. Transfer weight and lift up onto each hand and then lower to each elbow. Alternate the hand that moves first.
- 6 reps

Prone plank crab crawl
- Lift up into plank position with weight on feet and hands. Lift one hand and the same foot and move 3cm to the side. Repeat moving back to the starting position. Repeat to opposite side. Alternate which side you move to first.
- 1 rep = 1 movement to each side - e.g. centre to right to centre to left to centre
- 6 reps

Prone plank arm & leg lift
- Lift up into plank position with weight on feet and hands. Lift one hand and the opposite foot off the floor, keeping arm and leg straight and keeping balance. Repeat with opposite arm and leg.
- 1 rep = lift with each arm and opposite leg
- 6 reps

Exercise Competency Criteria
- Try to be a ‘plank’
- Keep head, shoulders, trunk, hips and knees in a straight line
- Do not lift the hips too high or let them drop
- Emphasise control when moving to a new position
- Breathe normally

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Appendices

Landing Re-Training Exercise Set 1:

Side lying bottom leg lift

- Lie on the side with the top leg bent at the hip and knee. Lift bottom leg slowly off the ground and then lower it slowly to return to ground.
- Exercise Tempo - 3-2 (2 seconds to lift and 3 seconds to lower)
- 5 Reps x 3 Sets

Body lifts

- Lie on your side and lift top leg up to a partner (about 0.5m). Your partner holds the raised leg around the ankle, as you lift your bottom leg slightly off the ground (2 seconds) and raise your hips about 10cm off the ground using the muscles on the inside of the top leg to push down against partner’s hands (2 seconds). Hold raised position (2 seconds) then lower hips and bottom leg down (2 seconds). Do 2 repetitions on one leg with a 3 second rest between reps. Then perform 3 repetitions on the other leg.
- Perform 3 sets of 3 reps on each leg

Running man

- Stand on one leg with one arm raised above the head. Keep the heel on the ground, do not let the other foot touch the ground. Squat down as far as possible while keeping the heel on the ground. Lower the raised arm as both arms are down. Rise from the squat and raise the other arm over head. Squat down again as far as possible while keeping the heel on the ground.
- Repeat on the other leg.
- Exercise Tempo - 2-2 (2 seconds up - 2 seconds down). Continue squatting on the same leg while alternating arms for 23 repetitions.
- 12 reps x 2 sets on each leg. Rest for 30 seconds between each set

Running man jumps

- Stand on one leg with one arm raised above the head. Do not let the other foot touch the ground. Squat down as far as possible while keeping the heel on the ground. Lower the raised arm as both arms are down. Rise from the squat and perform a small single leg jump and raise the other arm over head. Squat down again as far as possible while keeping the heel on the ground.
- Repeat on the other leg.
- Exercise Tempo - 2-2 (2 seconds up - 2 seconds down). Continue squatting and jumping on the same leg while alternating arms for 23 repetitions.

Exercise Competency Criteria

- Knee does not medially collapse
- Prevent toes from pointing inward
- Do not lift leg forward
- Do not rotate body forwards or backwards
- Do not bend forward at the hips
- Maintain head, shoulders, trunk, hips, knees and ankles in alignment
- Trunk kept stable and upright throughout landing
- Maintain synchronised movement during entire movement
Landing Re-Training Exercise Set 2:

Side lying top leg lift
- Lie on the side with both legs straight. Lift your top leg slowly towards the sky and then lower it slowly to return to the other leg.
- Exercise Tempo – 2-2 (2 seconds to lift and 2 seconds to lower)
- 10 reps x 2 sets

Rapid abduction/adduction
- While standing with your knees slightly bent perform rapid jumps with your right foot moving to the right and your left foot moving to your left, then jumping back to the center
- 15 reps x 2 sets

Drop Jumps
- Stand on a step or box approximately 20-30cm high. Step off the step/box (do not jump) and performing a controlled landing. Step back onto the step/box and prepare for the next drop.
- 10 reps x 2 sets

Tuck Jump
- Stand with your feet together and perform a vertical jump tucking your knees up towards your chest at the top of the jump. Keep your trunk upright. Immediately following landing, perform the next jump.
- 15 reps x 2 sets

Exercise Competency Criteria
- Knee, trunk, pelvis, ankle remains stable
- Controlled movements
- Pelvis remains parallel throughout movement
- Foot placement remains neutral
- Knees do not move over the toes
- Knees do not medially collapse
- Feet land simultaneously
Landing Re-Training Exercise Set 3:

