



SEX-SPECIFIC NEUROMUSCULAR AND KINEMATIC ANALYSIS OF UNANTICIPATED SINGLE-LEG LANDINGS IN YOUNG ATHLETES

Nicholas Romanchuk, BPHE (Honours)

Thesis submitted to the University of Ottawa
in partial fulfillment of the requirements for the
MSc Degree in Human Kinetics

School of Human Kinetics
Faculty of Health Sciences
University of Ottawa

Supervisor:
Daniel L. Benoit, PhD

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ACKNOWLEDGEMENTS

I would like to thank all of the people who helped contribute to the completion of my Master's Thesis. First, I would like to thank my family for their continuous and unconditional support over the past two years. I would also like to thank my girlfriend, and best friend, Nicole Morse for her love and friendship through this experience. Her work ethic and dedication has been instrumental in setting the example for what it means to be a researcher.

I would also like to thank my colleagues at the Clinical Biomechanics Research Unit for their support and guidance: Olivia Bayliss-Zajdman, Olivier Miguel, Luis Roberto Licón Cano, Laryssa Kemp, Céline Girard, and Lisa Ek Orloff. Additionally, I would like to acknowledge Michael Del Bel and Kenneth (Brent) Smale, for their friendship, mentorship, and contributions to my personal development as a person and researcher. Finally, if it were not for Dr. Daniel Benoit, my experience would not have been as fulfilling as it was. Through his guidance and encouragement, I was able to explore avenues that spoke to my interests as a researcher. I gained valuable skills in programming and how to run data collections, which wouldn't have been possible without his patience and leadership. Under his tutelage, I have grown into a better academic and person.

I would also like to take this opportunity to acknowledge the various funding sources that facilitated my Master's thesis. I am very thankful for the University of Ottawa and for their financial support through Admission Scholarships, Excellence Scholarships, and Conference Travel Grants. In addition, I am greatly appreciative of the following contributors: the Ontario Graduate Scholarship, the AMTI Force & Motion Foundation and University of Ottawa Graduate Student Association.

CONTRIBUTIONS

Manuscript 1: Sex-specific landing strategies during unanticipated drop-jumps in young athletes (*preliminary results presented at the 8th World Congress of Biomechanics and the 2018 Canadian Society of Biomechanics Conference*)

The first manuscript of this thesis focused on describing kinematic and neuromuscular sex-differences during unanticipated single-leg landings in a youth population. The theoretical conception of this experiment was a concerted effort between N. Romanchuk and M. Del Bel. Participant recruit for this study was a combined effort of N. Romanchuk, M. Del Bel, L. Ek Orloff, C. Girard, and L. Kemp. With regards to the data collections, N. Romanchuk led 31 of the 32 collections with C. Girard leading the remaining collection. Vicon labeling of the unanticipated landings for all 32 participants was performed by N. Romanchuk. With respect to calculating joint angles and moments, N. Romanchuk was responsible for adapting a new hybrid cluster marker set to the previously used Vicon Nexus Bodybuilder model. In addition, N. Romanchuk was responsible for writing all processing and analysis scripts for the electromyography, kinematic and kinetic data. Finally, N. Romanchuk was responsible for all statistical analyses performed regarding this manuscript. The manuscript was written by N. Romanchuk and edited by L. Kemp, M. Del Bel, L. Roberto Licón Cano, and D. Benoit.

Manuscript 2: Kinematic and neuromuscular predictors of successful drop-jump landings (*preliminary results present at the 2018 Ontario Biomechanics Conference*)

The second manuscript of this thesis used the previously collected data to develop a novel model for predicting successful landings. The theoretical conceptualization for comparing between failed and successful landings and implementing a logistic regression was led by N.

Romanchuk. Vicon labeling of the failed unanticipated landings for all 32 participants was performed by N. Romanchuk. N. Romanchuk was also responsible for writing all necessary code to extract the neuromuscular, kinematic and kinetic predictors. N. Romanchuk performed all statistical analysis, including building the logistic regression. The manuscript was written by N. Romanchuk and edited by L. Kemp, L. Roberto Licón Cano, and D. Benoit.

LIST OF ACRONYMS

ACL	Anterior Cruciate Ligament
BF	Biceps Femoris
BMI	Body Mass Index
CI	Co-Activation Index
CNS	Central Nervous System
CoM	Centre-of-Mass
DAQ	National Instruments Data Acquisition Box
EMD	Electromechanical Delay
EMG	Electromyography
FDR	False Discovery Rate
GMed	Gluteus Medius
GRF	Ground Reaction Force
LG	Lateral Gastrocnemius
LOOCV	Leave-One-Out Cross-Validation
MOT	Muscle Onset Time
MSE	Mean Square Error
MG	Medial Gastrocnemius
MVIC	Maximum Voluntary Isometric Contraction
HSS Pedi-FABS	Hospital for Special Surgery Pediatric Functional Activity Brief Scale
KOOS-Child	Knee injury and Osteoarthritis Outcome Score Children
RF	Rectus Femoris
ROC	Receiver Operating Characteristic
SEC	Series Elastic Component
SnPM	Statistical Non-Parametric Mapping
SPM	Statistical Parametric Mapping
ST	Semitendinosus
VL	Vastus Lateralis
VM	Vastus Medialis
Q-H	Quadriceps and Hamstring Co-Activation Index
Q-G	Quadriceps and Gastrocnemius Co-Activation Index

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GENERAL ABSTRACT

Despite the higher incidence of anterior cruciate ligament injuries in pediatric female populations, limited research has investigated sex-differences in youth biomechanics. Furthermore, research involving jump mechanics typically requires participant to follow a set protocol, such as sticking the landing. To reduce variability and improve reliability, trials where participants fail to meet the required protocol are discarded; however, significant clinical findings may be elucidated from these trials. The purpose of this thesis was to provide a complete biomechanical analysis of unanticipated single-leg drop-jump landings in youth athletes.

Thirty-two healthy youth athletes completed unanticipated single-leg drop-jump landings on their dominant limb. Trials where participants shifted foot position or touched the ground with the contralateral leg were categorized as failed. Drop-jump landings were time-normalized using landmarks within the drop-jump task. Statistical parametric mapping (SPM) determined time-varying sex-differences in muscle onset time, co-activation, kinematics and kinetics. Wilcoxon signed-rank tests and paired sample *t*-tests compared lower-limb kinematics, centre-of-mass excursion and muscle activation amplitudes during the successful and failed landings. A logistic regression model was also fit to predict the likelihood of a successful landing.

SPM identified significantly greater trunk flexion angle in males during the deceleration, flight, and landing phase of the drop-jump. Greater quadriceps-gastrocnemius co-activation was identified during the flight phase in female participants and independent sample *t*-test identified longer muscle onset time in the vastus lateralis of male participants. When comparing failed and successful landings greater hip abduction and less external rotation angles were observed during the successful trials. In addition, greater preparatory muscle activation was observed in the rectus

femoris and semitendinosus during the flight phase of the failed landings. A logistic regression model, which included eight kinematic and neuromuscular variables, offered a training classification accuracy of 70% and a leave-one-out cross-validation accuracy of 65%.

In conclusion, females land in a more erect posture and may be less effective at dissipating landing forces. In addition, greater co-activation and shorter pre-activations of the lower limb musculature may indicate a less effective muscle activation strategy in females. Furthermore, hip kinematics and the surrounding musculature play an important role in controlling successful and failed unanticipated landings. The variables included in the logistic regression model indicate which key factors are linked to landing a jump successfully. Training modalities aimed at improving landing mechanics should therefore focus on modifying these variables.

CHAPTER 1: INTRODUCTION

Despite the higher incidence of anterior cruciate ligament (ACL) injuries in pediatric female populations (Herzog et al., 2017), limited research has investigated sex-differences in neuromuscular control and biomechanics in youth (<18 yrs. old). In addition, most neuromechanical predictors of ACL injury risk are generated from laboratory-based assessments of pre-planned movements. However, given the inherently random nature of sport activities, inferring injury risk from such assessments has severe limitations. Integrating an unanticipated component within the *in-vivo* testing environment could provide insight into the causal factors for ACL injuries. The limited studies investigating unanticipated movements in pediatric participants either didn't report kinematics (Landry, McKean, Hubley-Kozey, Stanish, & Deluzio, 2009), muscle onset time (MOT) (Ford et al., 2005; Kim et al., 2014; Sell et al., 2005) or muscle co-activation (Ford et al., 2005; Kim et al., 2014). Thus, to our knowledge no study has performed a complete neuromuscular and kinematic analysis of an unanticipated movement in a youth population.

This thesis combined a sport relevant factor (visual cue) with a commonly used injury screening tool (drop-jump landings) (Hewett et al., 2005; Padua et al., 2009), to produce a novel assessment of the neuromechanical factors associated with ACL injury. Analyses of neuromuscular control and lower-limb mechanics established sex-differences in drop-jump landing strategies. In addition, by exploring the kinematic and neuromuscular differences between 'failed' and 'successful' landings, this thesis developed a novel assessment of the biomechanical predictors for a successful jump landing. The results of this thesis could be used to inform sex-specific ACL prevention strategies.

CHAPTER 2: LITERATURE REVIEW

2.1 Injury Incidence

The ACL is the most frequently damaged knee ligament (Majewski, Susanne, & Klaus, 2006), with an estimated incidence of 0.17-0.23 per 1000 athlete exposures (Agel, Rockwood, & Klossner, 2016). However, recent data suggests rising injury rates in both professional and amateur sport levels (Erickson et al., 2013; Mall et al., 2014; Werner, Yang, Looney, & Gwathmey, 2016). The trauma and extensive rehabilitation of this injury can prevent participation in sports for extended periods, accounting for the most time missed of any sports injury (Brooks, Fuller, Kemp, & Reddin, 2005). According to a recent systematic review, on average only 65% of athletes will return to their pre-injury level of sport and only 55% will return to competitive sports following an ACL reconstruction (Ardern, Taylor, Feller, & Webster, 2014). Furthermore, ACL injuries have been linked to the development of knee osteoarthritis (Hame & Alexander, 2013; Lohmander, Englund, Dahl, & Roos, 2007; Myklebust, Holm, Mæhlum, Engebretsen, & Bahr, 2003; Oiestad, Holm, Engebretsen, & Risberg, 2011) and the dysfunction of adjacent joints and limbs (Oberländer, Brüggemann, Höher, & Karamanidis, 2014; Simon et al., 2015; Whittaker, Woodhouse, Nettel-Aguirre, & Emery, 2015).

ACL injury rates are not consistent between sexes; females tear their ACLs two to four times more often when accounting for sport and exposure time (Agel & Klossner, 2014; Joseph et al., 2013; Swenson et al., 2013). In addition, when looking at a youth population, ACL injury rates have significantly risen across both sexes over the last decade (Beck, Lawrence, Nordin, DeFor, & Tompkins, 2015; Gornitzky et al., 2016). Females aged between 13-17 yrs. now possess the highest injury incidence of any sex-age strata (Herzog et al., 2017). To understand the discrepancy in ACL injury rates, sex-differences in neuromuscular factors have been

extensively investigated, with female movement patterns typically interpreted as ‘riskier’ (McLean, 2008). Females commonly land in a more erect posture (Hewett, Torg, & Boden, 2009), utilize more quadriceps activation (Griffin et al., 2006; Krishnan & Williams, 2009; Landry et al., 2009; Sigward & Powers, 2006), have delayed MOT (McLean, Borotikar, & Lucey, 2010; Myer, Ford, & Hewett, 2005) and greater co-activation of the quadriceps-hamstrings (Sell et al., 2005) than males. Although biomechanical research continues to shape neuromuscular training strategies (Mandelbaum et al., 2005; Myer, Ford, & Hewett, 2004), ACL injuries and the associated sex disparity have not diminished (Werner et al., 2016). Thus, further investigation into ACL injuries, in particular sex- and age-related factors, is warranted.

2.2 Youth Population

With the rise of ACL injury rates in youth athletes (Beck et al., 2015; Gornitzky et al., 2016), it is crucial that research is conducted to understand injury mechanisms in this population. Although different neuromuscular control strategies have been found in females (Flaxman, Speirs, & Benoit, 2012; Krishnan & Williams, 2009; Landry et al., 2009; Sigward & Powers, 2006), this research has typically focused on adult populations. Limited research has investigated sex-differences in neuromuscular activation and biomechanically related variables using populations under 18 yrs. of age.

Research on this population is especially relevant given that puberty can lead to biomechanical and neuromuscular changes linked to ACL injury risk. During puberty, rapid growth occurs in bone structures, causing significant increases in height and weight (LaBella et al., 2014), and an associated increase in external knee joint moments (Hewett, Myer, & Ford, 2004; Jensen & Nassas, 1988). Females also experience greater pelvic growth during puberty (Coleman, 1969), leading to altered alignment of the lower extremities compared to males. The

quadriceps angle, defined as the angle between the force vector of the quadriceps muscle group and the patellar tendon (Brattström, 1964), is significantly larger in females (Tillman, Bauer, Cauraugh, & Trimble, 2005). This has been linked to an increase in hip width and is associated with increased strain on the knee joint (Gray et al., 1985; Haycock & Gillette, 1976; Zelisko, Noble, & Porter, 1982). Furthermore, several studies have shown that following pubertal growth, young females demonstrate greater knee valgus motion and reduced knee flexion during landings when compared to young males (Lephart, Ferris, Riemann, Myers, & Fu, 2002; Pappas, Hagins, Sheikhzadeh, Nordin, & Rose, 2007; Pollard, Sigward, & Powers, 2010). Since pubescent males experience greater increases in muscular power and strength mediated by testosterone, it has been suggested that females may possess altered neuromuscular activation patterns in response to rapid skeletal growth (LaBella et al., 2014). Given the anatomical changes that occur in females during puberty, our understandings of the neuromechanical contributions to injury risk in adults may not be applicable in youth. This is particularly relevant considering that no sex-specific ACL injury prevention programs exist for youth. Identifying sex-differences in muscle activations strategies in a youth population could help develop neuromuscular targets for prevention programs that are both age- and sex-specific.

2.3 Unanticipated Movements

When assessing neuromechanical contributions to ACL injury risk, it is imperative that research replicates factors that are inherent and relevant to sport participation. Although evaluating high risk postures during pre-planned laboratory-based movements holds value, sports in which ACL injuries occur are largely governed by an unplanned series of dynamic events. Video analyses of ACL injuries reveal that the majority of ACL ruptures occur during non-contact movements (72-95%), such as the landing phase of a jump or in preparation for a rapid

change of direction (Boden et al., 2000; Koga et al., 2010; Olsen, Myklebust, Engebretsen, & Bahr, 2004). These movements typically follow a reaction to an external stimulus (i.e. avoiding an opposing player) and are therefore unanticipated in nature.

To accurately replicate dynamic knee loading in a sport environment, researchers have incorporated unanticipated components into their testing protocols. This has typically been performed by randomly providing a directional cue in the form of a light (Beaulieu, Lamontagne, & Xu, 2009; Iguchi, Tateuchi, Taniguchi, & Ichihashi, 2014; Kipp, Brown, McLean, & Palmieri-Smith, 2013; McLean et al., 2010; Mornieux, Gehring, Fürst, & Gollhofer, 2014; Park, Lee, Ryue, Sohn, & Lee, 2011) or an arrow (Fong et al., 2014; Kim et al., 2014; Malloy, Morgan, Meinerz, Geiser, & Kipp, 2016). A threshold may exist for stimulus onset time, above which the central control mechanisms are not sufficiently compromised to elicit an unanticipated response (Meyer, Abrams, Kornblum, Wright, & Smith, 1988; Mornieux et al., 2014). Although the stimulus threshold is influenced by task complexity and participant skill level, it appears that for athletes performing a jumping maneuver the threshold is located between 600-850ms (Brown, Palmieri-Smith, & McLean, 2009; Mornieux et al., 2014). The onset of the directional cue has varied across studies, ranging from 300ms to 650ms prior to performing the desired change of direction (Cowley, Ford, Myer, Kernozek, & Hewett, 2006; McLean et al., 2010). By incorporating this sport-relevant factor into the *in-vivo* testing environment, further insight into the causal factors of noncontact ACL injury can be elucidated (McLean, 2008).

2.4 Drop-Jump Landings

Effective injury screening tools and prevention methods should accurately reflect the demands of the sport environment. Although largely sport dependant, landing from a jump is one of the primary movements associated with ACL injury (Gray et al., 1985; Piasecki, Spindler,

Warren, Andrish, & Parker, 2003). Drop-jump landings have subsequently been validated as a reliable movement screening tool (Padua et al., 2009) and can retrospectively predict ACL injury (Hewett et al., 2005). During a jump landing, the body's centre-of-mass (CoM) must decelerate and stabilize as it travels in a downward direction (Wikstrom, Tillman, Schenker, & Borsa, 2007). Increased trunk flexion could be an effective strategy to help decelerate the CoM, since greater trunk flexion angles are associated with reduced impact forces during landing (Blackburn & Padua, 2009) and lower valgus loading through the knee (Hewett, Torg, & Boden, 2009). However, as the trunk is moved into a flexed position, the CoM moves farther from the base of support, increasing the reliance on the hip extensors to maintain an upright position. Thus, if the lower extremity muscles are unable to adequately contribute to the deceleration of the CoM during landing, a compensatory strategy must be employed where the CoM is maintained over the base of support. This is consistent with previous research demonstrating a more erect landing posture in females (Schmitz, Kulas, Perrin, Riemann, & Shultz, 2007) and a reduce reliance on the hip extensors for force absorption (Decker, Torry, Wyland, Sterett, & Richard Steadman, 2003; Pollard et al., 2010). However, this research has typically used preplanned landings, which has limited applications to real sport scenarios.

Although some authors have successfully incorporated unanticipated components into their testing protocols, no research to date has combined an unanticipated component with a movement screening tool. Furthermore, given that between limb differences in isokinetic strength have been identified as a predictor for altered landing mechanics at the knee joint (Baumhauer, Alosa, Renström, Trevino, & Beynnon, 1995; Hewett et al., 2005; Hewett, Stroupe, Nance, & Noyes, 1996; Hewett, Myer, & Ford, 2004), leg asymmetry could be an important factor when evaluating injury risk. Training programs and movement screen tools should focus

on identifying between limb neuromuscular and biomechanical imbalances during unanticipated movements (Heitkamp, Horstmann, Mayer, Weller, & Dickhuth, 2001; Hewett et al., 2005; Knapik, Bauman, Jones, Harris, & Vaughan, 1991; Paterno, Myer, Ford, & Hewett, 2004). Thus, the unanticipated single-leg drop-jump landing task (*CHAPTER 4.3.4*) was designed with the goal of improving previously established injury screening tools (Hewett et al., 2005; Padua et al., 2009) with a relevant sport component (visual cue). Implementing an unanticipated component into a controlled environment may be a viable option to safely identify athletes most at risk for sustaining an ACL injury, while simultaneously improving their neurocognitive processing and motor control strategies.

It is also important to note that previous research investigating jump landings has typically isolated ‘successful’ landings, as failed trials (falling, losing balance etc.) are generally discarded following data collection. Although removing failed trials is advantageous for reducing variation and improving reliability, significant clinical findings may be elucidated by examining the failed trials. To date, only one study has compared the differences between successful and failed landings (Wikstrom, Tillman, Schenker, & Borsa, 2008). They identified earlier muscle activation times and greater preparatory electromyography (EMG) amplitude during the successful jump landings (Wikstrom et al., 2007). However, since kinematics were not recorded during this study, it is not clear how changes in joint mechanics can influence balance during landing. Balance typically refers to minimizing the angular displacement of the CoM from the base of support (Jacobson & Shepard, 2014). By maintaining the body’s CoM over the base of support, the destabilizing force of gravity is reduced (Jacobson & Shepard, 2014). Postural adjustments, such as alterations in trunk position, can shift the CoM and reduce the potential for hazardous knee joint loading (Donnelly et al., 2012; Chaudhari & Andriacchi, 2006; Chaudhari

et al., 2005; Dempsey et al., 2009; McLean et al., 2005). Reduced trunk flexion during landing has also been observed during ACL injury (Hewett, Torg, & Boden, 2009), and is associated with lower attenuation of GRFs (Blackburn & Padua, 2009). Furthermore, alterations in whole-body kinematics during dynamic movements, especially at initial contact, can have a large influence on knee loading and stability (Donnelly, Lloyd, Elliott, & Reinbolt, 2012; Chaudhari & Andriacchi, 2006; Chaudhari, Hearn, & Andriacchi, 2005; Dempsey, Lloyd, Elliott, Steele, & Munro, 2009; McLean et al., 2005). Thus, it appears that whole-body kinematics could play an important role when examining the differences between successful and failed jump landings.

2.5 ACL Injury Mechanisms

To improve ACL prevention strategies in a youth population, variables which are both modifiable in nature (i.e. muscle activation, joint mechanics) and associated with ACL injury should be investigated. Video analyses of ACL injury events reveal that rapid decelerations performed with reduced knee flexion as well as greater knee abduction and internal rotation (valgus collapse) are linked to ACL injury (Hewett, Torg, & Boden, 2009; Koga et al., 2010; Krosshaug et al., 2007; Wang, Malik, Bartel, Wright, & Padgett, 2016). These altered rotations can increase loading at the knee joint and prospectively predict ACL injuries (Boden, Dean, Feagin, & Garrett, 2000; Hewett et al., 2005; Hewett et al., 2009). Specifically, individual abduction and internal rotation knee loads have elevated ACL strain in cadaver models (Markolf et al., 1995; Shin, Chaudhari, & Andriacchi, 2009) and when combined, associations between multi-plane joint loading greatly increase ACL injury risk in both males and females (Shin, Chaudhari, & Andriacchi, 2011). Therefore, the biomechanical risk factors for ACL injury are likely multi-planar in nature, with increased valgus collapse, as well as anterior translation and reduced knee flexion believed to increase ACL injury risk (Markolf et al., 1995; McLean et al.,

2005; Shin et al., 2011). *In-vitro* testing of ACL mechanical properties have estimated that ruptures occur at approximately 1,200-2,200N (Chandrashekar, Mansouri, Slauterbeck, & Hashemi, 2006; Noyes & Grood, 1976; Woo, Hollis, Adams, Lyon, & Takai, 1991). However, due to contributions of passive restraints and the surrounding musculature, the *in-vivo* critical loads are far less understood. Regardless, excessive deviations in knee joint angle, especially during a high impact movement, are associated with an increased risk for ACL injury (Hewett et al., 2005).

Previous research has demonstrated that increased co-activation of the knee flexor and extensor muscles can aid in regulating joint stability by increasing stiffness and reducing the associated deviations in knee alignment (Baratta et al., 1988; Louie & Mote, 1987). Individual activation of the gluteus medius and hamstring muscle groups have also shown to decrease valgus collapse and anterior translation of the tibia (More et al., 1993; Pope, Johnson, Brown, & Tighe, 1979). Given the importance of the surrounding knee musculature for maintaining joint alignment (Wagner, 1999), investigating how differences in neuromuscular activation affect knee alignment is crucial for understanding the underlying mechanisms of ACL injury.

2.6 Sex-Specific Biomechanical Factors

When evaluating sex-differences in neuromuscular control, the relative timing of muscle activation should be considered, given the electromechanical delay (EMD) between the onset of muscle activity and the development of muscle tension (Cavanagh & Komi, 1979). The duration of the EMD is influenced by the i) conduction of the action potential along the T-tubule system; ii) release of calcium by the sarcoplasmic reticulum; iii) cross-bridge formation between actin and myosin filaments; iv) stretching of the series elastic component (SEC) (Cavanagh & Komi, 1979). However, given the relatively short duration of events i-iii, stretching of the SEC is

suggested to have the largest influence on EMD (Cavanagh & Komi, 1979). During contraction, the muscle must overcome the passive properties within the contractile element before force can be exerted on the skeletal structures. To properly stabilize the knee joint, muscle activation must occur with sufficient time for adequate force contribution during the desired movement. The longer rate of force development observed in females suggests that females may not balance the external moments quickly enough during dynamic movements to maintain knee joint alignment (Bell & Jacobs, 1986; Häkkinen & Häkkinen, 1991; Huston & Wojtys, 1996; Komi & Karlsson, 1978; Winter & Brookes, 1991).

In addition, co-activation of agonist and antagonist muscles has been identified as a common strategy to increase joint stability during dynamic movements (Besier, Lloyd, & Ackland, 2003; Rudolph, Axe, Buchanan, Scholz, & Snyder-Mackler, 2001). Increased co-activation of the quadriceps and hamstring muscle groups affects knee joint stability by increasing joint compressive forces (Tsai, McLean, Colletti, & Powers, 2012). Females consistently show increased quadriceps-hamstring co-activation during movements requiring a high level of stability, such as change of direction tasks or following an ACL reconstruction (Besier et al., 2003; Hubley-Kozey, Deluzio, Landry, McNutt, & Stanish, 2006; Llewellyn, Yang, & Prochazka, 1990; Sell et al., 2005; Tsai et al., 2012). During unanticipated movements, the combined loads applied to the knee lead to a generalized co-activation strategy of the quadriceps-hamstring muscles (Besier et al., 2003; Sell et al., 2005). These findings indicate that female athletes may have adopted compensatory muscle activation patterns in an attempt to maintain joint alignment (Besier et al., 2003; Hubley-Kozey et al., 2006; Llewellyn et al., 1990; Sell et al., 2005; Del Bel., 2017). It is likely that increased co-activation simplifies the role of the

central nervous system (CNS) to stabilize the knee joint, as a generalized co-activation strategy is employed regardless of the predicted knee loading (Besier et al., 2003).

Females also demonstrate greater quadriceps dominance, as opposed to a balanced activation with hamstrings, during dynamic movements, increasing the potential for anterior shear forces at the knee joint and ACL loading (Huston & Wojtys, 1996; Myer, Ford, & Hewett, 2005; Sell et al., 2007). Considering that *in-vitro* studies have demonstrated greater quadriceps activation at small knee flexion angles (Renström, Arms, Stanwyck, Johnson, & Pope, 1986) as well as increased ACL strain during the combined knee valgus and anterior shear loading (Markolf et al., 1995), these biomechanical differences may partially explain the increased rate of ACL injury in adult females. However, it is also plausible that the altered neuromuscular control patterns observed in females reflect a compensatory mechanism to accommodate for variations in mechanical joint properties (McLean, 2008). Due to differences in the articular geometry (LaPrade & Burnett, 1994; Tillman et al., 2005) and laxity of the knee joint (Arendt, Bershadsky, & Agel, 2002; Wojtys, Huston, Lindenfeld, Hewett, & Greenfield, 1998), as well as decreased musculature strength (McKay et al., 2017), it is possible that the altered activation strategies observed in females present a more effective way to stabilize the knee based on their individual joint vulnerabilities (Flaxman, Smith, & Benoit, 2014; McLean, 2008). Thus, investigating sex-differences in MOT and co-activation strategies during dynamic movements is crucial to understanding the relevant muscle activation strategies for maintaining knee joint alignment.

2.7 Task-Specific Biomechanical Factors

During unanticipated drop-jump landings there is limited time for the CNS to identify the relevant stimulus and perform the required motor plan (McLean et al., 2010; McLean &

Samorezov, 2009). The subsequent compromise in the motor response increases the demand for joint stabilization and can lead to an increased likelihood for failing the landing (Wikstrom, Tillman, Schenker, & Borsa, 2007). Unanticipated movements consistently result in greater ground reaction forces (GRFs) (Cowley et al., 2006; Kim et al., 2014; Park et al., 2011; Sell et al., 2005), knee abduction angles (Borotikar et al., 2008; Brown et al., 2009; Cowley et al., 2006; Fong et al., 2014; Ford et al., 2005; Kim et al., 2014; Kipp et al., 2013; Malloy et al., 2016; Sell et al., 2005), external knee abduction moments (Brown et al., 2009; Cowley et al., 2006; Kim et al., 2014; Kipp et al., 2013; Malloy et al., 2016), as well as decreased hip abduction angles (Houck et al., 2006; McLean & Samorezov, 2009; Sell et al., 2005). This is concerning since these mechanics may increase ACL strain (Fleming et al., 2001; Shin, Chaudhari, & Andriacchi, 2009; Shin, Chaudhari, & Andriacchi, 2011), and can retrospectively predict ACL injuries (Hewett et al., 2005). In addition, unanticipated manoeuvres produced greater quadriceps activity (Beaulieu et al., 2009; Kim et al., 2014), greater lateral gastrocnemius activity (Beaulieu et al., 2009; Kim et al., 2014) and a more generalized co-activation strategies of the quadriceps/hamstrings muscles (Sell et al., 2005). However, research evaluating MOT during unanticipated movements has been inconsistent, with both longer delays (McLean et al., 2010) and faster pre-activations observed in the medial hamstrings of female athletes (Beaulieu et al., 2009). One reason for this discrepancy could be differences in how the tasks were performed, with MOTs measured prior to a change of direction from a resting position (McLean et al., 2010) and an approach run (Beaulieu et al., 2009). It is likely that an increased demand for knee stabilization when the movement was performed from an approach run could have resulted in the quicker pre-activations observed in females (Beaulieu et al., 2009). It is also important to note that although both studies used a double threshold detector to identify activation onset, Mclean et

al. (McLean et al., 2010) used a 50ms window for the second threshold where Beaulieu et al. (Beaulieu et al., 2009) used a window containing only one sample. The stricter criteria used by Mclean et al. could have accounted for the longer delays they observed (McLean et al., 2010).

Studies evaluating unanticipated side-cuts using populations under 18 yrs. of age found that female athletes performed the tasks with greater knee abduction angles (Ford, Myer, Toms, & Hewett, 2005), as well as altered hamstring activation timing (Landry et al., 2009), increased rectus femoris and gastrocnemii activation compared to their male counterparts (Kim et al., 2014; Landry et al., 2009). In addition, young female athletes performed unanticipated lateral jumps with greater knee flexion and abduction angles, and greater semitendinosus activation (Sell et al., 2005). Considering the association between knee abduction and ACL injury (Hewett et al., 2005), and the importance of neuromuscular activation for maintaining knee alignment, these findings could partially explain the increased rate of ACL injury in pediatric females (Herzog et al., 2017). However, these studies either did not report kinematics (Landry et al., 2009), MOT (Ford et al., 2005; Kim et al., 2014; Sell et al., 2005) or muscle co-activation (Ford et al., 2005; Kim et al., 2014). Thus, providing a complete neuromuscular and kinematic analysis of unanticipated landings in a youth population could provide new insight into the modifiable factors of ACL injuries in youth athletes.

CHAPTER 3: RESEARCH QUESTIONS AND HYPOTHESIS

The aim of this Master's Thesis was two-fold: i) improve our understanding of how neuromuscular activation patterns and lower-limb mechanics differ between young male and female populations during an unanticipated landing task, and ii) to determine which neuromuscular and kinematic variables are the strongest predictors of a successful drop-jump landing. To achieve this aim, two specific research questions were tested:

Q1) Do sex-differences exist in muscle onset times, co-activation and lower-limb mechanics during an unanticipated drop-jump landing task?

We hypothesised that females would demonstrate greater knee flexion (H1) and greater knee abduction (H2) angles during the unanticipated landings (Ford et al., 2005; Myer, Ford, & Hewett, 2005; Sell et al., 2005). Additionally, based on previous research examining co-activation (Besier et al., 2003) and MOTs (Beaulieu et al., 2009), we hypothesised that females would demonstrate greater co-activation (H3) and earlier pre-activation (H4) of the lower-limb musculature during successful unanticipated landings.

Q2) Which kinematic or neuromuscular factors are the strongest predictors of a successful drop-jump landing?

Based on the association between trunk CoM and knee loading (Donnelly et al., 2012), we hypothesized that larger excursions in whole-body CoM would decrease the likelihood for landing a jump successfully (H5). In addition, based on previous research investigating failed landings (Wikstrom et al., 2007), we hypothesised that larger preparatory muscle activation amplitudes would also increase the likelihood for landing a jump successfully (H6).

CHAPTER 4: METHODOLOGY

4.1 Study Design

This thesis is comprised of *in-vivo* data collections and subsequent data processing and analysis. The *in-vivo* data collections followed a cross-sectional design comparing kinematics, kinetics and neuromuscular control between young healthy male and female participants. All data collections were conducted in the Human Movement and Biomechanics Laboratory at the University of Ottawa from February 2018 – September 2018.

This thesis is part of a larger investigation to establish objective baseline measurements for movement biomechanics and neuromuscular control in healthy young athletes (males and females; 10-18 yrs.). Therefore, in addition to the outlined anticipated and unanticipated single- and two-legged drop-jump landings, participants also performed a series of isometric and dynamic strength testing (Table A.1). However, this thesis focused on unanticipated single-leg landings on the dominant limb. Despite similar between limb injury rates (Matava, Freehill, Grutzner, & Shannon, 2002; Negrete, Schick, & Cooper, 2007), some studies have shown an effect of leg dominance on lower-limb kinematics (Brown et al., 2009; Niu, Wang, He, Fan, & Zhao, 2011). Thus, in order to eliminate any confounding affect of leg dominance, only the dominant limb was examined in this thesis. This study was approved by the University of Ottawa Research Ethics Board (H09-17-10).

4.2 Participants

A priori power analysis in G*Power software (3.1.0, Dusseldorf, Germany), based on previous data evaluating sex-differences in peak knee abduction angle during an unanticipated movement (Beaulieu et al., 2009), revealed that to achieve a power of 0.8, with an input effect size of 0.99 at $\alpha = 0.05$, a total sample size of 28 is required. To account for attrition, thirty-two

healthy participants (16 males; 16 females; 13-18 yrs.) were recruited from the Ottawa/Gatineau community. All participants actively participated in organized competitive sports at the time of testing. Exclusion criteria included: i) a history of previous traumatic knee injury (i.e. meniscal tear, ligament rupture), ii) any recent injury to the lower extremity (previous six months), and iii) any diseases that might affect neuromuscular function.

4.3 Data Collection

4.3.1 Consent and questionnaires

Prior to data collection all participants read and signed a consent form approved by the University of Ottawa Research Ethics Board (H09-17-10). Participants also completed the following questionnaires: i) an assessment of sport exposure (HSS Pedi-FABS) (Fabricant et al., 2013), ii) a subjective assessment of knee joint function (KOOS-Child) (Örtqvist, Roos, Broström, Janarv, & Iversen, 2012), iii) a pubescent-stage self-assessment form (Tanner Stage) (Taylor et al., 2001), and iv) Waterloo Footedness Questionnaire (Elias, Brydent, & Bulman-Fleming, 1998). Male and female participants had comparable age, body mass index (BMI), HSS Pedi-FABS activity level score (Fabricant et al., 2013) and Tanner Stage (Taylor et al., 2001). Group matches for age had a mean offset of 0.13 yrs., BMI a mean offset of 0.01 kg/m², activity level score a mean offset of 2.6, and Tanner Stage a mean offset of 0.06 (Table A.2).

4.3.2 Participant preparation and equipment

Each participant completed a 5 min. warm-up on a cycle ergometer (Monark 828E, Vansbro, Sweden) with minimum resistance. Participants were then introduced to the drop-jump protocol through a demonstration by the researcher and a progression through each component of

the drop-jump task. The familiarization period consisted of three successful landings at each stage of the drop-jump (*CHAPTER 4.3.4*).

To reduce the inter-participant variability of impact forces (Fu, Liu, Zhang, & Liu, 2013), each participant was provided with standardized athletic shoes (KBS7FW3343; MS7F505027, Joe Fresh, ON, Canada). Anthropometrics, including height (cm), weight (kg), pelvic, knee and ankle width (cm), thigh and shank length and circumference (cm) were recorded. Following these measurements, sites were prepared for EMG electrode placement (shaved and cleaned with isopropyl alcohol) to ensure optimal signal detection by the electrodes. Bipolar surface EMG electrodes (Trigno Standard; Trigno Mini, Delsys Inc., Boston, MA, USA) connected to a 16-channel EMG system (Trigno Wireless System, Delsys Inc., Boston, MA, USA) were placed over the muscle bellies and in line with the muscles fibers of the rectus femoris (RF), vastus lateralis (VL), vastus medialis (VM), biceps femoris (BF), semitendinosus (ST), lateral gastrocnemius (LG), medial gastrocnemius (MG), gluteus medius (GMed) and gluteus maximus (GMax) of the dominant limb according to recommendations of SENIAM (Hermens et al., 1999) and DeLuca (De Luca, 1993). Similarly, EMG electrodes were placed over the RF, VL, VM, BF, ST, MG, and GMed muscles of the non-dominant limb. These muscles were selected based on their contributions to muscle co-activation (Rudolph et al., 2001; Zeni, Rudolph, & Higginson, 2010) and their previously demonstrated differences in MOT (McLean et al., 2010). When necessary, minor adjustments were made to account for individual differences in anatomy and ensure proper placement of the sensors. The EMG electrodes contained two sets of differential EMG inputs; with detection surfaces 5mm long, 1mm wide and located 10mm apart. EMG signals were sampled at 2000 Hz, band-pass filtered at 20 - 450 Hz with a 12 dB/octave filter roll off and a common mode rejection ratio of > 80 dB.

To record full-body kinematics, 84 retroreflective markers (14 mm diameter) were placed on anatomical landmarks according to a hybrid cluster marker set (Mantovani & Lamontagne, 2017; Figure A.1). Marker trajectories were sampled at 200 Hz using a 10-camera infrared motion analysis system (Vero; Vantage, Vicon, Oxford, UK) and recorded using the supporting software (Nexus v2.7, Vicon, Oxford, UK). The supporting software was also used to synchronously collect GRFs from a force platform sampling at 2000 Hz and amplified with an internal gain of 1000 (FP4060-08, Bertec Corp., Columbus, OH, USA).

4.3.3 Maximum voluntary isometric contractions

Maximum voluntary isometric contractions (MVICs) were used to record maximum activation magnitudes of the sixteen muscles. Despite some limitations noted in the literature (Clarys, 2000), MVICs were deemed as most appropriate for making inter-participant comparisons of muscle activation patterns during a drop-jump landing (Burden, 2010). MVICs were performed in the following positions: i) knee extension and flexion with the participant seated and the hip and knee joint held at 90° and 60° respectively (Beaulieu, Lamontagne, & Beaulé, 2010), ii) hip abduction with the participant standing and their hip and knee held at 180° and 0° respectively, and iii) plantar flexion with the participants seated and their hip and knee flexed to 90° and 0° respectively and the ankle held at -10° (Sale, Quinlan, Marsh, McComas, & Belanger, 1982). Each MVIC was performed on an isokinetic dynamometer (System 4 Pro, Biodex Medical Systems, New York, USA). Participants were instructed to gradually increase their perceived force and to maintain their maximal force for 5 s. MVICs were repeated three times, with at least 1 min. of rest between each trial. Vocal encouragement was provided by the researchers to help elicit a maximal contraction.

4.3.4 Drop-jump landing task

Drop-jumps consisted of: i) stepping off a raised platform, ii) landing with two feet on to an in-ground force platform, iii) immediately performing a maximal vertical jump, and iv) landing back on the force platform with either one or two legs. *(Note: Based on results from pilot testing only one force plate was used for the drop-jump protocol. A common strategy when performing the single-leg landings was to draw the landing foot medially, so it was centered under the trunk CoM prior to landing. When two force plates were used, participants either i) landed in between the two force plates, or ii) altered their movement strategy so they only landed on one force plate. Thus, to minimize alterations in the participant's natural kinematics, only one force plate was used.)* Participants were instructed to jump as high as possible and to initiate take-off as soon as contact with the force plate is made. The height of the platform was aligned to the tibial plateau of each participant and the platform was placed directly behind the force plate.

Participants performed the drop-jump maneuver under two conditions (anticipated and unanticipated). The unanticipated condition was conducted through a monitor and external trigger configured in the motion capture system. A projector set-up in front of the participants displayed three white circles. When the participants stepped-off the raised platform on to the force plates, the measured GRF (set at a threshold of 10 N) sent an external trigger of 4.3 volts to a National Instruments Data Acquisition Box (DAQ) (BNC – 2090A, National Instrument, Hungary). The DAQ read directly into a Matlab (vR2018a, Mathworks Inc., Natick, MA, USA) script running parallel to the motion capture system, and triggered the script to change one of the circles to red. Based on which circle was coloured red, the participants were required to perform one of three possible landings: middle circle indicated two-legged landing, left circle indicated

single-leg landing on the left leg, and right circle indicated a single-leg landing on the right leg (Figure A.2). For the unanticipated trials, the visual cue was displayed approximately 500 ms before landing. Based on previous research using similar tasks, a 500 ms pre-land stimulus time was deemed adequate to elicit an unanticipated response (Brown et al., 2009; Mornieux et al., 2014). For the anticipated condition, the red circle was displayed approximately 5 s. before landing, such that participants knew well in advance which leg(s) they were required to land on (Mornieux et al., 2014). The order for which circle was coloured red was randomized for both the anticipated and unanticipated conditions.

Following each drop-jump, the landings were categorized as either ‘successful’ or ‘failed’. Trials were deemed successful if the participant landed with the designated leg and was able to ‘stick’ the landing (i.e. didn’t shift foot position to regain balance or touch the ground with the contralateral foot (for single-leg landings)). A failed trial was defined as the loss of balance forcing a participant to either touch the ground with the contralateral foot or perform an additional hop(s) after landing (Wikstrom et al., 2007). Drop-jumps were performed until at least five successful trials had been recorded for each landing condition. In order to eliminate confounding factors from between limb differences, only the failed and successful unanticipated single-leg landings for dominant limb were used in the subsequent analysis.

4.4 Data Analysis

4.4.1 Sex-specific landing strategies during unanticipated single-leg landings in young athletes

Kinematics and Kinetics

Marker trajectories for the successful landing on the dominant limb were labelled in Vicon Nexus (v2.7, Vicon, UK) and c3d files were imported into MatLab for the subsequent

analysis. Trajectories and GRFs were filtered using a 4th order zero-lag low-pass Butterworth filter with matching cut-off frequencies of 15 Hz (Bezodis, Salo, & Trewartha, 2013; Bisseling & Hof, 2006; Kristianslund, Krosshaug, & van den Bogert, 2012). Filter order and cut-off frequency was chosen based on a residual analysis (Winter, 2009) and visual inspection of filter performance. Trunk, hip and knee angles as well as, hip and knee moments in the frontal and sagittal planes were then calculated over each successful drop-jump landing on the dominant limb using a modified University of Ottawa Motion Analysis Model (Mantovani & Lamontagne, 2017).