**Vertical Jump**
- Stand with weight equally distributed through both feet. Squat down and perform a maximal jump vertically straight up swinging your arms upwards as you jump. Following the landing phase, pause for two seconds and perform the following vertical jump.
- 15 reps x 2 sets

**Forward Jumps**
- Stand with feet together, jump forwards and land with both feet at the same time. Start with a small jump and slowly increase jumping distance while maintaining control and landing technique. Emphasise ‘sticking’ the landing with balance and control. After a brief pause, jump forwards again.
- 10 reps x 2 sets

**Single leg forwards jumps**
- Stand on the right foot, jump forwards and land on the right foot. Start with a small jump and slowly increase jumping distance while maintaining control and landing technique. Emphasise ‘sticking’ the landing with balance and control. After a brief pause, jump forwards and land on the right foot again.
- 10 reps x 2 sets (on each leg)

**Stop Jump**
- Athlete performs a small run up, landing with both feet at the same time, followed immediately by a vertical jump and landing again with two feet.
- Emphasis on maintaining good landing technique.
- Perform 10 stop jumps.

**Exercise Competency Criteria**
- Controlled movement
- Knee does not collapse medially
- Heels remain on the ground
- Trunk, pelvis and knees remain stable throughout movement
- Pelvis remains parallel throughout movement
### Landing Re-Training Exercise Set 4:

#### Lateral Jumps
- Stand with feet together and perform a small jump to the right, landing with your feet together. Immediately following landing perform a small jump to the left (1 repetition).
- 10 reps x 2 sets

#### Single Leg Lateral Jumps
- Stand on one leg and perform a small jump to the right. Immediately following landing perform a small jump to the left (1 repetition).
- 10 reps x 2 sets (on each leg)

#### Anticipated Cut
- The athlete stands facing a stationary person about 10m away, the athlete runs toward the stationary person and when about 2m away, performs a side-step or "cut" to the left and continues running for about 3m. The new running direction should be about 45° from the original forward run.
- Each athlete performs 20 side-steps in total, alternating between cutting to the left and the right.

#### Unanticipated Cut
- The athlete stands facing a stationary person about 10m away, the athlete runs toward the stationary person and when about 2m away, the stationary person indicates the direction which is required for the cut. The athlete then performs a side-step or "cut" to the left or right and continues running for about 3m. The new running direction should be about 45° from the original forward run.
- Each athlete performs 20 side-steps in total, randomized between cutting to the left and the right.

### Exercise Competency Criteria
- Knee, trunk, pelvis, ankle remains stable
- Controlled movements
- Full ROM (not more than 90°)
- Eyes up not looking at the ground
- Pelvis remains parallel throughout movement
- Knee not medially collapsing
- Keeping trunk over planted leg
Core and Landing Re-training Exercise Set 1:

Prone Plank
- Rest on elbows with weight distributed on forearms. Lift hips to form a ‘plank’ between the shoulders and feet (or knees if too difficult on feet - progress to feet).
- Exercise Tempo - 2-2-2 (i.e. 2 seconds to raise, 2 second hold, 2 seconds to lower). Hold raised position for 2 seconds.
- 6 reps

Prone plank elbows to hands - hands to elbows
- Lift up into plank position with feet and elbows on the floor. Transfer weight and lift up onto each hand and then lower to each elbow. Alternate the hand that moves first.
- 6 reps

Prone plank crab crawl
- Lift up into plank position with weight on feet and hands. Lift one hand and the same foot and move 3cm to the side. Repeat moving back to the starting position. Repeat to opposite side. Alternate which side you move to first.
- 1 rep = 1 movement to each side - e.g. centre to right to centre to left to centre
- 6 reps

Prone plank arm & leg lift
- Lift up into plank position with weight on feet and hands. Lift one hand and the opposite foot off the floor, keeping arm and leg straight and keeping balance. Repeat with opposite arm and leg.
- 1 rep = lift with each arm and opposite leg
- 6 reps

Exercise Competency Criteria
- Try to be a ‘plank’
- Keep head, shoulders, trunk, hips and knees in a straight line
- Do not lift the hips too high or let them drop
- Emphasise control when moving to a new position
- Breathe normally
Appendices

Core and Landing Re-training Exercise Set 2:

**Side plank - with arm lift**
- Lie on the side with one leg on top of the other, distributing the body weight evenly over the forearm. Raise the hips and the top arm simultaneously to achieve a straight body. (If necessary, start with weight on bent knees rather than the feet, then progress to feet) Lower arm and hips to floor simultaneously, repeat on the other side.
- **Exercise Tempo** - 2-2-2 (i.e. 2 seconds to raise, 2 second hold, 2 seconds to lower)
- Steps each side

**Side plank - Lift and lower hips**
- Lie on the side with one leg on top of the other, distributing the body weight evenly over the forearm. Slowly lift the hips to achieve a straight body. Slowly lower the hips to the ground. Repeat on the other side.
- **Exercise Tempo** - 2-2-2 (2 seconds to lift and 2 seconds to lower)
- Steps x 2 sets on each side, with a 3 second rest between sets.