Electromyography

To calculate co-activation indexes (CI), the collected EMG data were high-pass filtered at 20 Hz with a 2nd order dual-pass Butterworth filter, full-wave rectified, and low-pass filtered at 6 Hz with 2nd order dual-pass Butterworth filter. A 10 ms moving average algorithm identified maximum EMG amplitude for each muscle during the MVIC trials; these amplitudes were then used to normalize the filtered EMG data. The CI of the knee joint was defined as the ratio between the antagonists and agonists activation of the drop-jump landing multiplied by the summed EMG from both muscles (Lewek, Ramsey, Snyder-Mackler, & Rudolph, 2005; Rudolph et al., 2001):

$$CI = \left(\frac{EMG_{lower}}{EMG_{higher}} \right) * (EMG_{lower} + EMG_{higher}) \quad (1)$$

CI's were calculated between the summed quadriceps and hamstring activity (Q-H) and quadriceps and gastrocnemius muscle activity (Q-G). The Q group included the VL and VM; the H group included BF and ST; and the G group included the LG and MG. Low CI values represent lower activation of both muscles, or low-level activation of one muscle and high activation of the other muscle in the pair. Larger CI values denote higher activation of both

agonist and antagonist muscles (Lewek et al., 2005). CIs provide a comprehensive description of the relative muscle activation ratio and the summed magnitude of the muscle activation.

To calculate MOT, raw EMG data for the nine muscles on the dominant limb were low-pass filtered at 50 Hz with 2nd order dual-pass Butterworth filter (Hodges, 1996). MOT was determined using a double threshold method set at the point when the EMG signal exceeded three standard deviations of the baseline signal for at least 50 ms (Hodges, 1996), and was confirmed through visual inspection. The baseline signal was calculated as the lowest 200 ms of EMG activity during the *flight phase* of the drop-jump for each participant. MOT was calculated relative to the single-leg landing (GRF > 10 N) such that negative values indicated longer preparatory muscle activation and positive values indicated that MOT did not occur until after the landing.

Time Normalization

Prior to statistical analyses the CI, kinematic, and kinetic waveform data were time normalized into four phases using landmarks within the drop-jump cycle. The phases were defined as: i) *deceleration phase* (initial impact (GRF > 10 N) until maximum knee flexion), ii) *jump phase* (maximum knee flexion until take-off (GRF < 10 N)), iii) *flight phase* (take-off (GRF < 10 N) until second landing (GRF > 10 N)), and iv) *landing phase* (second landing (GRF > 10 N) until 500 ms. following landing). Since one force plate was used to collect GRFs, kinetic data was only calculated for the *landing phase* of the drop-jump (i.e. only one leg was in contact with the force plate). The time normalized waveforms were averaged over the successful trials for each participant.

Statistical Analysis

For the non-discrete variables (CIs, kinematics and kinetics) outliers were determined by calculating a moving threshold of 1.5 times the interquartile range. Any waveform that exceeded this threshold was further inspected to determine the appropriate treatment. Outliers that were a result of irreducible errors in the data collection process were excluded (ex. EMG electrode looses contact with skin). If an outlier reflected real and accurate data (no apparent errors with data collection nor observed difficulties during the tasks), it was included in the subsequent analysis. The assumption of normality was evaluated through a Shapiro-Wilk test using statistical parametric mapping (SPM). If a variable failed-to-reject the assumption of normality, an independent t -test using SPM identified differences between male and female successful drop-jump landings. If a variable rejected the assumption of normality, then an independent t -test using statistical non-parametric mapping (SnPM) evaluated sex-differences in the successful drop-jump landings. SPM applies random field theory to make statistical inferences about the topological features of multi-dimensional data (Pataky, Robinson, & Vanrenterghem, 2013). In this context, SPM included all data within the drop-jump waveforms and determined the time-varying differences throughout the jump cycle (Pataky et al., 2013). The assumption of homogeneity of variances was not evaluated since SPM implements a non-sphericity correction by adjusting the degrees-of-freedom using a Satterthwaite approximation from restricted maximum likelihood estimates of covariance components (Pataky et al., 2013). This non-sphericity correction was implemented for all tests involving SPM.

For the discrete variables (MOT) outliers were identified through visual inspection of box-plot graphs. Any value that exceeded 1.5 times the interquartile range was further inspected to determine the appropriate treatment. Outliers that were a result of irreducible errors in the data

collection process were excluded, all other data was included in the subsequent analysis. The assumption of normality was evaluated through a Shapiro-Wilk test and the assumption of homogeneity of variances was evaluated through a Levene test. If an assumption was rejected, then a Mann-Whitney U test compared male and female differences in MOT during the successful drop-jump landings. If both tests failed-to-reject an assumption, then independent t -tests were used to compare sex-differences in MOT. Significance was set at $p < 0.05$ for all parametric assumptions, discrete and non-discrete statistical tests.

Effect size was calculated for each statistical comparison. For data which met the parametric assumptions, Cohen's effect size (d) was calculated to quantify the size of the difference:

$$d = \frac{(m_2 - m_1)}{\sqrt{((SD_1^2) + (SD_2^2))/2}} \quad (2)$$

where m_1 and SD_1 are the mean and standard deviation of the first group and m_2 and SD_2 are the mean and standard deviation of the second group (Cohen, 2013). For data which did not meet the parametric assumptions, effect size (r) was calculated as:

$$r = \frac{Z}{\sqrt{N}} \quad (3)$$

where Z is the non-parametric test score and N is the number of participants included in the comparison (Field, 2013). A small effect size was considered to be $d < 0.3$, medium $0.3 < d < 0.5$, and large $d > 0.5$ (Cohen, 2013).

Once all statistical tests were completed a Benjamini-Hochberg procedure was performed with a false discovery rate (FDR) of 0.05. A Benjamini-Hochberg procedure was selected since it preserves greater statistical power while also limiting the familywise *Type I* error rate (Benjamini & Hochberg, 1995; Thissen, Steinberg, & Kuang, 2002). This procedure works by first ranking the individual p values in order, from smallest to largest (i.e. the smallest p value has a rank of i

= 1, then next smallest has $i = 2$, etc.). The individual p values are then compared to their respective Benjamini-Hochberg critical values, calculated as:

$$\text{Critical Value} = (i/m)Q \quad (4)$$

where i is the rank, m is the total number of statistical tests, and Q is the false discovery rate (Benjamini & Hochberg, 1995; Thissen et al., 2002). The largest p value which has $p < (i/m)Q$ is significant, and all other smaller p values are also significant, even if they aren't less than their respective critical values (Benjamini & Hochberg, 1995; Thissen et al., 2002). SPM analyses were conducted in MatLab; all other statistical tests were conducted in R (v3.03, The R Foundation, Vienna, AUT).

4.4.2 Kinematic and neuromuscular predictors of successful drop-jump landings

Kinematics

Joint angles were calculated over the successful and failed drop-jump landings as previously described (*CHAPTER 4.4.1*). Three-dimensional hip, knee and ankle angles were then extracted and used in the subsequent analysis. The mass and CoM location for the head, trunk, upper arms, forearms, thighs, shanks, and foot were calculated using the body segment parameters from Zatsiorsky (Zatsiorsky, Seluyanov, & Chugunova, 1990), as modified by de Leva (de Leva, 1996) (Table A.3). Whole-body CoM location was then calculated in each of the three axes as:

$$a_0 = \frac{m_1 a_1 + m_2 a_2 + m_3 a_3 \dots m_n a_n}{M} \quad (5)$$

where M is the participant's mass, m_i is the body segment mass, and a_i is the body segment CoM location in the 'a' axis (Winter, 2009). Whole-body CoM excursion was then calculated relative to take-off (GRF > 10 N) and normalized to height.

Electromyography

To calculate EMG linear envelopes for each drop-jump, EMG data were high-pass filtered at 20 Hz with a 2nd order dual-pass Butterworth filter, full-wave rectified, and low-pass filtered at 6 Hz with 2nd order dual-pass Butterworth filter. A 10 ms moving average algorithm identified maximum EMG amplitude for each muscle during the MVIC trials; these amplitudes were then used to normalize the filtered EMG data.

Data Reduction

Prior to statistical analysis, hip, knee and ankle angles, EMG amplitude were averaged over the flight phase of the drop-jump landing (take-off (GRF < 10 N) until second landing (GRF > 10 N)). The *flight phase* was chosen based on the principal of temporal precedence (Field, 2013); in order to establish a cause and effect relationship between a given variable and the failed landings, the change in the variable must occur before the landing. In addition, preparatory EMG has already been established as an important variable when examining failed landings (Wikstrom et al., 2007).

Statistical Analysis

EMG amplitude, knee, hip, ankle angles and CoM excursion was averaged over the successful and failed landings for each participant. Outliers were identified and eliminated as previously described (*CHAPTER 4.4.1*). The assumption of normality was evaluated through a Shapiro-Wilk test. If an assumption was rejected, then a Wilcoxon signed-rank test determined differences between successful and failed landings. If a variable failed-to-reject the assumption of normality, then paired-sample *t*-tests were used to determine differences between successful and failed landings. Appropriate calculations for effect size were also performed for each statistical comparison (*CHAPTER 4.4.1*). A correction for multiple comparisons was not

performed. Given that this study was exploratory in nature, a greater emphasis was put on avoiding *Type II* errors than avoiding *Type I* errors (Field, 2013).

A binomial logistic regression was then used to predict the likelihood of a successful landing. Predictors were standardized to their respective Z scores:

$$Z = \frac{x - \bar{x}}{\sigma} \quad (6)$$

Best subset selection was performed to select the optimal predictors for inclusion in the model.

To perform best subset selection, a separate logistic regression curve was fit for each possible combination of predictors (James, Witten, Hastie, & Tibshirani, 2013). That is, where pr is the number of predictors ($pr = 29$) and $k = 1, 2, \dots, pr$, all $\binom{pr}{k}$ models that contain k predictors were fit:

$$\binom{pr}{k} = pr(pr - 1)/k \quad (7)$$

The best among these $\binom{pr}{k}$ models was then selected and called M_k (James et al., 2013). In this context best was defined as having the smallest deviance, calculated as negative two times the maximized log-likelihood (James et al., 2013). Since deviance is a measure for training error rate and decreases monotonically as the number predictors in the model increases, the best M_0, \dots, M_k model was then selected using leave-one-out cross-validation (LOOCV) (Chapelle, Vapnik, Bousquet, & Mukherjee, 2002; Vapnik & Chapelle, 2000). LOOCV uses one observation as the testing set and builds the logistic regression on the remaining $n - 1$ training observations (Chapelle et al., 2002; Vapnik & Chapelle, 2000). A prediction (\hat{y}_I) is then made for the excluded observation (y_I), since it was not included in the fitting process the mean square error $(y_I - \hat{y}_I)^2$ (MSE) provides an approximate unbiased estimate for the test error (James et al., 2013). The LOOCV estimate was the average of these n test error estimates:

$$LOOCV_{(n)} = \frac{1}{n} \sum_{i=1}^n MSE_i \quad (8)$$

LOOCV was performed for each M_k model and the model which balanced simplicity with error reduction (i.e. adding one more variable did not offer a substantial reduction in MSE) was chosen (James et al., 2013). Model accuracy was then assessed on all observations (training accuracy) by calculating a receiver operating characteristic (ROC) curve and determining the classification threshold which balanced model sensitivity and specificity (Metz, 1978). A confusion matrix was then calculated based on the misclassified observations. Similarly, model accuracy was assessed using LOOCV, such that the classification threshold which balanced sensitivity and specificity was calculated each time a model was fit on the $n - 1$ observations (Metz, 1978). A confusion matrix was then calculated based on the LOOCV misclassified observations. Statistical significance for the logit of each predictor included in the final model and their respective odds ratios were calculated. All statistical analyses were conducted in R with statistical significance set at $p < 0.05$

CHAPTER 5: MANUSCRIPT 1

Sex-specific landing strategies during unanticipated single-leg landings in young athletes

Nicholas J. Romanchuk¹, Micheal Del Bel², Daniel L. Benoit^{1,2}

¹ School of Human Kinetics, University of Ottawa, Canada

² School of Rehabilitation, University of Ottawa, Canada

Abstract

Purpose: Despite the higher incidence of anterior cruciate ligament injuries in pediatric female populations, limited research has investigated sex-differences in youth biomechanics. The purpose of this study was to identify sex-differences in muscle onset time, co-activation and lower-limb mechanics during an unanticipated landing task in a youth population.

Methods: Thirty-two healthy youth athletes completed unanticipated single-leg drop-jump landings on their dominant limb. Participants were required to hold the landing, trials where participants shifted foot position to regain balance or touched the ground with the contralateral foot were excluded. Drop-jump landings were time-normalized using landmarks within the drop-jump task. Statistical parametric mapping (SPM) determined time-varying statistically significant differences in muscle onset time, co-activation, kinematics and kinetics. Independent *t*-tests and Mann-Whitney U tests determined statistical differences in muscle onset times.

Results: SPM identified significantly greater trunk flexion angle in males during 9-38% (male= $11.1 \pm 5.57^\circ$, female= $-0.26 \pm 7.97^\circ$, $p=0.0009$) of the *deceleration phase*, 87-100% of the *flight phase* (male= $10.4 \pm 5.04^\circ$, female= $-5.01 \pm 10.4^\circ$, $p=0.0000005$), and 1-100% (male= $16.9 \pm 7.45^\circ$, female= $6.84 \pm 12.5^\circ$, $p=0.0000005$) of the *landing phase*. SPM identified significantly lower hip flexion moment in females during 5-13% (male= 196 ± 46 Nm/kg, female= 141 ± 37 Nm/kg, $p=0.003$), 35-40% (male= 92.5 ± 19.1 Nm/kg, female= 61.4 ± 29.7 Nm/kg, $p=0.007$), and 53-65% (male= 93 ± 18.1 Nm/kg, female= 70.2 ± 22.6 Nm/kg, $p=0.002$) of the drop-jump *landing phase*. SPM also identified significantly lower knee flexion moment in females during 22-29% (male= 83.1 ± 9.4 Nm/kg, female= 67.9 ± 12.5 Nm/kg, $p=0.003$), and 46-51% (male= 41 ± 4.7 Nm/kg, female= 33.39 ± 7.1 Nm/kg, $p=0.01$). Independent sample *t*-test identified longer muscle onset time in the vastus lateralis (male= -81 ± 64.3 ms, female= -0.35 ± 101 ms, $p=0.02$). Greater quad-gastroc co-activation was identified in female participants during 37-48% (male= 0.16 ± 0.1 , female= 0.41 ± 0.24 , $p=0.008$) of the *flight phase* of the drop-jump.

Conclusion: These findings indicate that females land in a more erect posture through their trunk, hip and knee and may be less effective at dissipating landing forces. In addition, greater co-activation of the quadriceps-gastrocnemius and shorter pre-activation of the vastus lateralis may indicate a less effective muscle activation strategy in females.

Introduction

The anterior cruciate ligament (ACL) is the most frequently damaged knee ligament (Majewski, Susanne, & Klaus, 2006), with an estimated injury incidence of 0.17-0.23 per 1000 athlete exposures (Agel, Rockwood, & Klossner, 2016). ACL injury rates are not consistent between sexes; females are two to four times more likely to tear their ACL when accounting for sport and exposure time (Agel & Klossner, 2014; Joseph et al., 2013; Swenson et al., 2013). In addition, when looking at a youth population, ACL injury rates have significantly risen across both sexes over the last decade (Beck, Lawrence, Nordin, DeFor, & Tompkins, 2015; Gornitzky et al., 2016). Females aged between 13-17 yrs. now possess the highest injury incidence of any sex-age strata (Herzog et al., 2017). Although biomechanical research continues to shape neuromuscular training strategies (Mandelbaum et al., 2005; Myer, Ford, & Hewett, 2004), ACL injuries and the associated sex disparity have not diminished (Werner, Yang, Looney, & Gwathmey, 2016). As such, further investigation into ACL injuries, in particular sex related factors, is warranted.

When assessing neuromechanical contributions to ACL injury risk it is imperative that research replicate factors inherent in sport participation. Although evaluating high risk postures during pre-planned laboratory-based movements holds value, sports in which ACL injuries occur are largely governed by an unanticipated series of events. Video analyses of ACL injuries reveal that the majority of ACL ruptures occur during non-contact movements, such as the landing phase of a jump or in preparation for a rapid change of direction (Boden, Dean, Feagin, & Garrett, 2000; Koga et al., 2010; Olsen, Myklebust, Engebretsen, & Bahr, 2004). These movements typically follow a reaction to an external stimulus (ex. avoiding an opposing player) and are therefore unanticipated in nature. Research which brings together laboratory and field

environments, especially in a higher risk population (females 13-17 yrs.), could provide valuable information regarding the modifiable risk factors for ACL injury.

Research which has simulated the sport environment through unanticipated components consistently observe greater knee abduction angles (Borotikar et al., 2008; Brown et al., 2009; Cowley et al., 2006; Fong et al., 2014; Ford et al., 2005; Kim et al., 2014; Kipp et al., 2013; Malloy et al., 2016; Sell et al., 2005), external knee abduction moments (Brown et al., 2009; Cowley et al., 2006; Kim et al., 2014; Kipp et al., 2013; Malloy et al., 2016), as well as decreased hip abduction angles (Houck et al., 2006; McLean & Samorezov, 2009; Sell et al., 2005) during the unanticipated task. This is concerning since these mechanics may increase ACL strain (Fleming et al., 2001; Shin, Chaudhari, & Andriacchi, 2009; Shin, Chaudhari, & Andriacchi, 2011), and can retrospectively predict ACL injuries (Hewett et al., 2005). In addition, unanticipated manoeuvres produced greater quadriceps activity (Beaulieu, Lamontagne, & Xu, 2009; Kim et al., 2014), greater lateral gastrocnemius activity (Beaulieu et al., 2009; Kim et al., 2014) and a more generalized co-activation strategy of the quadriceps-hamstrings muscles (Sell et al., 2005). However, research evaluating muscle onset times (MOT) during unanticipated movements has been inconsistent, with both longer (McLean, Borotikar, & Lucey, 2010) and shorter delays observed in the medial hamstrings of female athletes (Beaulieu et al., 2009; Landry, McKean, Hubley-Kozey, Stanish, & Deluzio, 2009). One reason for this discrepancy may be differences in how the tasks were performed, with MOTs measured prior to a change of direction from a resting position (McLean et al., 2010) and an approach run (Beaulieu et al., 2009). However, this research was predominately conducted using adult populations and rarely focused on making between-sex comparisons.

Studies evaluating unanticipated movements using populations under 18 yrs. of age found that female athletes performed the tasks with greater knee flexion (Sell et al., 2005) and knee abduction angles (Ford, Myer, Toms, & Hewett, 2005; Myer et al., 2005; Sell et al., 2005), as well as altered hamstring activation timing (Landry et al., 2009), increased semitendinosus (Sell et al., 2005), rectus femoris and gastrocnemii activation compared to their male counterparts (Kim et al., 2014; Landry et al., 2009). Considering the association between knee abduction and ACL injury (Hewett et al., 2005), and the importance of neuromuscular activation for maintaining knee alignment, these findings could partially explain the increased rate of ACL injury in pediatric females (Herzog et al., 2017). However, these studies either did not report kinematics (Landry et al., 2009), MOT (Ford et al., 2005; Kim et al., 2014; Sell et al., 2005) or muscle co-activation (Ford et al., 2005; Kim et al., 2014). Thus, providing a complete neuromuscular and kinematic analysis of unanticipated landings in a youth population could provide new insight into the modifiable factors of ACL injuries in youth athletes. This study will combine a commonly used injury screening tool (drop-jump landing) (Hewett et al., 2005; Padua et al., 2009) with a relevant sport component (unanticipated visual cue) to identify sex-differences in MOT, co-activation and lower-limb mechanics in youth athletes.

Methods

Participants

Thirty-two healthy male (n=16; age: 15.9±1.87 yrs.; BMI: 21.1±2.66 kg/m²; Tanner Stage: 4.12±1.09) and female (n=16; age: 15.7±1.7 yrs.; BMI: 21.1±2.9 kg/m²; Tanner Stage: 4.06±1.12) athletes were recruited from the Ottawa/Gatineau region (Table A.2). Each participant actively participated in organized sports at the time of testing as assessed through the HSS Pedi-FABS activity level questionnaire (Fabricant et al., 2013). Participants had no history

of traumatic knee injury (i.e. meniscal tear, ligament rupture), no recent injury to the lower extremity (previous six months), or any diseases that might affect neuromuscular function.

Procedure

All participants read and signed a consent form approved by the University of Ottawa Research Ethics Board (H09-17-10) and completed the following questionnaires; i) an assessment of sport exposure (HSS Pedi-FABS) (Fabricant et al., 2013), ii) a subjective assessment of knee joint function (KOOS-Child) (Örtqvist, Roos, Broström, Janarv, & Iversen, 2012), iii) a pubescent-stage self-assessment form (Tanner Stage) (Taylor et al., 2001), and iv) Waterloo Footedness Questionnaire (Elias, Brydent, & Bulman-Fleming, 1998) (Table A.2).

Following the questionnaires, each participant completed a 5 min. warm-up on a cycle ergometer (Monark 828E, Vansbro, Sweden) with minimum resistance. Bipolar surface EMG electrodes (Trigno Standard; Trigno Mini, Delsys Inc., Boston, MA, USA) were then placed over the muscle bellies and in line with the muscles fibers of the rectus femoris (RF), vastus lateralis (VL), vastus medialis (VM), biceps femoris (BF), semitendinosus (ST), lateral gastrocnemius (LG), medial gastrocnemius (MG), gluteus medius (GMed) and gluteus maximus (GMax) of the dominant limb according to recommendations of SENIAM (Hermens et al., 1999) and DeLuca (De Luca, 1993). Maximum voluntary isometric contractions (MVICs) were performed on a isokinetic dynamometer (System 4 Pro, Biodex Medical Systems, New York, USA) in the following positions: i) knee extension and flexion with the participant seated and the hip and knee joint held at 90° and 60° respectively (Beaulieu, Lamontagne, & Beaulé, 2010), ii) hip abduction with the participant standing and their hip and knee held at 180° and 0° respectively, iii) plantar flexion with the participants seated and their hip and knee flexed to 90° and 0° degrees respectively and the ankle held at -10° (Sale, Quinlan, Marsh, McComas, & Belanger,

1982). MVICs were repeated three times, held for 5 s. with at least 1 min. of rest between each trial. To record full-body kinematics, 84 retroreflective markers (14 mm diameter) were placed on anatomical landmarks according to a hybrid cluster marker set. Marker trajectories were sampled at 200 Hz using a 10-camera infrared motion analysis system (8 Vero; 2 Vantage, Vicon, Oxford, UK) and recorded using the supporting software (Nexus v2.7, Vicon, Oxford, UK). GRFs were also synchronously collected from a force platform sampling at 2000 Hz (FP4060-08, Bertec Corp., Columbus, OH, USA).

Drop-jumps consisted of: i) stepping off a raised platform; ii) landing with two feet on to an in-ground force platform; iii) immediately performing a maximal vertical jump; iv) landing back on the force platform with either one or two legs. The height of the platform was aligned to the tibial plateau of each participant and the platform was placed directly behind the force plate. A projector set-up directly in front of the participants displayed three white circles. Following the maximal vertical jump, the required landing leg was randomly signalled by changing one of the white circles to red (i.e. left circle=left leg; middle circle=two leg; right circle=right leg) (Figure A.2). To simulate an unanticipated task, the visual cue was displayed approximately 500 ms before landing. Based on previous research using similar unanticipated tasks, a 500 ms pre-land stimulus time was deemed adequate to elicit an unanticipated response (Brown et al., 2009; Mornieux, Gehring, Fürst, & Gollhofer, 2014). Participants were instructed to ‘stick’ the landing, trials were excluded if the participant shifted foot position to regain balance or touched the ground with the contralateral foot (Wikstrom, Tillman, Schenker, & Borsa, 2007). Drop-jumps were performed until at least five successful single-leg landings had been recorded on the dominant limb. For the subsequent analysis, only unanticipated single-leg landings on the dominant limb were considered.

Data Processing and Analysis

Kinematics

Trajectories and GRFs were filtered using a 4th order zero-lag low-pass Butterworth filter at 15 Hz (Bezodis, Salo, & Trewartha, 2013; Bisseling & Hof, 2006; Kristianslund, Krosshaug, & van den Bogert, 2012). Filter order and cut-off frequency were chosen based on a residual analysis (Winter, 2009) and visual inspection of filter performance. Trunk, hip and knee angle as well as hip and knee moments in the frontal and sagittal planes were then calculated over each successful drop-jump landing on the dominant limb using a modified University of Ottawa Motion Analysis Model (Mantovani & Lamontagne, 2017).

Electromyography

EMG was high-pass filtered at 20 Hz with a 2nd order dual-pass Butterworth filter, full-wave rectified, and low-pass filtered at 6 Hz with 2nd order dual-pass Butterworth filter. A 10ms moving average algorithm identified maximum EMG amplitude for each muscle during the MVIC trials; these amplitudes were then used to normalize the filtered EMG data. The co-activation index of the knee joint was defined as the ratio between the antagonists and agonists activation (EMG) of the drop-jump landing multiplied by the summed EMG from both muscles (Lewek, Ramsey, Snyder-Mackler, & Rudolph, 2005; Rudolph, Axe, Buchanan, Scholz, & Snyder-Mackler, 2001):

$$CI = \left(\frac{EMG_{lower}}{EMG_{higher}} \right) * (EMG_{lower} + EMG_{higher}) \quad (1)$$

CI's were calculated between the summed quadriceps and hamstring activity (Q-H) and between the quadriceps and gastrocnemius muscle activity (Q-G). The Q group included the VL and VM; the H group included BF and ST; and the G group included the LG and MG.

To calculate MOT, raw EMG data for the nine muscles on the dominant limb were low-pass filtered at 50 Hz with 2nd order dual-pass Butterworth filter (Hodges, 1996). MOT was determined using a double threshold method set at the point when the EMG signal exceeds three standard deviations of the baseline signal for at least 50 ms (Hodges, 1996). The baseline signal was calculated as the lowest 100 ms of EMG activity during the flight phase of the drop-jump. MOT was calculated relative to the single-leg landing (GRF > 10N) such that negative values indicate longer preparatory muscle activation and positive values indicate MOT occurred after the landing.

Time Normalization

CI, kinematic, and kinetic waveform data were time normalized into four phases using landmarks within the drop-jump cycle. The phases were defined as: i) *deceleration phase* (initial impact (GRF > 10N) until maximum knee flexion), ii) *jump phase* (maximum knee flexion until take-off (GRF < 10N)), iii) *flight phase* (take-off (GRF < 10N) until second landing (GRF > 10N)), and iv) *landing phase* (second landing (GRF > 10N) until 500 ms. following landing). Since one force plate was used to collect GRFs, kinetic data was only calculated for the *landing phase* of the drop-jump (i.e. only one leg was in contact with the force plate). The time normalized waveforms were averaged over the successful trials for each participant.

Statistical Analysis

For the non-discrete variables (CI, kinematics and kinetics) outliers were determined by calculating a moving threshold of 1.5 times the interquartile range. Any waveform that exceeded this threshold was further inspected to determine the appropriate treatment. Outliers that resulted from irreducible errors in the data collection process were excluded (ex. EMG electrodes losing contact with the skin). If an outlier reflected real and accurate data, it was included in the

subsequent analysis. Following the identification of outliers, individual trials within each participant were examined. If the outlier was a result of irreducible errors during data collection the trial was excluded. The assumption of normality was evaluated using statistical parametric mapping (SPM). If a variable failed-to-reject the assumption of normality, an independent t -test using SPM identified differences between male and female drop-jump landings. If a variable rejected the assumption of normality, then an independent t -test using statistical non-parametric mapping (SnPM) evaluated sex-differences in the drop-jump landings. SPM analyses were conducted in MatLab (vR2013a, Mathworks Inc., Natick, MA, USA).

For MOT (discrete variable) outliers were treated as described above. The assumption of normality was evaluated through a Shapiro-Wilk test and the assumption of homogeneity of variances was evaluated through a Levene test. If an assumption was rejected, then a Mann-Whitney U test compared male and female differences in MOT. If both tests failed-to-reject an assumption, then independent t -tests were used to compare sex-differences in MOT. Statistical significance was set at $p < 0.05$ for all statistical tests. Effect size calculations were also performed for each statistical comparison. Discrete analyses were conducted in R (v3.03, The R Foundation, Vienna, Austria). Once all statistical tests were completed a Benjamini-Hochberg correction for multiple comparisons was performed with a false discovery rate (FDR) of 0.05 (Benjamini & Hochberg, 1995).

Results

All 32 participants were able to complete the unanticipated drop-jumps and every participant was included in the analysis. Results of all statistical tests including parametric assumptions can be found in Table 5.1. Results from the Benjamini-Hochberg procedure can be found in Table 5.2.

Table 5.1

Results from all statistical tests run on the kinematic, kinetic and EMG variables prior to the Benjamini-Hochberg procedure

Variables	Normality (m=male; f=female)	Equal Variances	Statistical Test	Statistical Significance
Q-H	0.000002	-	SnPM	$p > 0.05$
Q-G	0.0000002	-	SnPM	0.0078*
Trunk Flexion Angle	$p > 0.05$	-	SPM	0.0009* 0.0000005*
Trunk Lateral Tilt	0.001	-	SnPM	$p > 0.05$
Hip Flexion Angle	0.0005	-	SnPM	$p > 0.05$
Hip Abduction Angle	$p > 0.05$	-	SPM	$p > 0.05$
Hip Flexion Moment	0.0083	-	SnPM	0.0026* 0.0072* 0.0016*
Hip Abduction Moment	$p > 0.05$	-	SPM	$p > 0.05$
Knee Flexion Angle	$p > 0.05$	-	SPM	0.0428*
Knee Abduction Angle	$p > 0.05$	-	SPM	$p > 0.05$
Knee Flexion Moment	0.007	-	SnPM	0.0032* 0.0097*
Knee Abduction Moment	$p > 0.05$	-	SnPM	$p > 0.05$
RF MOT	m=0.25 f=0.02	0.27	Mann-Whitney U	0.36
VL MOT	m=0.21 f=0.22	0.12	<i>t</i> -test	0.0172*
VM MOT	m=0.7 f=0.46	0.86	<i>t</i> -test	0.37
BF MOT	m=0.59 f=0.56	0.13	<i>t</i> -test	0.092
SM MOT	m=0.02 f=0.18	0.27	Mann-Whitney U	0.53
LG MOT	m=0.28 f=0.43	0.06	<i>t</i> -test	0.46
MG MOT	m=0.13 f=0.97	0.55	<i>t</i> -test	0.54
GMed MOT	m=0.07 f=0.82	0.71	<i>t</i> -test	0.63
GMax MOT	m=0.18 f=0.087	0.41	<i>t</i> -test	0.42

Note. SPM assessments of normality yield multiple time-varying p -values, only smallest p -value shown. *indicates a statistical difference of $p < 0.05$

Table 5.2

Results from the Benjamini-Hochberg procedure, correcting for a FDR of 0.05

Variable	<i>p</i> -value	Rank	Benjamini-Hochberg	Corrected Significance
Trunk Flexion Angle	0.0000005	1	0.0024	*
Trunk Flexion Angle	0.00009	2	0.0048	*
Hip Flexion Moment	0.0016	3	0.0071	*
Hip Flexion Moment	0.0026	4	0.0095	*
Knee Flexion Moment	0.0032	5	0.0119	*
Hip Flexion Moment	0.0072	6	0.0143	*
Q-G CI	0.0078	7	0.0167	*
Knee Flexion Moment	0.0097	8	0.0190	*
VL MOT	0.0172	9	0.0214	*
Knee Flexion Angle	0.0428	10	0.0238	

*indicates statistical significance following the Benjamini-Hochberg procedure

Kinematic and Kinetics (Males vs. Females)

SPM identified significantly greater trunk flexion angle in males during 9-38% (male=11.1±5.57°, female=-0.26±7.97°, $p=0.0009$, $d=1.65$) of the *deceleration phase*, 87-100% of the *flight phase* (male=10.4±5.04°, female=-5.01±10.4°, $p=0.0000005$, $d=0.66$) and 1-100% (male=16.9±7.45°, female=6.84±12.5°, $p=0.0000005$, $d=0.98$) of the *landing phase* (Figure 5.1). No statistically significant differences were identified for the hip and knee joint angles during the drop-jump landing task (Figure 5.1). SPM identified significantly lower hip flexion moment in females during 5-13% (male=196±46 Nm/kg, female=141±37 Nm/kg, $p=0.003$, $r=0.70$), 35-40% (male=92.5±19.1 Nm/kg, female=61.4±29.7 Nm/kg, $p=0.007$, $r=0.49$), and 53-65% (male=93±18.1 Nm/kg, female=70.2±22.6 Nm/kg, $p=0.002$, $r=0.4$) of the drop-jump *landing phase* (Figure 5.2). SPM also identified significantly lower knee flexion moment in females during 22-29% (male=83.1±9.4 Nm/kg, female=67.9±12.5 Nm/kg, $p=0.003$, $r=0.51$), and 46-51% (male=41±4.7 Nm/kg, female=33.39±7.1 Nm/kg, $p=0.01$, $r=0.55$) (Figure 5.2).

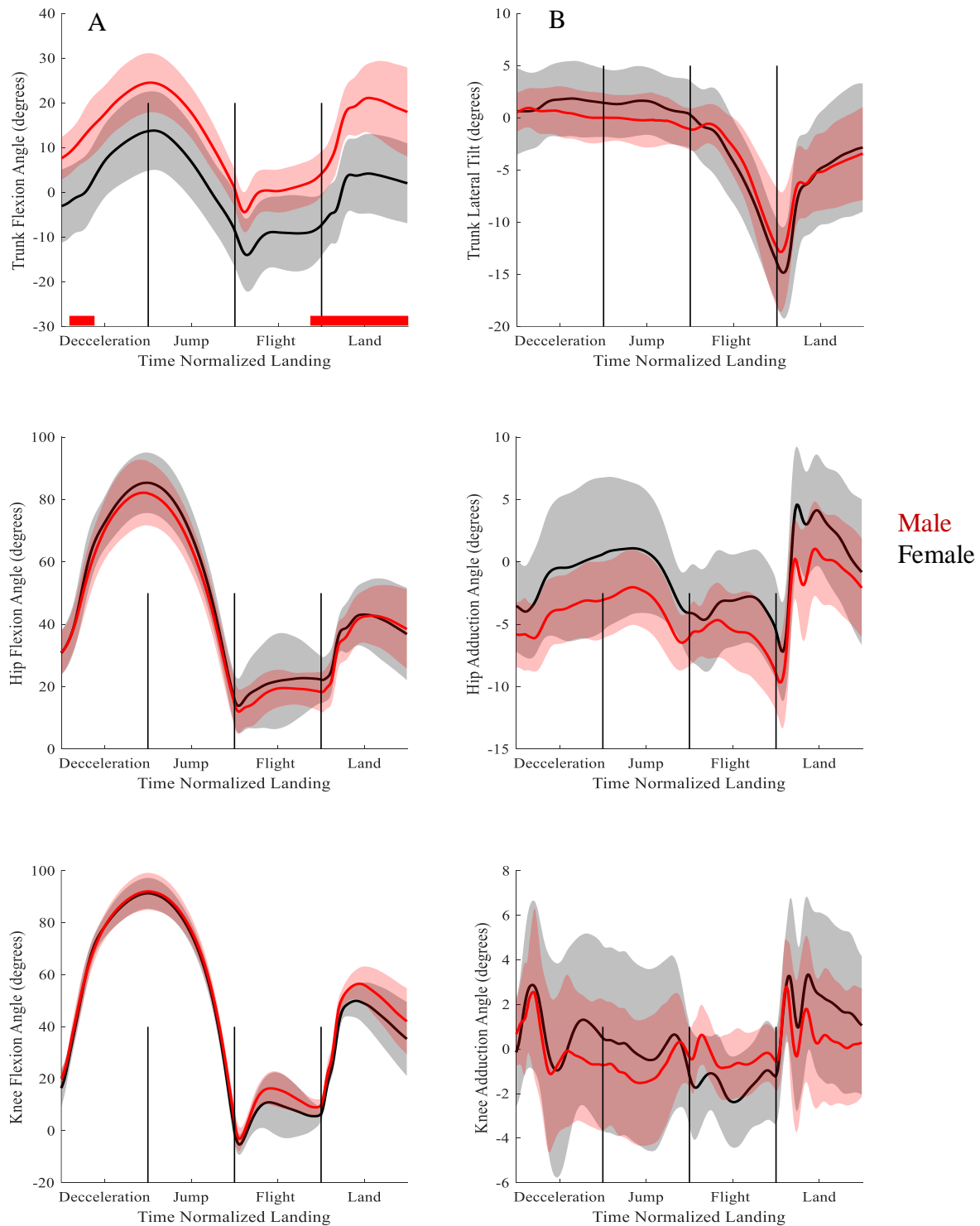


Figure 5.1. Sagittal (A) and frontal (B) angles for the trunk, hip and knee over the drop-jump task. Positive values for trunk lateral tilt indicate a lateral lean towards the landing limb. For all other angles positive values indicate flexion/adduction and negative values indicate extension/abduction. Black vertical lines separate the four time-normalized phases. Red horizontal bar indicates statistical significance between male and female participants.

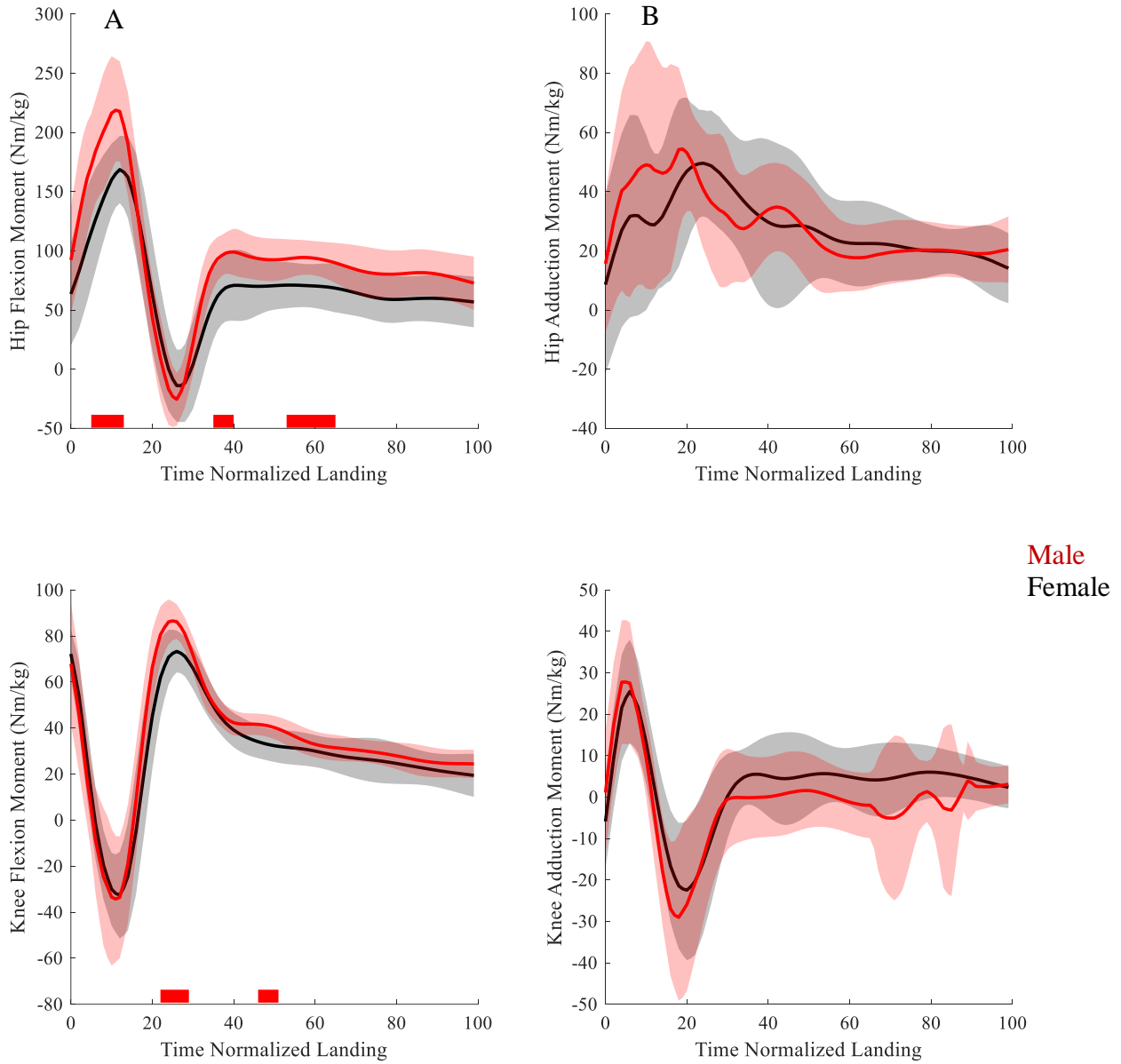


Figure 5.2. Sagittal (A) and frontal (B) moments during the drop-jump landing phase. Positive values indicate flexion/adduction and negative values indicate extension/abduction. Red horizontal bar indicates statistical significance between male and female participants.

Muscle Onset Time (Males vs. Females)

Independent sample *t*-test identified longer MOT in the VL (male=-81±64.3 ms, female=-0.35±101 ms, *p*=0.02, *d*=0.95) (Figure 5.3). No statistically significant differences were identified in the remaining eight muscles (Figure 5.3).