**Side plank, plank, side plank**
- Start in a front plank position with the weight resting evenly on the forearms; hold for 1 second. Roll to the side position; hold for 1 second. Roll again back to the front; hold for 1 second. Roll to the other side; hold for 1 second.
- One repetition is when each of these four positions has been held for 1 second.
- Steps

**Side plank with arm and leg lift**
- Lie on the side with one leg on top of the other, distributing the body weight evenly over the forearm. Lift the hips to achieve a straight body. Raise the arm at the same time. Raise the top leg above 90° and hold for 3 seconds. Lower the top leg, hips and arm. Repeat on the other side.
- Rest for 3 seconds between repetitions.
- Steps

**Exercise Competency Criteria**
- Try to be a 'plank'!
- Keep head, shoulders, trunk, hips and knees in a straight line.
- Keep shoulders in line with the trunk.
- Do not drop the hips.
- Do not hold for longer than the correct body form can be maintained.
- Do not roll shoulders forward or back.
- Do not bend forward or backwards at the hips.
- Emphasize control - maintain a straight body when moving to a new position.
- Breathe normally.
Core and Landing Re-training Exercise Set 3:

**Vertical Jump**
- Stand with weight equally distributed through both feet. Squat down and perform a maximal jump vertically straight up swinging your arms upwards as you jump. Following the landing phase, pause for two seconds and perform the following vertical jump.
- 15 reps x 2 sets

**Forward Jumps**
- Stand with feet together, jump forwards and land with both feet at the same time. Start with a small jump and slowly increase jumping distance while maintaining control and landing technique. Emphasise ‘sticking’ the landing with balance and control. After a brief pause, jump forwards again.
- 10 reps x 2 sets

**Single leg forwards jumps**
- Stand on the right foot, jump forwards and land on the right foot. Start with a small jump and slowly increase jumping distance while maintaining control and landing technique. Emphasise ‘sticking’ the landing with balance and control. After a brief pause, jump forwards and land on the right foot again.
- 10 reps x 2 sets (on each leg)

**Stop Jump**
- Athlete performs a small run up, landing with both feet at the same time, followed immediately by a vertical jump and landing again with two feet.
- Emphasis on maintaining good landing technique.
- Perform 10 stop jumps.

**Exercise Competency Criteria**
- Controlled movement
- Knee does not collapse medially
- Heels remain on the ground
- Trunk, pelvis and knees remain stable throughout movement
- Pelvis remains parallel throughout movement
Core and Landing Re-training Exercise Set 4:

Lateral Jumps
- Stand with feet together and perform a small jump to the right, landing with your feet together. Immediately following landing perform a small jump to the left (1 repetition).
- 10 reps x 2 sets

Single leg lateral Jumps
- Stand on one leg and perform a small jump to the right. Immediately following landing perform a small jump to the left (1 repetition).
- 10 reps x 2 sets (on each leg)

Anticipated cut
- The athlete stands facing a stationary person about 10m away, the athlete runs toward the stationary person and when about 2m away, performs a side-step or "cut" to the left and continues running for about 3m. The new running direction should be about 45° from the original forward run.
- Each athlete performs 20 side-steps in total, alternating between cutting to the left and the right.

Unanticipated cut
- The athlete stands facing a stationary person about 10m away, the athlete runs toward the stationary person and when about 2m away, the stationary person indicates the direction which is required for the cut. The athlete then performs a side-step or "cut" to the left or right and continues running for about 3m. The new running direction should be about 45° from the original forward run.
- Each athlete performs 20 side-steps in total, randomized between cutting to the left and the right.

Exercise Competency Criteria
- Knees, trunk, pelvis, ankle remain stable
- Controlled movements
- Full ROM (not more than 90°)
- Eyes up not looking at the ground
- Pelvis remains parallel throughout movement
- Knees not mediolaterally collapsing
- Keeping trunk over planted leg
Appendix 4 – Effect of lower limb dominance during stop-jump in pre-elite youth athletes.