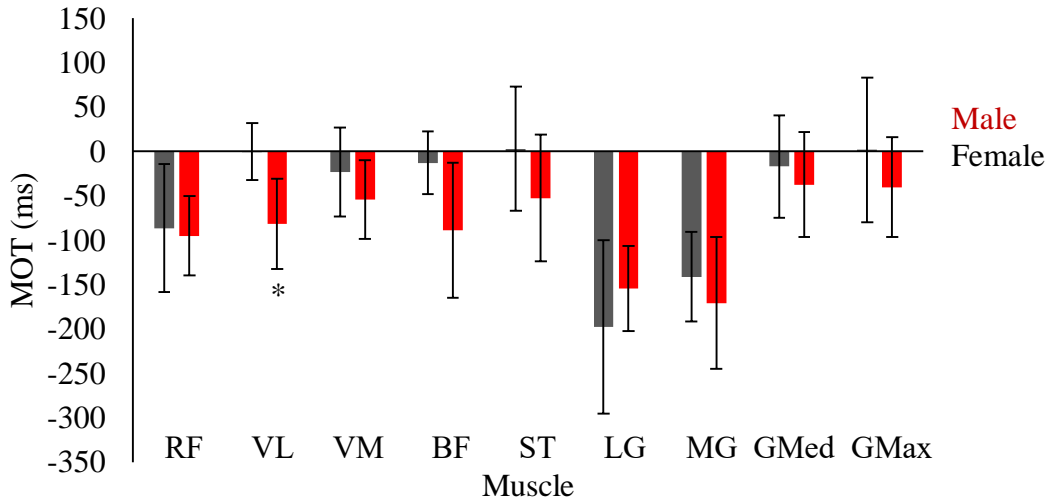


Figure 5.3. MOT for the nine muscles on the dominant limb. Times calculated relative to second landing of the drop-jump. *indicates statistical significance between male and female participants.

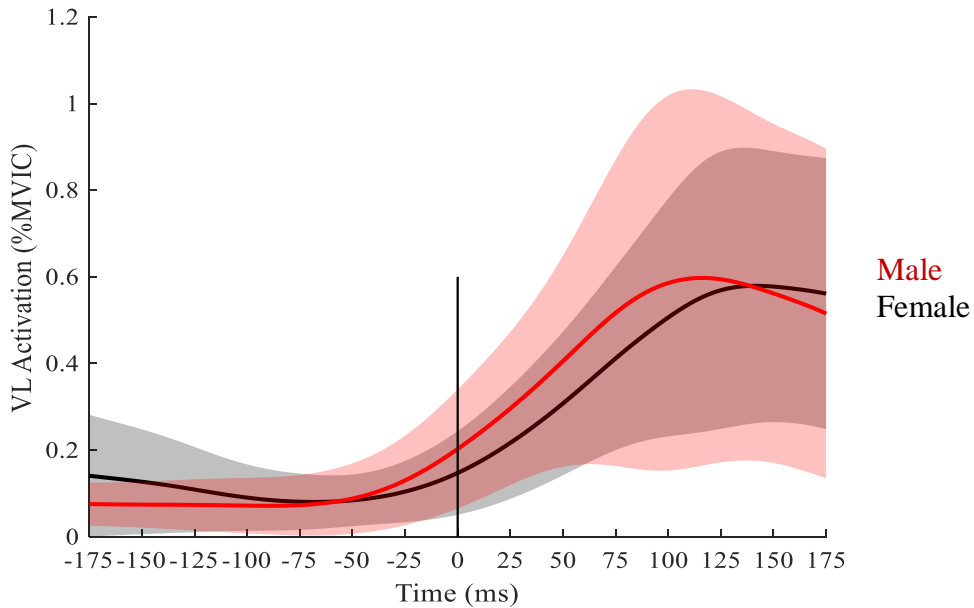


Figure 5.4. Male and female VL waveforms for MOT of the drop-jump landing. Zero value indicates the point of impact for the second landing.

Co-activation Indexes (Males vs. Females)

Greater Q-G co-activation was identified in female participants during 37-48% (male=0.16±0.1, female=0.41±0.24, $p=0.008$, $r=0.58$) of the *flight phase* of the drop-jump (Figure 5.5). No statistical differences for Q-H co-activation were identified. Normalized EMG waveforms for the muscles used to calculate the CIs are also shown (Figure 5.6).

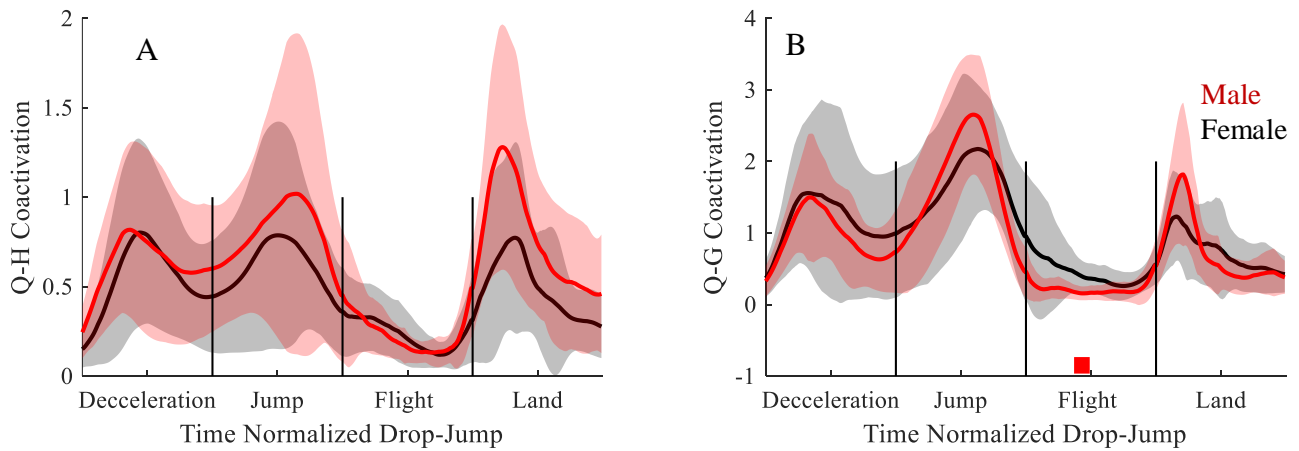


Figure 5.5. CI of the Q-H (A) and Q-G (B) during the drop-jump task. Positive values indicate increased co-activation. Black vertical lines separate the four time-normalized phases. Red horizontal bar indicates statistical significance between male and female participants.

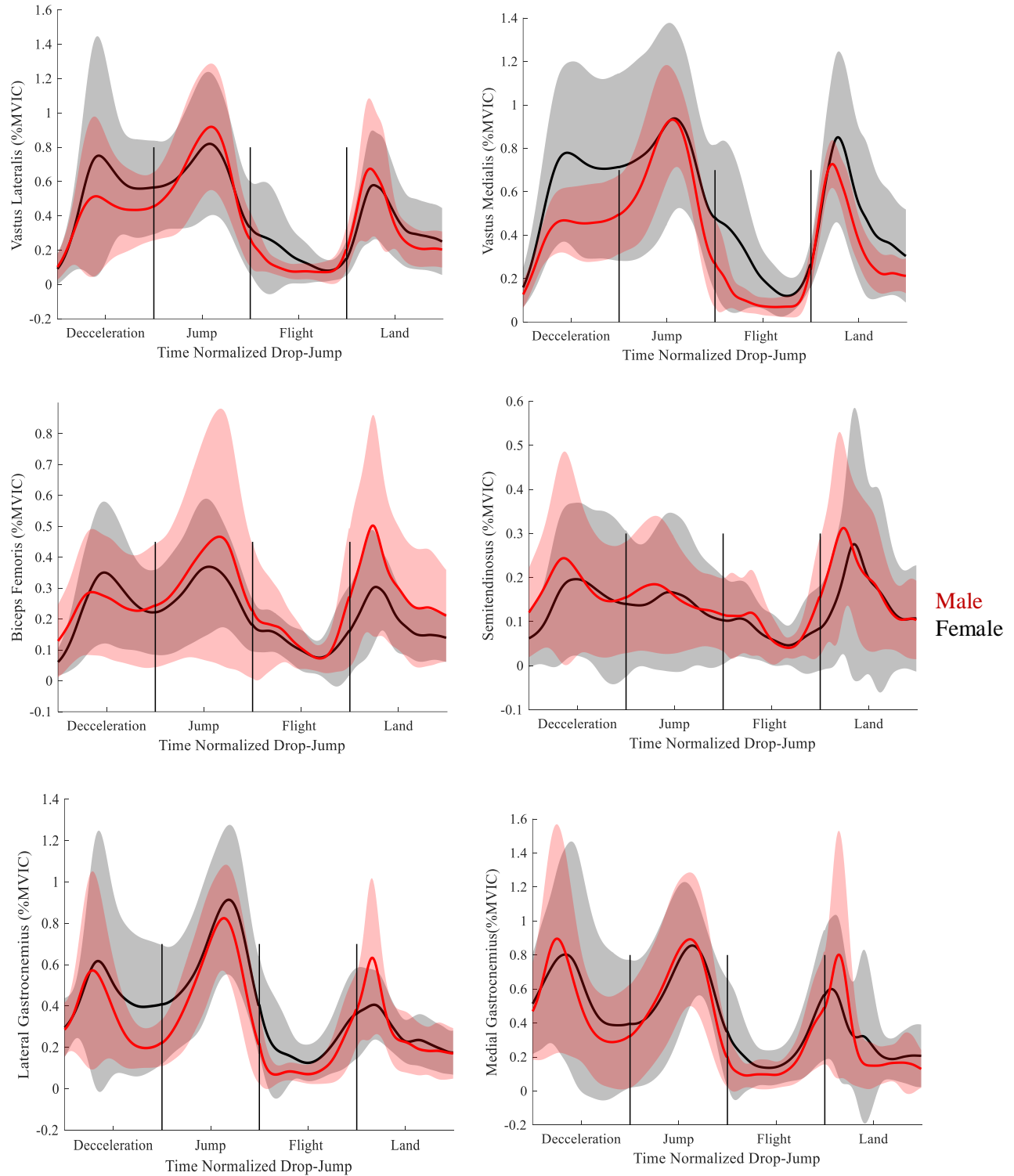


Figure 5.6. Time-normalized EMG waveforms for the VL (A), VM (B), BF (C), ST (D), LG (E), and MG (F) during the drop-jump task. Black vertical lines separate the four time-normalized phases.

Discussion

The purpose of this study was to examine neuromuscular and biomechanical characteristics in young male and female athletes during a task which simulated a sport-like scenario. Contrary to previous research looking at unanticipated movements in youth athletes (Ford et al., 2005; Sell et al., 2005), no statistically significant kinematic differences were identified between males and females at the hip and knee joint. This is likely a product of restrictions put on the single-leg landing task. Previous research looking at unanticipated movements had participants either perform a jump (Sell et al., 2005) or a side-cut (Ford et al., 2005) following the onset of the visual cue. In this study, rather than perform an additional movement, the participants were required to alter their landing leg (i.e. the visual cue signalled landing leg as opposed to movement direction). By requiring participants to ‘stick’ the landing and excluding trials where participants performed additional movements to regain their balance (ex. contralateral foot touches the ground), the variability between jumps was systematically minimized.

The female participants did, however, land with less trunk flexion during the drop-jump *deceleration, flight, and landing phase* when compared to their male counterparts. To prevent musculoskeletal injury during jump landings, the neuromuscular system must safely dissipate the loading of the passive tissues surrounding the knee (Devita & Skelly, 1992). The trunk, hip and knee joints are major contributors for absorbing the kinetic energy of landing (Decker, Torry, Wyland, Sterett, & Richard Steadman, 2003; Zhang, Bates, & Dufek, 2000). Through the eccentric contraction of the associated musculature, landing forces can be safely dissipated across multiple joints in the kinetic chain (Mizrahi & Susak, 1982). Furthermore, during a jump landing, the body’s CoM must be decelerated and stabilized as it travels in a downward direction

(Wikstrom et al., 2007). The increased trunk flexion observed in males could be a strategy to help decelerate the CoM, since greater trunk flexion angles are associated with reduced impact forces during landing (Blackburn & Padua, 2009). However, as the trunk is moved into a flexed position, the CoM moves farther from the base of support, increasing the reliance on the eccentric contraction of hip extensors to maintain an upright position. This is also consistent with the lower hip flexion moments observed in females. In this context, joint moments represented the external loads applied at each joint (i.e. hip flexion moment is an external load that moved the hip into a flexed posture). A lower forward trunk lean would move the GRF vector posteriorly, decreasing the demand on the hip extensors, and lowering the recorded hip flexion moment. This is consistent with previous research demonstrating a more erect landing posture in females (Schmitz, Kulas, Perrin, Riemann, & Shultz, 2007) and a reduced reliance on the hip extensors for force absorption (Decker et al., 2003; Pollard, Sigward, & Powers, 2010). Thus, the lower trunk flexion angle and hip flexion moment could reflect a compensatory strategy for hip extensor weakness, where the CoM is maintained over the base of support. Similarly, lower knee flexion moments were observed in females when compared to males during the *landing phase*. Thus, these findings indicate that females land in a more erect posture through their trunk, hip and knee, and may therefore, be less effective at dissipating landing forces (Blackburn & Padua, 2009; Schmitz et al., 2007; Yeow, Lee, & Goh, 2011; Zhang et al., 2000).

Despite male and female participants performing the unanticipated landing with similar hip and knee kinematics, different muscle activation patterns were employed to achieve the joint motions. Greater co-activation of the quadriceps and gastrocnemius muscles were observed during the *flight phase* of the drop-jump landing in females. The employed measure for calculating muscle co-activation combined the relative activation of the quadriceps and

gastrocnemius muscles (ratio) and multiplied it by the sum of the magnitudes. This method characterizes the co-activation that could result in higher joint compressive forces (Lewek et al., 2005). The concurrent activation of muscles crossing the knee joint has been suggested as strategy for increasing joint stiffness (Lewek et al., 2005) and resisting frontal plane loads (Lloyd & Buchanan, 2001). The greater co-activation of the Q-G is also similar to the larger Q-H co-activation observed when an unanticipated lateral jump was performed in youth athletes (Sell et al., 2005). Although the direct cause of the co-activation strategy employed by females can not be demonstrated in this study, previous research has suggested that females may possess inherently greater joint laxity than their male counterparts (Hicks, Onambele-Pearson, Winwood, & Morse, 2013; Wang, De Vito, Ditroilo, Fong, & Delahunt, 2015). These findings may reflect a compensatory mechanism to increase joint stiffness and functional stabilization through increased joint compression when preparing to land. It is also important to note that females have a strength deficit compared to males, as indicated by our findings (Table A.4) and previous research (McKay et al., 2017). If there is inadequate muscular strength to overcome the GRFs and momentum of the body during landing, then compensatory muscle activation strategies must be employed. Increased co-activation during the *flight phase* of the drop-jump landing could reflect a strategy to increase functional stability while reducing the demand on individual joint actuators. However, given that sex-related differences in neuromuscular responses are frequently cited as a potential mechanism of ACL injury (Flaxman, Speirs, & Benoit, 2012; Krishnan & Williams, 2009; Landry et al., 2009; Sigward & Powers, 2006), these compensatory strategies may also increase the risk for sustaining an ACL injury. Specifically, the simultaneous activation of quadriceps and gastrocnemius significantly increased *in-vivo* ACL strain compared to isolated contractions (Fleming et al., 2001).

Finally, delayed MOT was identified in the VL of female participants. Although statistical significance was not identified in the remaining muscles, based on the descriptive statistics males had longer mean MOT in eight of the nine recorded muscles. The delayed MOT in females is different to previous findings comparing sex-differences in MOT during unanticipated movements, which found longer MOT of the hamstring muscles in females (Beaulieu et al., 2009; Landry et al., 2009). A longer pre-activation of the VL indicates that males are more effective at responding to the visual cue and preparing their muscles prior to landing. Considering that to properly stabilize the knee joint, muscle activation must occur with sufficient time for adequate force contribution during the movement, and that longer rates of force development have been observed in females (Bell & Jacobs, 1986; Häkkinen & Häkkinen, 1991; Huston & Wojtys, 1996; Komi & Karlsson, 1978; Winter & Brookes, 1991), these findings suggest that females may not sufficiently dissipate external moments during dynamic movements. In addition, previous studies have identified that females are less effective at force absorption during a single-leg landing (Schmitz et al., 2007). A delayed MOT suggest that females are less effective at preparing for the unanticipated landing and are therefore less effective at dissipating impact forces.

It should also be noted that knee joint mechanics are governed by a combination of sex-dependent geometry, laxity, and tissue factors (Arendt, Bershadsky, & Agel, 2002; Faber et al., 2001; Fung & Zhang, 2003; LaPrade & Burnett, 1994; Shultz, Sander, Kirk, & Perrin, 2005). Although this manuscript focused on sex-specific landing strategies, with female movement patterns interpreted as “riskier,” these patterns may reflect a compensatory mechanism to accommodate the differing joint anatomy. In this case, simply training females to adjust to a male-based movement strategy would be problematic. It is possible that the ‘ideal’ movement

strategy is entirely sex-dependent, with different criteria depending on anatomical and physiological considerations.

Limitations

Although this study implemented a sport relevant component, the unanticipated stimulus is not entirely consistent with the random movement demands of sport participation. Despite the inclusion of a randomized unanticipated task, participants were only required to react to one of three stimuli, each being predefined. Within sport activities, however, there are multiple random stimuli with multiple corresponding movement requirements. Also, given their training and physical activity history, the athletes recruited for this study may have different neuromuscular activation patterns than a sedentary or non-athletic population. When considering our calculation of CIs, some authors have cautioned against using MVICs to normalize muscle activation (Clarys, 2000). Muscle activation levels greater than 100% of the MVIC have been reported during various sporting activities when using this technique (Clarys, 2000). Despite this limitation, an MIVCs normalization protocol was deemed most appropriate for this study (Burden, 2010). Additionally, female participants may have a strength deficit compared to males (McKay et al., 2017). As such, a higher level of normalized EMG cannot be directly linked to higher force generation from that muscle, since a weaker individual would require more activation to generate the same level of force.

Conclusion

This study is the first to date to provide a complete kinematic and neuromuscular analysis of an unanticipated movement in youth athletes (13-18 yrs.). Reduced trunk flexion and lower hip flexion and knee flexion moments indicate that females land in a more erect posture through their trunk, hip and knee during landing. This may be a critical finding given that reduced trunk

control (Zazulak, Hewett, Reeves, Goldberg, & Cholewicki, 2007) and hip strength (Khayambashi, Ghoddosi, Straub, & Powers, 2016) predict ACL injury. Thus, intervention programs aimed at improving landing position in females may benefit from targeting hip and trunk mechanics. Immediately prior to landing from the drop-jump females had greater co-activation of their quadriceps and gastrocnemius muscles compared to males. This could indicate a compensatory strategy to increase joint compressive forces, and therefore functional knee stability. Increased strength through the lower-limb musculature may reduce the reliance on quadriceps-gastrocnemius co-activation patterns in females. Males tended to activate their muscle sooner (i.e. for a longer duration), prior to landing the drop-jump. This indicated that males had a greater ability to prepare for the unanticipated landing, when compared to females, and may be more effective at dissipating impact forces during the landing.

Acknowledgments

The authors would like to thank Lisa Ek Orloff, Saskia Hanssen, Laura Boonstra and Céline Girard for their contributions in data collections. They would also like to thank the Ontario Graduate Scholarship, Natural Sciences and Engineering Research Council of Canada and the University of Ottawa for their support in the form of student and operating grants.

Conflict of Interest

The authors have no professional relationships that stand to gain from the current study. The results of the present study are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation.

References

- Agel, J., & Klossner, D. (2014). Epidemiological Review of Collegiate ACL Injury Rates Across 14 Sports: National Collegiate Athletic Association Injury Surveillance System Data 2004-05 Through 2011. *British Journal of Sports Medicine*, *48*(7), 560.2-560.
- Agel, J., Rockwood, T., & Klossner, D. (2016). Collegiate ACL Injury Rates Across 15 Sports. *Clinical Journal of Sport Medicine*, *26*(6), 518–523.
- Arendt, E. A., Bershadsky, B., & Agel, J. (2002). Periodicity of noncontact anterior cruciate ligament injuries during the menstrual cycle. *The Journal of Gender-Specific Medicine : JGSM : The Official Journal of the Partnership for Women's Health at Columbia*, *5*(2), 19–26.
- Beaulieu, M. L., Lamontagne, M., & Beaulé, P. E. (2010). Lower limb biomechanics during gait do not return to normal following total hip arthroplasty. *Gait and Posture*.
- Beaulieu, M. L., Lamontagne, M., & Xu, L. (2009). Lower limb muscle activity and kinematics of an unanticipated cutting manoeuvre: a gender comparison. *Knee Surgery, Sports Traumatology, Arthroscopy*, *17*(8), 968–976.
- Beck, N., Lawrence, J., Nordin, J., DeFor, T., & Tompkins, M. (2015). ACL Tears in School-Aged Children and Adolescents: Has There Been an Increased Incidence over the Last 20 Years? In *AAP National Conference and Exhibition*. American Academy of Pediatrics.
- Bell, D. G., & Jacobs, I. (1986). Electro-mechanical response times and rate of force development in males and females. *Medicine and Science in Sports and Exercise*, *18*(1), 31–36.
- Benjamini, Y., & Hochberg, Y. (1995). *Controlling the False Discovery Rate: A Practical and Powerful Approach to Multiple*. Source: *Journal of the Royal Statistical Society. Series B*

(*Methodological*) (Vol. 57).