METHODS

Statistical Analysis

A factorial analyses of variance (ANOVAs) was employed to determine if there were significant differences (p<0.05) between left and right lower limb variables during the stop-jump and R-COD tasks. Outcome variables included: joint angles, peak joint angles, ranges of motions (ROMs), ground reaction forces (GRFs) and joint moments. The primary test of the effect of side was then conducted into the following factors for the outcome variables. There were three factors for analyses of joint angles (side*events*angles). Events encompassing critical GRF points of the landings (IC, FV1, FV2, FV3, TO), while angles incorporated the 6 joints for R-COD (ankle, knee, hip, L5-S1, T12-L1, thoracic pelvis) and 3 joints for stop-jumps (ankle, knee, hip) in all 3 planes (x, y, and z). There were two factors for analyses of joint moments (side*moments), ROM (side*ROM), peak angles (side*peak angles), GRF timing (side*GRF timing, GRF peaks (side*GRF peaks) and GRF impulse (side*GRF impulse). Since the primary interest of the study was the difference between left and right lower limbs, only main effects and interactions involving a side factor will be reported in the results. All ANOVAs were calculated with using Statistica (v.13, StatSoft Inc., Tulsa, OK, USA), with Tukey Post hoc tests selected to identify which outcome variable produced the significant effect. All data were examined to satisfy the assumptions of normality of distribution and sphericity, with multivariate ANOVA used when sphericity was not satisfied. Assumptions of constant variance and normality were examined through residuals and were both satisfied and accepted. If Tukey Post hoc did not indicate a significant effect following a
Appendices

significant interaction of ANOVAs, univariate and independent t-tests were employed to assess which variable was responsible for the interaction and effect size analyses, respectively. Effects sizes ($\eta^2_p$) were defined as trivial (<0.0099), small (0.0099-0.0588), moderate (0.0588-0.1379), and large (>0.1379) sizes (Richardson 2011).

RESULTS

Stop-Jump Kinematics

Joint angles showed no significant main effect of side ($F_{1,87}=1.87$, $p=0.18$); however, a significant interaction for side*events ($F_{4,348}=2.46$, $p=0.45$), side*angles ($F_{8,696}=13.51$, $p<0.001$) and side*events*angles ($F_{32,2784}=1.73$, $p=0.01$, Figure 1A) was present. Post hoc tests showed when comparing the LEFT to the RIGHT, a greater grand mean across all angles for the TO stage only (LEFT= $-0.7\pm0.2^\circ$; RIGHT= $0.1\pm0.2^\circ$; $P<0.001$) and forefoot abduction across all events (LEFT= $-12.4\pm0.8^\circ$; RIGHT= $-6.7\pm0.6^\circ$; $p<0.001$). It was revealed the LEFT when compared to the RIGHT displayed significantly greater inversion at IC ($p<0.05$), $F_{V1}$ ($p<0.05$) and $F_{V2}$ ($p<0.001$), forefoot abduction across the whole stance phase (IC $p<0.001$; $F_{V1}$: $p<0.001$; $F_{V2}$: $p<0.001$; $F_{V3}$: $p<0.001$) and TO ($p<0.001$), knee internal rotation at $F_{V3}$ ($p<0.001$), with a decrease in knee flexion at TO ($p<0.05$).
Figure 1  Mean ± standard error (SE) of joint angles for left and right lower limbs (A) joint angles (°) (B) joint angles range of motion (°) (C) peak joint angles (°) during the horizontal landing phase of a stop-jump movement.
Joint range of motion displayed a main effect of side ($F_{1,87}=47.88$, $p=0.01$), and a significant side*ROM interaction ($F_{8,696}=3087.43$, $p=0.01$, Figure 1B). *Post hoc* analysis identified an increase in LEFT when compared to the RIGHT in knee adduction/abduction ($p<0.001$), knee internal/external rotation ($p<0.01$), hip flexion/extension ($p<0.001$), hip adduction/abduction ($p<0.001$), hip internal/external rotation ROM ($p<0.01$), with a decrease in ankle dorsiflexion/plantarflexion ($p<0.001$) and knee flexion/extension ($p<0.001$).

A main effect of side was shown in peak joint angles ($F_{1,87}=7.07$, $p=0.01$), with a significant side*peak angle interaction ($F_{17,1479}=12.49$, $p<0.001$, Figure 1C). *Post hoc* analysis determined a significant difference with increased peak angles in LEFT compared to the RIGHT eversion ($p<0.001$), inversion ($p<0.001$) and knee internal rotation ($p<0.05$).

*Stop-Jump Kinetics*

There was no main effect of side was present for joint moments ($F_{1,87}=0.40$, $p=0.53$); however, a side*moment significant interaction was present ($F_{17,1479}=3.48$, $p<0.001$, Figure 2A). *Post hoc* analysis indicated a significant difference in RIGHT compared to the LEFT hip extension moment ($p<0.001$).
Figure 2 Mean ± standard error (SE) of joint kinetics for left and right lower limbs (A) joint moments (BW) (B) peak GRFs (BW) (C) GRF timing (s) during the horizontal landing phase of a stop-jump movement.
A significant main effect of side was seen in peak GRF ($F_{1,87}=48.34$, $p=0.00$), with a side*peak force significant interaction ($F_{4,348}=11.89$, $p<0.01$, Figure 2B). When comparing LEFT versus RIGHT, a significant increase was identified in medial GRFs ($p<0.001$), with a significant decrease found in lateral GRFs ($p<0.001$). Although no main effect of timing was identified in GRF timing ($F_{1,87}=0.003$, $p=0.96$), a side*GRF timing interaction was evident ($F_{7,609}=3.78$, $p<0.001$, Figure 2C). Post hoc analysis identified a significant difference in LEFT compared to RIGHT with an increase in IC to peak anterior force time ($p<0.05$). Although there was a main effect of side was identified in GRF impulse ($F_{1,87}=6.09$, $p=0.02$), there was no side*impulse interaction and no significant differences identified in post hoc analysis.

**R-COD Kinematics**

A main significant effect of side was present in R-COD joint angles ($F_{1,86}=5.08$, $p=0.03$), with a side*angles interaction ($F_{17,1462}=8.77$, $p=0.00$, Figure 3A). Post hoc analysis determined significant differences when comparing the LEFT to the RIGHT with a decrease in forefoot abduction ($p<0.001$) and an increase in T12-L1 lateral flexion ($p<0.001$). A comparison of LEFT and RIGHT joint ROM did not display a main effect of side ($F_{1,64}=0.45$, $p=0.50$) and no other interaction was identified.

A significant main effect of side was displayed in peak joint angles ($F_{1,86}=4.41$, $p=0.04$), with a side*peak angles interaction ($F_{29,2494}=9.75$, $p=0.00$, Figure 3B). Post hoc analysis indicated significant differences in RIGHT compared to LEFT with an increase identified in peak ankle inversion ($p<0.001$), peak
T12-L1 left lateral flexion (p<0.001) and a decrease in T12-L1 right lateral flexion (p<0.001).
Figure 3  Mean ± standard error (SE) of joint angles for left and right lower limbs (A) joint angles (°) (B) peak joint angles (°) during the stance phase of an R-COD.
R-COD Kinetics

No significant main effect of side was displayed in joint moments (F_{1,86}=0.76, p=0.38); however, there was a side*moments interaction was present (F_{29,2494}=7.16, p=0.00), Figure 4A). Post hoc analysis identified a significant increase in LEFT versus RIGHT, L5-S1 left lateral flexion moment (p<0.001), T12-L1 left lateral flexion moment (p<0.01) and a decrease in L5-S1 right lateral flexion moment and T12-L1 right rotation moment (p<0.01).

A significant main effect of side was identified in peak GRFs (F_{1,86}=444.63, p=0.00), including a side*peak GRF interaction (F_{4,344}=225.91, p=0.00, Figure 4B). In a comparison of the LEFT and RIGHT sides, medial GRF was significantly decreased (p<0.001); however, lateral GRF was significantly increased (p<0.001). While there was no significant main effect of side present in GRF timing (F_{1,86}=2.40, p=0.13), there was a side*GRF timing interaction (F_{7,602}=27.01, p=0.00, Figure 4C). Post hoc analysis found significant differences between LEFT and RIGHT with an increase in IC to medial GRF (p<0.001) and a decrease in IC to lateral GRF (p<0.001). For GRF Impulse there was a main effect of side (F_{1,86}=66.53, p=0.00), with a side*impulse interaction (F_{3,258}=28.68, p=0.00,Figure 4D). Post hoc analysis indicated a significant difference between LEFT to RIGHT with increases in posterior force impulse (<0.001) and a decrease in medial force impulse (p<0.001).
Figure 4  Mean ± standard error (SE) of joint kinetics for left and right lower limbs (A) joint moments (BW), (B) peak GRF (BW), (C) GRF timing (s), and (D) impulse (BW) during the stance phase of a R-COD.
Appendices

Appendix 5 – Example Western Region Academy of Sport

Strength and Conditioning Program.