- Bezodis, N. E., Salo, A. I. T., & Trewartha, G. (2013). Excessive fluctuations in knee joint moments during early stance in sprinting are caused by digital filtering procedures. *Gait & Posture, 38*(4), 653–657.
- Bisseling, R. W., & Hof, A. L. (2006). Handling of impact forces in inverse dynamics. *Journal of Biomechanics, 39*(13), 2438–2444.
- Blackburn, J. T., & Padua, D. A. (2009). Sagittal-Plane Trunk Position, Landing Forces, and Quadriceps Electromyographic Activity. *Journal of Athletic Training, 44*(2), 174–179.
- Boden, B. P., Dean, G. S., Feagin, J. A., & Garrett, W. E. (2000). Mechanisms of anterior cruciate ligament injury. *Orthopedics, 23*(6), 573–578.
- Borotikar, B. S., Newcomer, R., Koppes, R., & McLean, S. G. (2008). Combined effects of fatigue and decision making on female lower limb landing postures: Central and peripheral contributions to ACL injury risk. *Clinical Biomechanics, 23*(1), 81–92.
- Brown, T. N., Palmieri-Smith, R. M., & McLean, S. G. (2009). Sex and limb differences in hip and knee kinematics and kinetics during anticipated and unanticipated jump landings: implications for anterior cruciate ligament injury. *British Journal of Sports Medicine, 43*(13), 1049–1056.
- Burden, A. (2010). How should we normalize electromyograms obtained from healthy participants? What we have learned from over 25 years of research. *Journal of Electromyography and Kinesiology, 20*(6), 1023–1035.
- Clarys, J. P. (2000). Electromyography in sports and occupational settings: an update of its limits and possibilities. *Ergonomics, 43*(10), 1750–1762.
- Cowley, H. R., Ford, K. R., Myer, G. D., Kernozek, T. W., & Hewett, T. E. (2006). Differences

- in neuromuscular strategies between landing and cutting tasks in female basketball and soccer athletes. *Journal of Athletic Training*, 41(1), 67–73.
- De Luca, C. J. (1993). The Use of Surface Electromyography in Biomechanics. *Journal of Applied Biomechanics*, 13(2), 135–163.
- Decker, M. J., Torry, M. R., Wyland, D. J., Sterett, W. I., & Richard Steadman, J. (2003). Gender differences in lower extremity kinematics, kinetics and energy absorption during landing. *Clinical Biomechanics*, 18(7), 662–669.
- Devita, P., & Skelly, W. A. (1992). *Effect of landing stiffness on joint kinetics and energetics in the lower extremity. Medicine & Science in Sports & Exercise* (Vol. 24).
- Elias, L. J., Brydent, M. P., & Bulman-Fleming, M. B. (1998). *Footedness is a better predictor than is handedness of emotional lateralization. Neuropsychologia* (Vol. 36).
- Faber, S. C., Eckstein, F., Lukasz, S., Mühlbauer, R., Hohe, J., Englmeier, K. H., & Reiser, M. (2001). Gender differences in knee joint cartilage thickness, volume and articular surface areas: assessment with quantitative three-dimensional MR imaging. *Skeletal Radiology*, 30(3), 144–150.
- Fabricant, P. D., Robles, A., Downey-Zayas, T., Do, H. T., Marx, R. G., Widmann, R. F., & Green, D. W. (2013). Development and Validation of a Pediatric Sports Activity Rating Scale. *The American Journal of Sports Medicine*, 41(10), 2421–2429.
- Flaxman, T. E., Speirs, A. D., & Benoit, D. L. (2012). Joint stabilisers or moment actuators: The role of knee joint muscles while weight-bearing. *Journal of Biomechanics*, 45(15), 2570–2576.
- Fleming, B. C., Renstrom, P. A., Beynonn, B. D., Engstrom, B., Peura, G. D., Badger, G. J., & Johnson, R. J. (2001). The effect of weightbearing and external loading on anterior cruciate

- ligament strain. *Journal of Biomechanics*, 34(2), 163–170.
- Fong, D. T.-P., Lam, M.-H., Lai, P.-K., Yung, P. S.-H., Fung, K.-Y., & Chan, K.-M. (2014). Effect of anticipation on knee kinematics during a stop-jump task. *Gait & Posture*, 39(1), 75–79.
- Ford, K. R., Myer, G. D., Toms, H. E., & Hewett, T. E. (2005). Gender differences in the kinematics of unanticipated cutting in young athletes. *Medicine and Science in Sports and Exercise*, 37(1), 124–129.
- Fung, D. T., & Zhang, L.-Q. (2003). Modeling of ACL impingement against the intercondylar notch. *Clinical Biomechanics (Bristol, Avon)*, 18(10), 933–941.
- Gornitzky, A. L., Lott, A., Yellin, J. L., Fabricant, P. D., Lawrence, J. T., & Ganley, T. J. (2016). Sport-Specific Yearly Risk and Incidence of Anterior Cruciate Ligament Tears in High School Athletes: A Systematic Review and Meta-analysis. *The American Journal of Sports Medicine*, 44(10), 2716–2723.
- Häkkinen, K., & Häkkinen, A. (1991). Muscle cross-sectional area, force production and relaxation characteristics in women at different ages. *European Journal of Applied Physiology and Occupational Physiology*, 62(6), 410–414.
- Hermens, H. J., Freriks, B., Merletti, R., Stegeman, D., Blok, J., Rau, G., ... Hägg, G. (1999). European Recommendations for Surface ElectroMyoGraphy Results of the SENIAM project. *Roessingh Research and Development*, 8(2), 13–54.
- Herzog, M. M., Marshall, S. W., Lund, J. L., Pate, V., Mack, C. D., & Spang, J. T. (2017). Incidence of Anterior Cruciate Ligament Reconstruction Among Adolescent Females in the United States, 2002 Through 2014. *JAMA Pediatrics*, 171(8), 808.
- Hewett, T., Myer, G. D., Ford, K. R., Heidt, R. S., Colosimo, A. J., McLean, S. G., ... Succop, P.

- (2005). Biomechanical Measures of Neuromuscular Control and Valgus Loading of the Knee Predict Anterior Cruciate Ligament Injury Risk in Female Athletes: A Prospective Study. *American Journal of Sports Medicine*, 33(4), 492–501.
- Hicks, K. M., Onambele-Pearson, G. L., Winwood, K., & Morse, C. I. (2013). Gender differences in fascicular lengthening during eccentric contractions: the role of the patella tendon stiffness. *Acta Physiologica*, 209(3).
- Houck, J. R., Duncan, A., & Haven, K. E. De. (2006). Comparison of frontal plane trunk kinematics and hip and knee moments during anticipated and unanticipated walking and side step cutting tasks. *Gait & Posture*, 24(3), 314–322.
- Huston, L. J., & Wojtys, E. M. (1996). Neuromuscular Performance Characteristics in Elite Female Athletes. *The American Journal of Sports Medicine*, 24(4), 427–436.
- Joseph, A. M., Collins, C. L., Henke, N. M., Yard, E. E., Fields, S. K., & Comstock, R. D. (2013). A Multisport Epidemiologic Comparison of Anterior Cruciate Ligament Injuries in High School Athletics. *Journal of Athletic Training*, 48(6), 810–817.
- Khayambashi, K., Ghoddosi, N., Straub, R. K., & Powers, C. M. (2016). Hip Muscle Strength Predicts Noncontact Anterior Cruciate Ligament Injury in Male and Female Athletes. *The American Journal of Sports Medicine*, 44(2), 355–361.
- Kim, J. H., Lee, K.-K., Kong, S. J., An, K. O., Jeong, J. H., & Lee, Y. S. (2014). Effect of Anticipation on Lower Extremity Biomechanics During Side- and Cross-Cutting Maneuvers in Young Soccer Players. *The American Journal of Sports Medicine*, 42(8), 1985–1992.
- Kipp, K., Brown, T. N., McLean, S. G., & Palmieri-Smith, R. M. (2013). Decision making and experience level influence frontal plane knee joint biomechanics during a cutting maneuver. *Journal of Applied Biomechanics*, 29(6), 756–762.

- Koga, H., Nakamae, A., Shima, Y., Iwasa, J., Myklebust, G., Engebretsen, L., ... Krosshaug, T. (2010). Mechanisms for Noncontact Anterior Cruciate Ligament Injuries: Knee Joint Kinematics in 10 Injury Situations From Female Team Handball and Basketball. *The American Journal of Sports Medicine*, 38(11), 2218–2225.
- Komi, P. V., & Karlsson, J. (1978). Skeletal muscle fibre types, enzyme activities and physical performance in young males and females. *Acta Physiologica Scandinavica*, 103(2), 210–218.
- Krishnan, C., & Williams, G. N. (2009). Sex differences in quadriceps and hamstrings EMG-moment relationships. *Medicine and Science in Sports and Exercise*, 41(8), 1652–1660.
- Kristianslund, E., Krosshaug, T., & van den Bogert, A. J. (2012). Effect of low pass filtering on joint moments from inverse dynamics: Implications for injury prevention. *Journal of Biomechanics*, 45(4), 666–671.
- Landry, S. C., McKean, K. A., Hubley-Kozey, C. L., Stanish, W. D., & Deluzio, K. J. (2009). Gender differences exist in neuromuscular control patterns during the pre-contact and early stance phase of an unanticipated side-cut and cross-cut maneuver in 15–18 years old adolescent soccer players. *Journal of Electromyography and Kinesiology*, 19(5), e370–e379.
- LaPrade, R. F., & Burnett, Q. M. (1994). Femoral Intercondylar Notch Stenosis and Correlation to Anterior Cruciate Ligament Injuries. *The American Journal of Sports Medicine*, 22(2), 198–203.
- Lewek, M. D., Ramsey, D. K., Snyder-Mackler, L., & Rudolph, K. S. (2005). Knee stabilization in patients with medial compartment knee osteoarthritis. *Arthritis & Rheumatism*, 52(9), 2845–2853.

- Lloyd, D. G., & Buchanan, T. S. (2001). Strategies of muscular support of varus and valgus isometric loads at the human knee. *Journal of Biomechanics*, *34*(10), 1257–1267.
- Majewski, M., Susanne, H., & Klaus, S. (2006). Epidemiology of athletic knee injuries: A 10-year study. *The Knee*, *13*(3), 184–188.
- Malloy, P. J., Morgan, A. M., Meinerz, C. M., Geiser, C. F., & Kipp, K. (2016). Hip External Rotator Strength Is Associated With Better Dynamic Control of the Lower Extremity During Landing Tasks. *Journal of Strength and Conditioning Research*, *30*(1), 282–291.
- Mandelbaum, B. R., Silvers, H. J., Watanabe, D. S., Knarr, J. F., Thomas, S. D., Griffin, L. Y., ... Garrett, W. (2005). Effectiveness of a Neuromuscular and Proprioceptive Training Program in Preventing Anterior Cruciate Ligament Injuries in Female Athletes: 2-Year Follow-up. *American Journal of Sports Medicine*, *33*(7), 1003–1010.
- Mantovani, G., & Lamontagne, M. (2017). How Different Marker Sets Affect Joint Angles in Inverse Kinematics Framework. *Journal of Biomechanical Engineering*, *139*(4), 044503.
- McKay, M. J., Baldwin, J. N., Ferreira, P., Simic, M., Vanicek, N., Burns, J., & 1000 Norms Project Consortium. (2017). Normative reference values for strength and flexibility of 1,000 children and adults. *Neurology*, *88*(1), 36–43.
- McLean, S. G., Borotikar, B., & Lucey, S. M. (2010). Lower limb muscle pre-motor time measures during a choice reaction task associate with knee abduction loads during dynamic single leg landings. *Clinical Biomechanics*, *25*(6), 563–569.
- Mclena, S. G., & Samorezov, J. E. (2009). Fatigue-Induced ACL Injury Risk Stems from a Degradation in Central Control. *Medicine & Science in Sports & Exercise*, *41*(8), 1662–1673.
- Mizrahi, J., & Susak, Z. (1982). Analysis of Parameters Affecting Impact Force Attenuation

- during Landing in Human Vertical Free Fall. *Engineering in Medicine*, 11(3), 141–147.
- Mornieux, G., Gehring, D., Fürst, P., & Gollhofer, A. (2014). Anticipatory postural adjustments during cutting manoeuvres in football and their consequences for knee injury risk. *Journal of Sports Sciences*, 32(13), 1255–1262.
- Myer, G. D., Ford, K. R., & Hewett, T. E. (2004). Methodological approaches and rationale for training to prevent anterior cruciate ligament injuries in female athletes. *Scandinavian Journal of Medicine and Science in Sports*, 14(5), 275–285.
- Myer, G. D., Ford, K. R., & Hewett, T. E. (2005). The effects of gender on quadriceps muscle activation strategies during a maneuver that mimics a high ACL injury risk position. *Journal of Electromyography and Kinesiology*, 15(2), 181–189.
- Olsen, O.-E., Myklebust, G., Engebretsen, L., & Bahr, R. (2004). Injury Mechanisms for Anterior Cruciate Ligament Injuries in Team Handball: A Systematic Video Analysis. *American Journal of Sports Medicine*, 32(4), 1002–1012.
- Örtqvist, M., Roos, E. M., Broström, E. W., Janarv, P.-M., & Iversen, M. D. (2012). Development of the Knee Injury and Osteoarthritis Outcome Score for Children (KOOS-Child). *Acta Orthopaedica*, 83(6), 666–673.
- P.W. Hodges, B. H. B. (1996). A comparison of computer-based methods for the determination of onset of muscle contraction using electromyography. *Electroencephalography and Clinical Neurophysiology/Electromyography and Motor Control*, 101(6), 511–519.
- Pollard, C. D., Sigward, S. M., & Powers, C. M. (2010). Limited hip and knee flexion during landing is associated with increased frontal plane knee motion and moments. *Clinical Biomechanics*, 25(2), 142–146.
- Rudolph, K. S., Axe, M. J., Buchanan, T. S., Scholz, J. P., & Snyder-Mackler, L. (2001).

- Dynamic stability in the anterior cruciate ligament deficient knee. *Knee Surgery, Sports Traumatology, Arthroscopy*, 9(2), 62–71.
- Sale, D., Quinlan, J., Marsh, E., McComas, A. J., & Belanger, A. Y. (1982). Influence of joint position on ankle plantarflexion in humans. *Journal of Applied Physiology: Respiratory, Environmental and Exercise Physiology*, 52(6), 1636–1642.
- Schmitz, R. J., Kulas, A. S., Perrin, D. H., Riemann, B. L., & Shultz, S. J. (2007). Sex differences in lower extremity biomechanics during single leg landings. *Clinical Biomechanics*, 22(6), 681–688.
- Sell, Ferris, C. M., Abt, J. P., Tsai, Y.-S., Myers, J. B., Fu, F. H., & Lephart, S. M. (2005). The Effect of Direction and Reaction on the Neuromuscular and Biomechanical Characteristics of the Knee During Tasks That Simulate the Noncontact Anterior Cruciate Ligament Injury Mechanism. *American Journal of Sports Medicine*, 34(1), 43–54.
- Shin, C. S., Chaudhari, A. M., & Andriacchi, T. P. (2009). The effect of isolated valgus moments on ACL strain during single-leg landing: A simulation study. *Journal of Biomechanics*, 42(3), 280–285.
- Shin, C. S., Chaudhari, A. M., & Andriacchi, T. P. (2011). Valgus Plus Internal Rotation Moments Increase Anterior Cruciate Ligament Strain More Than Either Alone. *Medicine & Science in Sports & Exercise*, 43(8), 1484–1491.
- Shultz, S. J., Sander, T. C., Kirk, S. E., & Perrin, D. H. (2005). Sex differences in knee joint laxity change across the female menstrual cycle. *The Journal of Sports Medicine and Physical Fitness*, 45(4), 594–603.
- Sigward, S., & Powers, C. M. (2006). The influence of experience on knee mechanics during side-step cutting in females. *Clinical Biomechanics*, 21(7), 740–747.

- Swenson, D. M., Collins, C. L., Best, T. M., Flanigan, D. C., Fields, S. K., & Comstock, R. D. (2013). Epidemiology of knee injuries among U.S. high school athletes, 2005/2006-2010/2011. *Medicine and Science in Sports and Exercise*, *45*(3), 462–469.
- Taylor, S. J., Whincup, P. H., Hindmarsh, P. C., Lampe, F., Odoki, K., & Cook, D. G. (2001). Performance of a new pubertal self-assessment questionnaire: a preliminary study. *Paediatric and Perinatal Epidemiology*, *15*(1), 88–94.
- Wang, D., De Vito, G., Ditroilo, M., Fong, D. T. P., & Delahunt, E. (2015). A comparison of muscle stiffness and musculoarticular stiffness of the knee joint in young athletic males and females.
- Werner, B. C., Yang, S., Looney, A. M., & Gwathmey, F. W. (2016). Trends in Pediatric and Adolescent Anterior Cruciate Ligament Injury and Reconstruction. *Journal of Pediatric Orthopaedics*, *36*(5), 447–452.
- Wikstrom, Tillman, M. D., Schenker, S., & Borsa, P. A. (2007). Failed jump landing trials: deficits in neuromuscular control. *Scandinavian Journal of Medicine & Science in Sports*, *18*(1), 55–61.
- Winter, D. A. (2009). *Biomechanics and motor control of human movement*. Wiley.
- Winter, E. M., & Brookes, F. B. C. (1991). Electromechanical response times and muscle elasticity in men and women. *Eur J Appl Physiol Eump~n ,Ou...o, Applied Physiology and Occupational Physiology*, *63*, 124–128.
- Yeow, C. H., Lee, P. V. S., & Goh, J. C. H. (2011). An investigation of lower extremity energy dissipation strategies during single-leg and double-leg landing based on sagittal and frontal plane biomechanics. *Human Movement Science*, *30*(3), 624–635.
- Zazulak, B. T., Hewett, T. E., Reeves, N. P., Goldberg, B., & Cholewicki, J. (2007). Deficits in

Neuromuscular Control of the Trunk Predict Knee Injury Risk. *The American Journal of Sports Medicine*, 35(7), 1123–1130.

Zhang, S. N., Bates, B. T., & Dufek, J. S. (2000). Contributions of lower extremity joints to energy dissipation during landings. *Medicine and Science in Sports and Exercise*, 32(4), 812–819.

CHAPTER 6: MANUSCRIPT 2
(preliminary results)

Kinematic and neuromuscular predictors of successful drop-jump landings

Nicholas J. Romanchuk¹, Daniel L. Benoit^{1,2}

¹School of Human Kinetics, University of Ottawa, Canada

²School of Rehabilitation, University of Ottawa, Canada

Abstract

Purpose: The purpose of this study was *i)* to describe the neuromuscular and kinematic differences during the preparatory phase of failed and successful landings, and *ii)* to determine which neuromuscular and kinematic variables are the best predictors for a successful landing.

Methods: Thirty-two health youth (13-18 yrs.) athletes completed unanticipated single-leg drop-jump landings on their dominant limb. Participants were required to stick and hold the landing. Trials during which participants shifted foot position to regain balance or touched the ground with the contralateral leg were categorized as failed. Wilcoxon signed-rank tests and paired sample *t*-tests compared lower-limb kinematics, centre-of-mass excursion and muscle activation amplitudes during the preparatory (*flight*) phase of the drop-jump. A logistic regression model was fit using best variable selection and leave-one-out cross-validation to predict the likelihood of a successful landing.

Results: Greater hip abduction (success: $5.1 \pm 3.88^\circ$; failed: $3.88 \pm 4.02^\circ$; $p=0.004$; $d=0.3$) and less external rotation (success: $6.84 \pm 7.38^\circ$; failed: $8.35 \pm 8.13^\circ$; $p=0.005$; $d=0.19$) angles were observed during the successful landings. In addition, greater preparatory muscle activation was observed in the rectus femoris (success: 14.5 ± 9.1 %MVIC; failed: 16.2 ± 9.88 %MVIC; $p=0.029$; $r=0.33$) and semitendinosus (success: 8.89 ± 6.64 %MVIC, failed: 11.9 ± 11.2 %MVIC, $p=0.001$ $r=0.55$) during the flight phase of the failed landings. An eight variable model including knee flexion, knee abduction, hip flexion, hip abduction, hip internal rotation, centre-of-mass excursion, rectus femoris preparatory muscle activation and vastus lateralis preparatory muscle activation. The model had a training classification accuracy of 70% and a leave-one-out cross-validation accuracy of 65%.

Conclusion: Hip kinematics and the surrounding musculature play an important role in controlling successful and failed unanticipated landings. In addition, a moderate classification accuracy for successful landings can be made using eight neuromuscular and kinematic variables from the preparatory phase of a jump landing.

Introduction

Research indicates that the majority of anterior cruciate ligament (ACL) injuries, occur during non-contact movements, such as the landing phase of a jump (Boden et al., 2000; Koga et al., 2010; Olsen et al., 2004). These movements typically follow a reaction to an external stimulus (ex. avoiding an opposing player) and are therefore unanticipated in nature. Jump landings are a commonly cited mechanism of ACL injury, with an estimated 60-88% of basketball players and 25-43% of soccer players injured while jumping (Gray et al., 1985). Although extensive research has investigated biomechanical links between jump landings and injury risk (Chappell et al., 2007; Hewett et al., 2005), limited research has investigated the potential difference between successful and failed jump landings (falling, losing balance etc.). Failed trials are generally discarded following data collection, to reduce variability and improve reliability; however, significant clinical findings may be elucidated from these trials. It has been suggested that failed landings possess similar biomechanical characteristics to landings which result in injury (Wikstrom, Tillman, Schenker, & Borsa, 2007).

To date, only one study has compared the differences between successful and failed unanticipated landings (Wikstrom et al., 2007). This study identified earlier muscle onset times (MOT) in the vastus medialis, semimembranosus, lateral gastrocnemius and tibialis anterior as well as greater preparatory activation amplitude in the vastus medialis, semimembranosus, and lateral gastrocnemius during the successful jump landings (Wikstrom et al., 2007). Given the short time participants have to react during unanticipated tasks, preparatory muscle activity activation is believed to play a much larger role in maintaining dynamic joint stability than the reactive activity (Wikstrom, Tillman, Chmielewski, & Borsa, 2006). Greater preparatory muscle activation around the knee joint could be reflective of a strategy to increase joint stability during

dynamic movements (Besier, Lloyd, & Ackland, 2003; Flaxman, Speirs, & Benoit, 2012; McKinley & Pedotti, 1992). By increasing compressive loads at the knee joint, increased muscular stiffness could provide greater joint stability and protection against joint injury (Riemann & Lephart, 2002).

Although muscle activation appears to be an important factor related to failed and successful landings, the contributions of joint kinematics have not been investigated. Alterations in whole-body kinematics during dynamic movements, especially at initial contact, can have a large influence on knee loading and stability (Chaudhari & Andriacchi, 2006; Chaudhari, Hearn, & Andriacchi, 2005; Dempsey, Lloyd, Elliott, Steele, & Munro, 2009; Donnelly et al., 2012; McLean, Huang, & van den Bogert, 2005). Postural adjustments, such as alterations in trunk position, can shift the centre-of-mass (CoM) and reduce the potential for hazardous knee joint loading (Chaudhari & Andriacchi, 2006; Chaudhari et al., 2005; Dempsey et al., 2009; Donnelly et al., 2012; McLean et al., 2005). In fact, re-positioning the CoM medially, towards the desired change of direction, is a common strategy used by athletes during change-of-direction tasks (Patla, Adkin, & Ballard, 1999) and is one of the recommended techniques to reduce peak valgus knee moments during sidestep (Dempsey et al., 2009). Furthermore, hip mechanics can play an important role in force absorption during landing (Decker, Torry, Wyland, Sterett, & Richard Steadman, 2003), with reduced hip extensor moments leading to increased loading at the knee (Pollard, Sigward, & Powers, 2010). In addition, since the hip is the most proximal link in the lower extremity kinematic chain, it has the potential to affect the mechanics of the entire lower limb. Specifically, increased hip adduction moment is correlated with increased knee abduction moment and implicated in ACL injury (Hewett et al., 2005). Thus, analysing whole-body kinematics during failed landings could provide new finding regarding the mechanical

contributions to maintaining balance during high impact movements. The purpose of this study was two-fold i) to describe both neuromuscular and kinematic differences during the preparatory phase of failed and successful landings, and ii) to determine which neuromuscular and kinematic variables are the best predictors for a successful jump landing.

Methods

Participants

Thirty-two healthy male (n=16; age: 15.91±1.87 yrs; BMI: 21.11±2.66 kg/m²; Tanner Stage: 4.12±1.09) and female (n=16; age: 15.69±1.7 yrs; BMI: 21.1±2.9 kg/m²; Tanner Stage: 4.06±1.12) athletes were recruited from the Ottawa/Gatineau region (Table A.2). Each participant actively participated in organized sports at the time of testing, as assessed through the HSS Pedi-FABS activity level questionnaire (Fabricant et al., 2013). Participants had no history of previous traumatic knee injury (i.e. meniscal tear, ligament rupture), any recent injury to the lower extremity (previous six months), or any diseases that might affect neuromuscular function.

Procedure

All participants read and signed a consent form approved by the University of Ottawa Research Ethics Board (H09-17-10) and completed the following questionnaires; i) an assessment of sport exposure (HSS Pedi-FABS) (Fabricant et al., 2013), ii) a subjective assessment of knee joint function (Pedi-IKDC) (Kocher et al., 2011) iii) a pubescent-stage self-assessment form (Tanner Stage) (Taylor et al., 2001), and iv) Waterloo Footedness Questionnaire (Elias, Brydent, & Bulman-Fleming, 1998) (Table A.2).

Following the questionnaires, each participant completed a 5 min. warm-up on a cycle ergometer (Monark 828E, Vansbro, Sweden) with minimum resistance. Bipolar surface EMG electrodes (Trigno Standard; Trigno Mini, Delsys Inc., Boston, MA, USA) were then placed over

the muscle bellies and in line with the muscles fibers of the rectus femoris (RF), vastus lateralis (VL), vastus medialis (VM), biceps femoris (BF), semitendinosus (ST), lateral gastrocnemius (LG), medial gastrocnemius (MG), gluteus medius (GMed) and gluteus maximus (GMax) of the dominant limb according to recommendations of SENIAM (Hermens et al., 1999) and DeLuca (De Luca, 1993). Maximum voluntary isometric contractions (MVICs) were performed on a isokinetic dynamometer (System 4 Pro, Biodex Medical Systems, New York, USA) in the following positions; i) knee extension and flexion with the participant seated and the hip and knee joint held at 90° and 60° respectively (Beaulieu, Lamontagne, & Beaulé, 2010) ii) hip abduction with the participant standing and their hip and knee held at 180° and 0° respectively, iii) plantar flexion with the participants seated and their hip and knee flexed to 90° and 0° degrees respectively and the ankle held at -10° (Sale, Quinlan, Marsh, McComas, & Belanger, 1982). MVICs were repeated three times, with at least 1 min. of rest between each trial. To record full-body kinematics, 84 retroreflective markers (14 mm diameter) were placed on anatomical landmarks according to a hybrid cluster marker set (Figure A.1). Marker trajectories were sampled at 200 Hz using a 10-camera infrared motion analysis system (8 Vero; 2 Vantage, Vicon, Oxford, UK) and recorded using the supporting software (Nexus v2.7, Vicon, Oxford, UK). The supporting software was also used to synchronously collect ground reaction forces (GRF) from a force platform at 2000 Hz (FP4060-08, Bertec Corp., Columbus, OH, USA).

Drop-jumps consisted of: i) stepping off a raised platform, ii) landing with two feet on to an in-ground force platform, iii) immediately performing a maximal vertical jump, iv) landing back on the force platform with either left or right legs. The height of the platform was aligned to the tibial plateau of each participant and the platform was placed directly behind the force plate. Following the maximal vertical jump, the required landing leg was randomly signalled through a

visual cue displayed on a projector in front of the participant. The visual cue was displayed approximately 500 ms before the second landing. Based on previous research using similar unanticipated tasks, a 500 ms pre-land stimulus time was deemed adequate to elicit an unanticipated response (Brown, Palmieri-Smith, & McLean, 2009; Mornieux, Gehring, Fürst, & Gollhofer, 2014). Following each drop-jump, the landings were categorized as either ‘successful’ or ‘failed’. Trials were deemed successful if the participant landed with the designated leg and was able to ‘stick’ the landing (i.e. didn’t shift foot position to regain balance or touch the ground with the contralateral foot). A failed trial was defined as the loss of balance forcing a participant to either touch the ground with the contralateral foot or perform an additional hop(s) after landing (Wikstrom et al., 2007). Drop-jumps were performed until at least five successful trials had been recorded on the dominant limb.

Data Processing and Analysis

Trajectories were filtered using a 4th order zero-lag low-pass Butterworth filter with a cut-off frequency of 15 Hz. Filter order and cut-off frequency was chosen based on a residual analysis (Winter, 2009) and visual inspection of filter performance. Joint angles were then calculated using a modified University of Ottawa Motion Analysis Model (Mantovani & Lamontagne, 2017). The mass and CoM location for the head, trunk, upper arms, forearms, thighs, shanks, and foot were calculated using the body segment parameters from Zatsiorsky (Zatsiorsky, Seluyanov, & Chugunova, 1990), as modified by de Leva (de Leva, 1996). Whole-body CoM location was then calculated in each of the three axis as:

$$a_0 = \frac{m_1 a_1 + m_2 a_2 + m_3 a_3 \dots m_n a_n}{M} \quad (1)$$

where M is the participant's mass, m_l is the body segment mass, and a_l is the body segment CoM location in the 'a' axis (Winter, 2009). Whole-body CoM excursion was then calculated relative to CoM location at take-off (GRF < 10 N) and normalized to height.

To calculate EMG amplitude, raw EMG data was high-pass filtered at 20 Hz with a 2nd order dual-pass Butterworth filter, full-wave rectified, and low-pass filtered at 6 Hz with 2nd order dual-pass Butterworth filter. A 10 ms moving average algorithm identified maximum EMG amplitude for each muscle during the MVIC trials; these maximums were then used to normalize the drop-jump data. Hip, knee and ankle angles, as well as EMG amplitude were then averaged over the *flight phase* of the drop-jump (take-off (GRF < 10 N) until second landing (GRF > 10 N)).

Statistical Analysis

Identifying Kinematic and EMG Differences

EMG amplitude, knee, hip, ankle angles and CoM excursion were averaged over the successful and failed landings for each participant. Outliers were identified as exceeding 1.5 times the interquartile range and were further inspected to determine the appropriate treatment. Outliers that resulted from irreducible errors in the data collection process were excluded (ex. EMG electrodes losing contact with the skin). If an outlier reflected real and accurate data, it was included in the subsequent analysis. The assumption of normality was evaluated through a Shapiro-Wilk's test. If the assumption was rejected, then a Wilcoxon signed-rank test determined differences between successful and failed landings. If the assumption was not rejected, then paired-sample t -tests were used to identify differences between successful and failed landings. Effect size calculations were also performed for each statistical comparison. Statistical tests were

conducted in R (v3.03, The R Foundation, Vienna, Austria) with statistical significance set at $p < 0.05$.

Model Construction

A binomial logistic regression was then used to model the probability of a successful landing. Predictors were standardized to their respective Z scores. Best subset selection was then performed to select the optimal predictors for inclusion in the model (James, Witten, Hastie, & Tibshirani, 2013). To perform best subset selection, a separate logistic regression was fit for each possible combination of predictors ($pr = 20$) (James et al., 2013). Best was defined as having the smallest deviance, calculated as negative two times the maximized log-likelihood (James et al., 2013). Leave-one-out cross-validation (LOOCV) was used to calculate the average mean square error (MSE) between the model prediction and the excluded observation:

$$LOOCV_{(n)} = \frac{1}{n} \sum_{i=1}^n MSE_i \quad (2)$$

The model which balanced simplicity with error reduction (i.e. adding one more variable didn't offer a substantial reduction in MSE) was then chosen (James et al., 2013). Model accuracy was then assessed on all observations (training accuracy) by calculating a receiver operating characteristic (ROC) curve and determining the classification threshold which balanced model sensitivity and specificity (Metz, 1978). A confusion matrix was then calculated based on the misclassified observations (James et al., 2013). Similarly, model accuracy was assessed using LOOCV, such that the classification threshold which balanced sensitivity and specificity was calculated each time a model was fit on the $n - 1$ observations (Metz, 1978). Statistical significance for the logit of each predictor included in the final model and their respective odds ratios were calculated. All statistical analyses were conducted in R (v3.03, The R Foundation, Vienna, AUT) with statistical significance set at $p < 0.05$.

Results

Identifying Kinematic and EMG Differences

One female participant did not record any failed landings and was excluded from the subsequent analysis. Means and standard deviations, p -values, and effect sizes for each comparison can be seen in Table 6.1. Significantly larger hip abduction (success: $5.1 \pm 3.88^\circ$; failed: $3.88 \pm 4.02^\circ$; $p=0.004$; $d=0.3$) and lower external rotation (success: $6.84 \pm 7.38^\circ$; failed: $8.35 \pm 8.13^\circ$; $p=0.005$; $d=0.19$) angles were observed during *flight phase* of the successful landings (Table 6.1). In addition, greater preparatory muscle activation was observed in the RF (success: 14.5 ± 9.1 %MVIC; failed: 16.2 ± 9.88 %MVIC; $p=0.029$; $r=0.33$) and ST (success: 8.89 ± 6.64 %MVIC, failed: 11.9 ± 11.2 %MVIC, $p=0.001$ $r=0.55$) during the *flight phase* of the failed landings (Table 6.1).

Table 6.1

Kinematic and EMG variables during failed and successful landings, angles and EMG amplitudes were averaged over the flight phase

Variable	Success <i>Mean±SD</i>	Failed <i>Mean±SD</i>	<i>p</i> -value	Effect Size
Ankle Dorsiflexion (°)	-117±7.78	-117±7.67	0.58	<i>d</i> =0.053
Ankle Inversion (°)	6.25±5.72	6.49±5.57	0.38	<i>d</i> =0.041
Ankle Internal Rotation (°)	3.38±5.15	3.81±27.8	0.16	<i>r</i> =0.17
Knee Flexion (°)	9.95±11.1	11.9±9.93	0.09	<i>d</i> =0.18
Knee Abduction (°)	0.42±2.14	0.3±2.07	0.4	<i>r</i> =0.045
Knee External Rotation (°)	16.5±7.88	16.8±8.57	0.65	<i>r</i> =0.068
Hip Flexion (°)	19.5±11	20.3±10.2	0.15	<i>r</i> =0.19
Hip Abduction (°)	5.1±3.88	3.88±4.02	0.004*	<i>d</i> =0.3
Hip External Rotation (°)	6.84±7.38	8.35±8.13	0.005*	<i>d</i> =0.19
CoM Path (cm)	4.37±0.8	4.15±1.06	0.21	<i>d</i> =0.23
RF preparatory amplitude (%MVIC)	14.5±9.1	16.2±9.88	0.029*	<i>r</i> =0.33
VL preparatory amplitude (%MVIC)	14.3±12.4	13.7±8.46	0.76	<i>r</i> =0.13
VM preparatory amplitude (%MVIC)	25.4±35.9	30.2±58.9	0.39	<i>r</i> =0.05
BF preparatory amplitude (%MVIC)	13.7±8.75	14.6±9.35	0.23	<i>r</i> =0.13
ST preparatory amplitude (%MVIC)	8.89±6.64	11.9±11.2	0.001*	<i>r</i> =0.55
LG preparatory amplitude (%MVIC)	16.5±8.87	17.7±8.41	0.16	<i>d</i> =0.14
MG preparatory amplitude (%MVIC)	48±143	57±192	0.26	<i>r</i> =0.11
GMed preparatory amplitude (%MVIC)	19.9±12	20.8±11.3	0.19	<i>r</i> =0.16
GMax preparatory amplitude (%MVIC)	14.5±12.8	14.1±10.2	0.96	<i>r</i> =0.31

*denotes statistical significance between successful and failed landings ($p < 0.05$)

Model Construction

Following data collections 230 successful and failed landing trials were identified (success=137; failed=93), between 3-6 successful and 1-5 failed landings were included from each participant. Using best variable selection 20 separate logistic regression models were fit to the observations. LOOCV revealed that the accuracy of the model began to plateau at approximately eight variables (MSE=0.23) and began overfitting at approximately 13 variables (MSE=0.23) (Figure 6.1). In order to balance model accuracy with model simplicity, the eight variable logistic regression was selected for further analysis (Table 6.3).

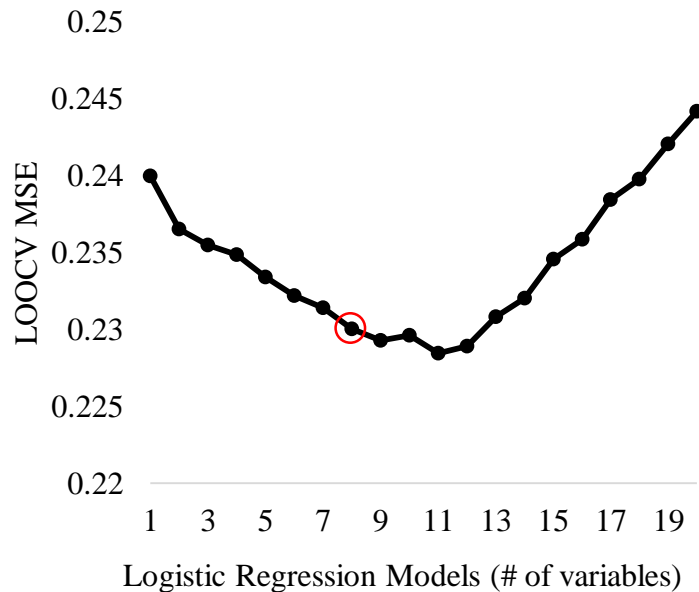


Figure 6.1. The LOOCV MSE of each logistic regression model fit using the variables selected by best variable selection. Red circle indicates the model chosen for further analysis.

Figure 6.2 displays the receiver operating characteristic (ROC) curve for the eight variable model; using the ROC curve a classification threshold of 0.55 was selected for determining the training accuracy. The model has an area under the curve (AUC) of 0.69 (Figure 6.2), a training

classification accuracy of 70% and a LOOCV classification accuracy of 63% (Table 6.2). The model had false positive rate of 23% and a false negative rate of 42% (Table 6.2).

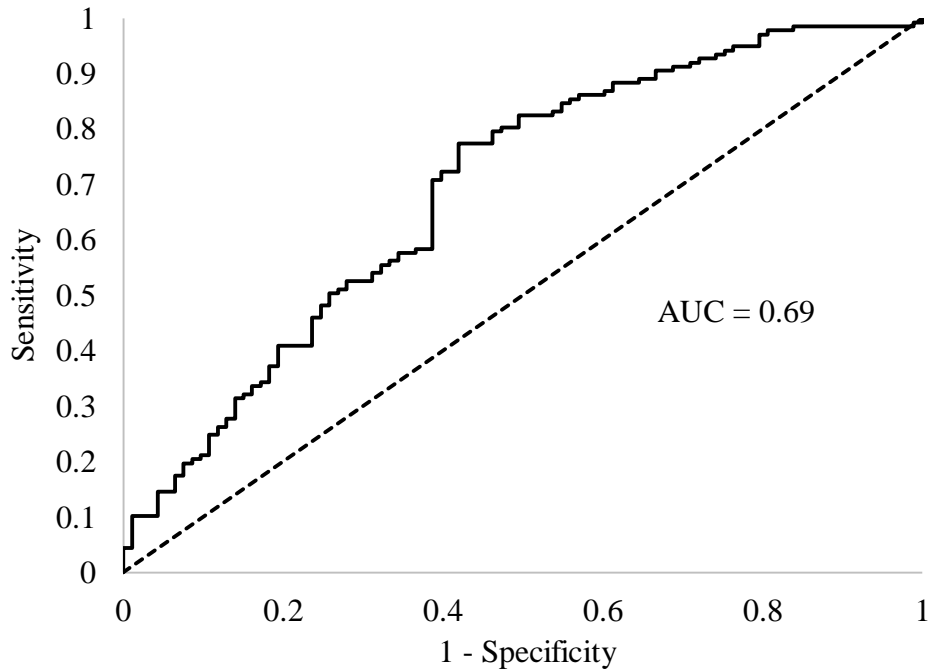


Figure 6.2. The eight variable logistic regression model had a moderate accuracy when assessed on the training cohort (n=230), as displayed in the ROC curve (AUC = 0.69). Dashed line represents a ROC curve for random chance.

Table 6.2

Confusion matrix fitting the logistic regression on all observations (training) and using LOOCV (validation)

	Training		Validation	
	Failed	Success	Failed	Success
Failed	54	31	51	39
Success	39	106	42	98

The eight predictors included in the model were knee flexion, knee abduction, hip flexion, hip abduction, hip internal rotation, CoM excursion, RF preparatory muscle activation and VL

preparatory muscle activation (Table 6.3). All variables included in the model, except hip flexion were statistically significant.

Table 6.3

The predictors included in the eight variable model with their respective logit, odds ratios, and p-values

	Logit	Odds Ratio	p-value
Knee Flexion	-0.56	0.58	0.023*
Knee Abduction	0.57	1.77	0.002*
Hip Flexion	0.42	1.52	0.074
Hip Abduction	0.52	1.68	0.003*
Hip External Rotation	-0.38	0.68	0.018*
CoM Excursion	0.35	1.39	0.023*
RF Preparatory Activation	-0.45	0.66	0.022*
VL Preparatory Activation	0.5	1.65	0.02*

* denotes statistical significant model coefficients (logit) ($p < 0.05$)

Discussion

The first objective of this study was to describe the neuromuscular and kinematic differences during the preparatory phase of failed and successful landings. Interestingly, the only identified kinematic differences occurred at the hip joint, with greater abduction and less external rotation during the successful landings. The alterations in hip kinematics likely reflect a strategy to improve balance during the single-leg landing. In this context balance refers to minimizing the angular displacement of the CoM from the base of support (Jacobson & Shepard, 2014). By maintaining the body's CoM over the base of support, the destabilizing force of gravity is reduced (Jacobson & Shepard, 2014). In the context of balancing a single-leg drop-jump landing, both the GRFs during landing and the momentum of the body motions must be overcome, such that re-establishing the base of support (ex. touching the ground with the contralateral foot) is not required. Considering the role of the hip in controlling lower-limb mechanics (Hewett et al.,

2005; Powers, 2010) and dissipating landing forces (Yeow, Lee, & Goh, 2011), the larger hip abduction and lower external rotation during the successful landings are logical. Significant correlations have also been observed between hip adduction and knee abduction angle at initial contact during jump landings (Hewett et al., 2005), and excessive deviations in hip posture can affect the orientation of the GRF vector, altering the moments acting on the knee and ankle (McLean et al., 2005). In addition, given that whole-body CoM is largely influenced by the mass of the trunk, changes in hip kinematics may alter trunk CoM position relative to the stance limb (Powers, 2010). Therefore, larger hip abduction and lower external rotation angles at the hip could be reflective of a strategy to orient the trunk CoM over the stance limb while preparing to land the jump. Greater preparatory activation of the RF and ST muscles were also observed during the failed landings. Increasing activation of the muscles surrounding the knee could increase joint stiffness (Lewek, Ramsey, Snyder-Mackler, & Rudolph, 2005) and reduce force absorption during landing (Schmitz, Kulas, Perrin, Riemann, & Shultz, 2007; Yeow et al., 2011). Furthermore, the RF and ST are bi-articular muscles, crossing both the hip and knee joints (van Deursen, Cavanagh, van Ingen Schenau, Becker, & Ulbrecht, 1998; van Ingen Schenau, Boots, de Groot, Snackers, & van Woensel, 1992). Increased activation of bi-articular muscles may complicate the neuromuscular control mechanisms required to land the jump successfully. A greater RF activation would require relatively more hip extension moments to balance the hip flexion moments as well as more knee flexion moments to counteract the subsequent RF knee extension moments (Flaxman et al., 2012). Although further research is required to determine the relationship between mono- and bi-articular muscles during failed landing, the preliminary results indicate that recruitment of bi-articular muscles could be less effective for landing a jump successfully.