Western Region Academy of Sport 2012/13
Strength and Conditioning Program

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<th>Athlete Name:</th>
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<th>Program Update</th>
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**DYNAMIC WARM UP - Movement preparation**

- Movement drills
  - 2x2min / 2x10@ / 2x20m
- Jump rope 00901
- Hip flexion walk 01198
- Caricca 00986
- Arabesque rotation 01479
- Wall push up rotation 04179
- Side step balance 01068

- BAPS
  - 2x6 / 2x10 / 2x6

**STRENGTH - Technique and control**

- Squat 01212
  - 12 x 12 x 15 x 15 x
  - 12 x 12 x 15 x 15 x
  - 12 x 12 x 15 x 15 x

- Walking lung + rotation 06209
  - 10 x 10 x 12 x 12 x
  - 10 x 10 x 12 x 12 x
  - 10 x 10 x 12 x 12 x

- Push up 04773
  - 10 x 10 x 12 x 12 x
  - 10 x 10 x 12 x 12 x
  - 10 x 10 x 12 x 12 x

- Seated row with theraband 01169
  - 10 x 10 x 12 x 12 x
  - 10 x 10 x 12 x 12 x
  - 10 x 10 x 12 x 12 x

- Bridge 06218
  - 10 x 10 x 12 x 12 x
  - 10 x 10 x 12 x 12 x
  - 10 x 10 x 12 x 12 x

**CORE - Engage core & body control (performed as a circuit)**

- Prone hold 00271
  - 30s x 40s x 50s x 60s x
  - 30s x 40s x 50s x 60s x

- Kneeling arm-leg raise 09096
  - 10 x 10 x 12 x 12 x
  - 10 x 10 x 12 x 12 x

- Side hip lifts 04422
  - 10 x 10 x 12 x 12 x
  - 10 x 10 x 12 x 12 x

**STRETCHING/RELEASE - Stretching strap/PNF/tennis ball**

- Hip flexor-quad stretch 02629
  - 30s x 40s x 50s x 60s x
  - 30s x 40s x 50s x 60s x

- Torso stretch 02634
  - 30s x 30s x 45s x 45s x
  - 30s x 30s x 45s x 45s x

- Self massage tennis ball upper back 04706
  - 30s x 40s x 50s x 60s x
  - 30s x 40s x 50s x 60s x
Appendix 6 – Additional Figures for Chapter 3.

Figure 1  Mean ± standard error (SE) for joint angles (°) pre- and post-intervention during the stop-jump task for four intervention groups (No additional training (N), Core (C), Landing (L) and Core+ Landing (CL)).

Ankle dorsiflexion-plantarflexion (Ankle DF/PF), ankle inversion-eversion (Ankle In/Ev), forefoot adduction-abduction (Forefoot Ad/Ab), knee flexion-extension (Knee Fl/Ex), knee adduction-abduction (Knee Ad/Ab), hip adduction-abduction (Hip Ad/Ab), hip internal-external rotation (Hip IR/ER), L5-S1 flexion-extension (L5-S1 Fl/Ex), L5-S1 left(+)/right(-) lateral flexion (L5-S1 Lat Flex), L5-S1 right(+)/left(-) rotation (L5-S1 Rot), T12-L1 flexion-extension (T12-L1 Fl/Ex), T12-L1 left(+)/right(-) lateral flexion (T12-L1 Lat Flex), L5-S1 rotation right(+)/left(-) (T12-L1 Rot), Trunk_Ab-Pelvis flexion-extension (TrAb_Pelv Fl/Ex), Trunk_Ab-Pelvis right(+)/left(-) lateral flexion (TrAb_Pelv Lat Flex), and Trunk_Ab-Pelvis left(+)/right(-) rotation (TrAb_Pelv Rot).
Figure 1  Mean ± standard error (SE) for (A) peak joint angle and (B) joint range of motion angles (°) pre- and post-intervention during the Stop-jump task for four intervention groups (No additional training (N), Core (C), Landing (L) and Core+ Landing (CL)).
Chapter 3: Intervention programs alters stop-jump technique

Figure 2  Mean ± standard error (SE) for segment angles (°) pre- and post-intervention during the stop-jump task for four intervention groups (No additional training (N), Core (C), Landing (L) and Core+ Landing (CL)).

Foot dorsiflexion-plantarflexion (Foot DF/PF), foot inversion-eversion (Foot In/Ev), foot adduction-abduction (Foot Ad/Ab), shank posterior-anterior inclination (Shank Post/Ant), shank adduction-abduction (Shank Ad/Ab), shank external-internal rotation (Shank Ex/In Rot), thigh posterior-anterior inclination (Thigh Post/Ant), thigh adduction-abduction (Thigh Ad/Ab), thigh external-internal rotation (Thigh Ex/In Rot), pelvis extension-flexion (Pelvis Ex/Fl), pelvis right+/left- lateral tilt (Pelvis R/L Tilt), pelvis right+/left- rotation (Pelvis R/L Rot), lumbar extension-flexion (Thoracic Ex/Fl), lumbar right+/left- lateral flexion (Thoracic R/L Lat Flex), lumbar rotation left+/right- (Lumbar L/R Rot), thoracic extension-flexion (Thoracic Ex/Fl), thoracic right+/left- lateral flexion (Thoracic R/L Lat Fl), thoracic left+/right- rotation (Thoracic L/R Rot), trunk Ab-Pelvis extension-flexion (TrunkAb Ex/Fl), trunk Ab-Pelvis right+/left- lateral flexion (TrunkAb R/L Lat Fl), and Trunk_Ab-Pelvis left+/right- rotation (TrunkAb Rot).
Figure 3  Mean ± standard error (SE) for peak net internal joint moments (normalised to body mass x height) pre- and post-intervention during the stop-jump task for four intervention groups (No additional training (N), Core (C), Landing (L) and Core+ Landing (CL)).
Figure 4  Mean ± standard error (SE) for (A) peak GRF (BW), (B) time to peak GRF (s) and (C) loading rate (BW·s⁻¹) pre- and post-intervention during the stop-jump task for four intervention groups (No additional training (N), Core (C), Landing (L) and Core+ Landing (CL)).
Chapter 3: Intervention programs alters stop-jump technique

Appendix 7 – Additional Figures for Chapter 4.
Chapter 3: Intervention programs alters stop-jump technique

Figure 5  Mean ± standard error (SE) for joint angles (°) pre- and post-intervention during the R-COD task for four intervention groups (No additional training (N), Core (C), Landing (L) and Core+ Landing (CL)).

Ankle dorsiflexion-plantarflexion (Ankle DF/PF), ankle inversion-eversion (Ankle In/Ev), forefoot adduction-abduction (Forefoot Ad/Ab), knee flexion-extension (Knee Fl/Ex), knee adduction-abduction (Knee Ad/Ab), hip adduction-abduction (Hip Ad/Ab), knee (Knee IR/ER), hip internal-external rotation (Hip IR/ER), L5-S1 flexion-extension (L5-S1 Fl/Ex), L5-S1 left(+)/right(-) lateral flexion (L5-S1 Lat Flex), L5-S1 right(+)/left(-) rotation (L5-S1 Rot), T12-L1 flexion-extension (T12-L1 Fl/Ex), T12-L1 left(+)/right(-) lateral flexion (T12-L1 Lat Flex), L5-S1 rotation right(+)/left(-) (T12-L1 Rot), Trunk_Ab-Pelvis flexion-extension (TrAb_Pelv Fl/Ex), Trunk_Ab-Pelvis right(+)/left(-) lateral flexion (TrAb_Pelv Lat Flex), and Trunk_Ab-Pelvis left(+)/right(-) rotation (TrAb_Pelv Rot).
Figure 6  Mean ± standard error (SE) for (A) peak joint angle and (B) joint range of motion angles (°) pre- and post-intervention during the R-COD task for four intervention groups (No additional training (N), Core (C), Landing (L) and Core+ Landing (CL).
Figure 7  Mean ± standard error (SE) for segment angles (°) pre- and post-intervention during the stop-jump task for four intervention groups (No additional training (N), Core (C), Landing (L) and Core+ Landing (CL)).

Foot dorsiflexion-plantarflexion (Foot DF/PF), foot inversion-eversion (Foot In/Ev), foot adduction-abduction (Foot Ad/Ab), shank posterior-anterior inclination (Shank Post/Ant), shank adduction-abduction (Shank Ad/Ab), shank external-internal rotation (Shank Ex/In Rot) thigh posterior-anterior inclination (Thigh Post/Ant), thigh adduction-abduction (Thigh Ad/Ab), thigh external-internal rotation (Thigh ER/IR), pelvic extension-flexion (Pelvis Ex/Fl), pelvic right(+)/left(-) lateral tilt (Pelvis R/L TilT), pelvic left(+)/right(-) rotation (Pelvis L/R Rot), lumbar extension-flexion (Thoracic Ex/Fl), lumbar right(+)/left(-) lateral flexion (Thoracic R/L Lat Flex), lumbar rotation left(+)/right(-) (Lumbar L/R Rot), thoracic Ex/Fl (Thoracic Ex/Fl), thoracic right(+)/left(-) lateral flexion (Thoracic R/L Lat Fl), thoracic left(+)/right(-) rotation (Thoracic L/R Rot), Trunk_Ab-Pelvis extension-flexion (TrunkAb Ex/Fl), Trunk_Ab-Pelvis right(+)/left(-) lateral flexion (TrunkAb R/L Lat Fl), and Trunk_Ab-Pelvis left(+)/right(-) rotation (TrunkAb Rot).
Chapter 4: Intervention programs alters R-COD technique

Figure 8 Mean ± standard error (SE) for peak net internal joint moments (normalised to body mass x height) pre- and post-intervention during the R-COD task for four intervention groups (No additional training (N), Core (C), Landing (L) and Core+ Landing (CL)).
Figure 9  Mean ± standard error (SE) for (A) peak GRF (BW), (B) time to peak GRF (s) and (C) loading rate (BW·s⁻¹) pre- and post-intervention during the R-COD task for four intervention groups (No additional training (N), Core (C), Landing (L) and Core+Landing (CL)).
Appendix 8 – Additional Figures for Chapter 5.

Figure 10  Mean ± standard error (SE) for joint angles (°) during the R-COD task for the three trunk-pelvic range of motion groups.

Ankle dorsiflexion-plantarflexion (Ankle DF/PF), ankle inversion-eversion (Ankle In/Ev), forefoot adduction-abduction (Forefoot Ad/Ab), knee flexion-extension (Knee Fl/Ex), knee adduction-adduction (Knee Ad/Ab), hip adduction-abduction (Hip Ad/Ab), knee (Knee IR/ER), hip internal-external rotation (Hip IR/ER), L5-S1 flexion-extension (L5-S1 Fl/Ex), L5-S1 left(+)/right(-) lateral flexion (L5-S1 Lat Flex), L5-S1 right(+) /left(-) rotation (L5-S1 Rot), T12-L1 flexion-extension (T12-L1 Fl/Ex), T12-L1 left(+) /right(-) lateral flexion (T12-L1 Lat Flex), T12-L1 rotation left(+) /right(-) (T12-L1 Rot), Trunk,Ab-Pelvis flexion-extension (TrAb_Pelv Fl/Ex), Trunk,Ab-Pelvis right(+) /left(-) lateral flexion (TrAb_Pelv Lat Flex), and Trunk,Ab-Pelvis left(+) /right(-) rotation (TrAb_Pelv Rot).
Figure 2  Mean ± standard error (SE) for (A) peak joint angles and (B) joint range of motion angles (°) during the R-COD task for the three trunk-pelvic range of motion groups.
Figure 11  Mean ± standard error (SE) for segment angles (°) during the R-COD task for the three trunk-ab-pelvic range of motion groups.

Foot dorsiflexion-plantarflexion (Foot DF/PF), foot inversion-eversion (Foot In/Ev), foot adduction-abduction (Foot Ad/Ab), shank posterior-anterior inclination (Shank Post/Ant), shank adduction-abduction (Shank Ad/Ab), shank external-internal rotation (Shank Ex/In Rot) thigh posterior-anterior inclination (Thigh Post/Ant), thigh adduction-abduction (Thigh Ad/Ab), thigh external-internal rotation (Thigh Ex/In Rot), pelvis extension-flexion (Pelvis Ex/Fl), pelvis right+/left- lateral tilt (Pelvis R/L Tilt), pelvis left+/right- rotation (Pelvis L/R Rot), lumbar extension-flexion (Thoracic Ex/Fl), lumbar right+/left- lateral flexion (Thoracic R/L Lat Flex), lumbar rotation left+/right- (Thoracic L/R Rot), thoracic Ex/Fl (Thoracic Ex/Fl), thoracic right+/left- lateral flexion (Thoracic R/L Lat Fl), thoracic left+/right- rotation (Thoracic L/R Rot), Trunk_Ab-Pelvis extension-flexion (TrunkAb Ex/Fl), Trunk_Ab-Pelvis right+/left- lateral flexion (TrunkAb R/L Lat Fl), and Trunk_Ab-Pelvis left+/right- rotation (TrunkAb Rot).
Figure 12  Mean ± standard error (SE) for peak net internal joint moments (normalised to body mass x height) during the R-COD task for the three trunkab-pelvic range of motion groups.
Figure 13 Mean ± standard error (SE) for (A) peak GRF (BW), (B) time to peak GRF (s) and (C) loading rate (BW·s\(^{-1}\)) during the R-COD task for the three trunk-pelvic range of motion groups.