The second objective of this study was to determine which combination of neuromuscular and kinematic variables were the best predictors for a successful jump landing. Following the statistical analysis, an eight variable model was chosen with knee flexion, knee abduction, hip flexion, hip abduction, hip internal rotation, CoM excursion, RF preparatory muscle activation and VL preparatory muscle activation included as predictors. However, it is important to note that hip flexion was not statistically significant, so its contribution to the model must be interpreted cautiously. These variables, in combination, offered a moderate training and validation accuracy of 70% and 65% respectively (Table 6.2).

The contributions of hip posture to successful jump landings are demonstrated again as hip abduction and external rotation angles were included in the model. In addition, increased knee abduction improved the likelihood of a successful landing. This is likely a result of how the jumps were performed, in order to transition from a two-leg takeoff to a single-leg landing, the base of support must be shifted so it is in-line with the CoM (Jacobson & Shepard, 2014). Thus, increased knee abduction would shift the femur closer to the midline of the trunk and therefore reduce the distance between the base of support and the CoM. This is further confirmed by greater CoM excursions improving the likelihood for landing a jump successfully. Although this may seem counter intuitive, this finding is likely reflective of participants moving the CoM so it is centered over the base of support.

The importance of muscle activation for landing a jump successfully was also evidenced by RF and VL preparatory activation amplitudes included in the model. However, increased RF activation decreased the likelihood of landing a jump successfully while increased VL activation increased the likelihood. During a jump landing, the lower extremity musculature must decelerate and stabilize the body's CoM as it travels in a downward direction (Wikstrom et al.,

2007). Increased RF activation would generate hip flexion moments and require relatively more hip extension moments to decelerate the trunk CoM. It appears that by generating knee extensor moments (VL activation), and less hip flexion moments (RF activation) participants are more effective at resisting the collapse of the lower extremity and are more likely to land the jump successfully (Zhang, Bates, & Dufek, 2000). In addition, given that RF is a bi-articular muscle, this provides further evidence that recruitment of mono-articular muscles may be more effective for landing a jump successfully.

It is also important to note which variables were not included in the model. Although sex was included as a potential predictor, it was not selected in the eight variable model. This indicates that despite the previously described sex-differences during successful jump landings (*Manuscript 1*), the relation between the variables included in the model and the prediction for successful landing does not change based on sex. In other words, the same variables were associated with successful landings in both male and female participants. In addition, neither ankle kinematics nor muscle activation from ankle joint actuators were included in the model. Thus, consistent with the observed differences between successful and failed landings, it seems that proximal joints have a larger contributing role to landing a jump successfully.

Limitations

It should be noted that failed trials encompassed a wide range of movements, trials were participants shifted their foot or fell completely were both categorized as ‘fails.’ This apparent difference in the degree to which a participant failed the landing was not accounted for, and could have confounded the results of the regression model. In addition, best variable selection was used to build the regression model since it examines every possible combination of predictors and determines the optimal combination. However, it does not select variables based

on their statistical significance, meaning some variables included in the model did not have statistically significant coefficients. This increases the difficulty of interpreting the results of the regression model and could indicate an interaction affect between the significant and non-significant variables. Finally, given the exploratory nature of this study, only kinematic and muscle activation predictors were included to simplify variable selection. However, future research should incorporate GRFs and joint kinetics as predictors for successful jump landings.

Conclusion

This is the first study to identify statistically significant differences between failed and successful landing kinematics. We found that hip kinematics and the surrounding musculature play an important role in controlling successful and failed landings. Activation of mono-articular muscles may offer a more effective means for decelerating the CoM and landing a jump successfully. In addition, participant sex was not a factor in predicting success or failure. Based on these findings, hip mechanics has the largest influence over the relatively likelihood of landing a jump successfully.

Acknowledgments

The authors would like to thank Mike Del Bel, Lisa Ek Orloff, Saskia Hanssen, Laura Boonstra and Céline Girard for their contributions in data collections. They would also like to thank the Ontario Graduate Scholarship, Natural Sciences and Engineering Research Council of Canada and the University of Ottawa for their support in the form of student and operating grants.

Conflict of Interest

The authors have no professional relationships that stand to gain from the current

study. The results of the present study are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation.

References

- Beaulieu, M. L., Lamontagne, M., & Beaulé, P. E. (2010). Lower limb biomechanics during gait do not return to normal following total hip arthroplasty. *Gait and Posture*.
- Besier, T. F., Lloyd, D. G., & Ackland, T. R. (2003). Muscle Activation Strategies at the Knee during Running and Cutting Maneuvers. *Med . Sci . Sports Exerc*, 35(1), 119–127.
- Boden, B. P., Dean, G. S., Feagin, J. A., & Garrett, W. E. (2000). Mechanisms of anterior cruciate ligament injury. *Orthopedics*, 23(6), 573–578.
- Brown, T. N., Palmieri-Smith, R. M., & McLean, S. G. (2009). Sex and limb differences in hip and knee kinematics and kinetics during anticipated and unanticipated jump landings: implications for anterior cruciate ligament injury. *British Journal of Sports Medicine*, 43(13), 1049–1056.
- Chappell, J. D., Creighton, R. A., Giuliani, C., Yu, B., & Garrett, W. E. (2007). Kinematics and Electromyography of Landing Preparation in Vertical Stop-Jump. *The American Journal of Sports Medicine*, 35(2), 235–241.
- Chaudhari, A. M., & Andriacchi, T. P. (2006). The mechanical consequences of dynamic frontal plane limb alignment for non-contact ACL injury. *Journal of Biomechanics*, 39(2), 330–338.
- Chaudhari, A. M., Hearn, B. K., & Andriacchi, T. P. (2005). Sport-Dependent Variations in arm Position during Single-Limb Landing Influence Knee Loading. *The American Journal of Sports Medicine*, 33(6), 824–830.
- de Leva, P. (1996). Adjustments to Zatsiorsky-Seluyanov's segment inertia parameters. *Journal*

of Biomechanics, 29(9), 1223–1230.

Decker, M. J., Torry, M. R., Wyland, D. J., Sterett, W. I., & Richard Steadman, J. (2003).

Gender differences in lower extremity kinematics, kinetics and energy absorption during landing. *Clinical Biomechanics*, 18(7), 662–669.

Dempsey, A. R., Lloyd, D. G., Elliott, B. C., Steele, J. R., & Munro, B. J. (2009). Changing

Sidestep Cutting Technique Reduces Knee Valgus Loading. *The American Journal of Sports Medicine*, 37(11), 2194–2200.

Donnelly, C. J., Elliott, B. C., Ackland, T. R., Doyle, T. L. A., Beiser, T. F., Finch, C. F., ...

Lloyd, D. G. (2012). An anterior cruciate ligament injury prevention framework: incorporating the recent evidence. *Research in Sports Medicine (Print)*, 20(3–4), 239–262.

Elias, L. J., Brydent, M. P., & Bulman-Fleming, M. B. (1998). *Footedness is a better predictor than is handedness of emotional lateralization. Neuropsychologia* (Vol. 36).

Fabricant, P. D., Robles, A., Downey-Zayas, T., Do, H. T., Marx, R. G., Widmann, R. F., &

Green, D. W. (2013). Development and Validation of a Pediatric Sports Activity Rating Scale. *The American Journal of Sports Medicine*, 41(10), 2421–2429.

Flaxman, T. E., Speirs, A. D., & Benoit, D. L. (2012). Joint stabilisers or moment actuators: The

role of knee joint muscles while weight-bearing. *Journal of Biomechanics*, 45(15), 2570–2576.

Gray, J., Taunton, J., McKenzie, D., Clement, D., McConkey, J., & Davidson, R. (1985). A

Survey of Injuries to the Anterior Cruciate Ligament of the Knee in Female Basketball Players. *International Journal of Sports Medicine*, 06(06), 314–316.

- Hewett, T., Myer, G. D., Ford, K. R., Heidt, R. S., Colosimo, A. J., McLean, S. G., ... Succop, P. (2005). Biomechanical Measures of Neuromuscular Control and Valgus Loading of the Knee Predict Anterior Cruciate Ligament Injury Risk in Female Athletes: A Prospective Study. *American Journal of Sports Medicine*, *33*(4), 492–501.
- Jacobson, G. P., & Shepard, N. T. (2014). *Balance Function Assessment and Management Second Edition*.
- James, G., Witten, D., Hastie, T., & Tibshirani, R. (2013). *An Introduction to Statistical Learning with Applications in R*. London: Springer.
- Kocher, M. S., Smith, J. T., Iversen, M. D., Brustowicz, K., Ogunwole, O., Andersen, J., ... Zurawski, D. (2011). Reliability, Validity, and Responsiveness of a Modified International Knee Documentation Committee Subjective Knee Form (Pedi-IKDC) in Children With Knee Disorders. *The American Journal of Sports Medicine*, *39*(5), 933–939.
- Koga, H., Nakamae, A., Shima, Y., Iwasa, J., Myklebust, G., Engebretsen, L., ... Krosshaug, T. (2010). Mechanisms for Noncontact Anterior Cruciate Ligament Injuries: Knee Joint Kinematics in 10 Injury Situations From Female Team Handball and Basketball. *The American Journal of Sports Medicine*, *38*(11), 2218–2225.
- Lewek, M. D., Ramsey, D. K., Snyder-Mackler, L., & Rudolph, K. S. (2005). Knee stabilization in patients with medial compartment knee osteoarthritis. *Arthritis & Rheumatism*, *52*(9), 2845–2853.
- Mantovani, G., & Lamontagne, M. (2017). How Different Marker Sets Affect Joint Angles in Inverse Kinematics Framework. *Journal of Biomechanical Engineering*, *139*(4), 044503.

- McKinley, P., & Pedotti, A. (1992). Motor strategies in landing from a jump: the role of skill in task execution. *Experimental Brain Research*, *90*(2), 427–440.
- McLean, S. G., Huang, X., & van den Bogert, A. J. (2005). Association between lower extremity posture at contact and peak knee valgus moment during sidestepping: Implications for ACL injury. *Clinical Biomechanics*, *20*(8), 863–870.
- Metz, C. E. (1978). Basic principles of ROC analysis. *Seminars in Nuclear Medicine*, *8*(4), 283–298.
- Mornieux, G., Gehring, D., Fürst, P., & Gollhofer, A. (2014). Anticipatory postural adjustments during cutting manoeuvres in football and their consequences for knee injury risk. *Journal of Sports Sciences*, *32*(13), 1255–1262.
- Olsen, O.-E., Myklebust, G., Engebretsen, L., & Bahr, R. (2004). Injury Mechanisms for Anterior Cruciate Ligament Injuries in Team Handball: A Systematic Video Analysis. *American Journal of Sports Medicine*, *32*(4), 1002–1012.
- Patla, A. E., Adkin, A., & Ballard, T. (1999). Online steering: coordination and control of body center of mass, head and body reorientation. *Experimental Brain Research*, *129*(4), 629–634.
- Pollard, C. D., Sigward, S. M., & Powers, C. M. (2010). Limited hip and knee flexion during landing is associated with increased frontal plane knee motion and moments. *Clinical Biomechanics*, *25*(2), 142–146.
- Powers, C. M. (2010). The Influence of Abnormal Hip Mechanics on Knee Injury: A Biomechanical Perspective. *Journal of Orthopaedic & Sports Physical Therapy*, *40*(2), 42–

51.

Riemann, B. L., & Lephart, S. M. (2002). The sensorimotor system, part I: the physiologic basis of functional joint stability. *Journal of Athletic Training, 37*(1), 71–79.

Sale, D., Quinlan, J., Marsh, E., McComas, A. J., & Belanger, A. Y. (1982). Influence of joint position on ankle plantarflexion in humans. *Journal of Applied Physiology: Respiratory, Environmental and Exercise Physiology, 52*(6), 1636–1642.

Schmitz, R. J., Kulas, A. S., Perrin, D. H., Riemann, B. L., & Shultz, S. J. (2007). Sex differences in lower extremity biomechanics during single leg landings. *Clinical Biomechanics, 22*(6), 681–688.

van Deursen, R. W. M., Cavanagh, P. R., van Ingen Schenau, G. J., Becker, M. B., & Ulbrecht, J. S. (1998). The role of cutaneous information in a contact control task of the leg in humans. *Human Movement Science, 17*(1), 95–120.

van Ingen Schenau, G. J., Boots, P. J. M., de Groot, G., Snackers, R. J., & van Woensel, W. W. L. M. (1992). The constrained control of force and position in multi-joint movements. *Neuroscience, 46*(1), 197–207.

Wikstrom, E. A., Tillman, M. D., Chmielewski, T. L., & Borsa, P. A. (2006). Measurement and Evaluation of Dynamic Joint Stability of the Knee and Ankle After Injury. *Sports Medicine, 36*(5), 393–410.

Wikstrom, Tillman, M. D., Schenker, S., & Borsa, P. A. (2007). Failed jump landing trials: deficits in neuromuscular control. *Scandinavian Journal of Medicine & Science in Sports, 18*(1), 55–61.

Winter, D. A. (2009). *Biomechanics and motor control of human movement*. Wiley.

Yeow, C. H., Lee, P. V. S., & Goh, J. C. H. (2011). An investigation of lower extremity energy dissipation strategies during single-leg and double-leg landing based on sagittal and frontal plane biomechanics. *Human Movement Science, 30*(3), 624–635.

Zatsiorsky, V., Seluyanov, V., & Chugunova, L. (1990). In vivo body segment inertial parameters determination using a gamma-scanner method. *Contemporary Problems of Biomechanics*.

Zhang, S. N., Bates, B. T., & Dufek, J. S. (2000). Contributions of lower extremity joints to energy dissipation during landings. *Medicine and Science in Sports and Exercise, 32*(4), 812–819.

CHAPTER 7: GENERAL DISCUSSION

The aim of this Master's Thesis was to provide a complete neuromuscular and kinematic analysis of unanticipated single-leg drop-jump landings in young athletes. To address this aim, two specific research questions were established. The first (*Q1*) was to determine if sex-differences exist in muscle onset times, co-activations and lower-limb mechanics during an unanticipated drop-jump landing task. This was achieved by combining a commonly used injury screening tool (drop-jump landing), with a relevant sport component (unanticipated visual cue). Following isolation of successful landings on the dominant limb, biomechanical variables were compared between male and female participants. The second question (*Q2*) was to examine which kinematic or neuromuscular variables are the strongest predictors of a successful landing. Single-leg landings were separated into failed and successful trials and a novel comparison of landing type was performed.

7.1 Do sex-differences exist in muscle onset times, co-activation and lower limb mechanics during an unanticipated drop-jump landing task?

We hypothesised that females would demonstrate greater knee flexion (H1) and greater knee abduction (H2) during the unanticipated landings (Ford et al., 2005; Myer, Ford, & Hewett, 2005; Sell et al., 2005). The first two hypotheses were rejected as no statistically significant kinematic differences were identified between males and females at the hip and knee joint. By requiring participants to 'stick' the landing and excluding trials where participants performed additional movements to regain their balance (ex. contralateral foot touches the ground), the variability between jumps was systematically minimized. However, lower trunk flexion was observed in females during the landing. A more erect landing posture suggests that females are less effective at attenuating forces during the landing (Blackburn & Padua, 2009). Female

participants also landed with less hip and knee flexion moments during the drop-jump when compared to their male counterparts. These findings appear to indicate that females land in a more erect posture through their trunk, hip and knee, and may be less effective at dissipating landing forces (Blackburn & Padua, 2009; Schmitz et al., 2007; Yeow, Lee, & Goh, 2011; Zhang, Bates, & Dufek, 2000).

Based on previous research examining co-activation (Besier et al., 2003) and MOTs (Beaulieu et al., 2009; Landry et al., 2009), we hypothesised that females would demonstrate greater co-activation (H3) and quicker pre-activation (H4) of the lower-limb musculature during successful unanticipated landings. Greater co-activation of the quadriceps and gastrocnemius muscles were observed during the flight phase of the drop-jump landing in females, confirming our hypothesis. The concurrent activation of muscles crossing the knee joint has been suggested as a strategy for increasing joint stiffness (Lewek et al., 2005) and resisting frontal plane loads (Lloyd & Buchanan, 2001). Although the direct cause of the co-activation strategy employed by females can not be demonstrated in this study, previous research has suggested that females possess inherently greater joint laxity than their male counterparts (Myer, Ford, Paterno, Nick, & Hewett, 2008; Rozzi, Lephart, Gear, & Fu, 1999). In addition, females may have a strength deficit compared to males (McKay et al., 2017) (Table A.4). These findings could reflect a compensatory mechanism to increase joint stiffness and functional stabilization through increased joint compression. Finally, contrary to our hypothesis, delayed MOT was identified in the VL of female participants. Longer VL activation suggests that males are more effective at responding to the visual cue and preparing their muscles prior to landing. To properly stabilize the knee joint, muscle activation must occur with sufficient time for adequate force contribution during the movement, however longer rates of force development have been observed in females

(Bell & Jacobs, 1986; Häkkinen & Häkkinen, 1991; Huston & Wojtys, 1996; Komi & Karlsson, 1978; Winter & Brookes, 1991). These findings suggest that females are less effective at preparing for the unanticipated landing and dissipating the subsequent impact forces.

7.2 Which kinematic or neuromuscular factors are the strongest predictors of a successful drop-jump landing?

The only identified kinematic differences occurred at the hip joint, with greater abduction and less external rotation during the successful landings. Considering the role of the hip in controlling lower-limb mechanics (Hewett et al., 2005; Powers, 2010) and dissipating landing forces (Yeow et al., 2011), the observed differences in hip kinematics are logical. In addition, given that whole-body CoM is largely influenced by the mass of the trunk, changes in hip kinematics may alter CoM position relative to the stance limb (Powers, 2010). However, greater preparatory activation of the RF and ST muscles were observed during the failed landings. Increasing activation of the muscles surrounding the knee can increase joint stiffness (Lewek et al., 2005) and reduce force absorption during landing (Schmitz et al., 2007; Yeow et al., 2011). Furthermore, the RF and ST are bi-articular muscles, crossing both the hip and knee joints (van Deursen, Cavanagh, van Ingen Schenau, Becker, & Ulbrecht, 1998; van Ingen Schenau, Boots, de Groot, Snackers, & van Woensel, 1992). These results appear to indicate that recruitment of mono-articular muscles may be more effective for landing a jump successfully. However, the role of bi-articular muscles are not well understood (Cleather, Goodwin, & Bull, 2011), although some research suggests that bi-articular muscles are less effective at generating force (Jacobs, Bobbert, & van Ingen Schenau, 1993), they may play an important role in transferring mechanical load between body segments (Gregoire, Veeger, Huijing, & van Ingen Schenau, 1984; van Ingen Schenau, Bobbert, & Rozendal, 1987).

Based on the association between trunk CoM and knee loading (Donnelly et al., 2012), we hypothesized that larger excursions in whole-body CoM location would increase the likelihood of failing a jump landing (H5). In addition, based on previous research investigating failed landings (Wikstrom et al., 2007), we hypothesised that reduced preparatory muscle activation amplitude would also increase the likelihood of failing a jump landing (H6). Following the statistical analysis, an eight variable model was chosen with knee flexion, knee abduction, hip flexion, hip abduction, hip internal rotation, CoM excursion, RF preparatory muscle activation and VL preparatory muscle activation included as predictors. These variables, in combination, offered a moderate training and validation accuracy of 70% and 65% respectively. Contrary to our hypothesis, greater CoM excursions improved the likelihood for landing a jump successfully. This is likely a result of how the jumps were performed, in order to transition from a two-leg takeoff to a single-leg landing, the CoM must be shifted so it is in-line with the base of support (Jacobson & Shepard, 2014). The contributions of hip posture to successful jump landings are demonstrated as hip abduction and external rotation angles were included in the model.

The importance of muscle activation for landing a jump successfully was also evidenced by RF and VL preparatory activation amplitudes included in the model. During a jump landing, the lower extremity musculature must decelerate and stabilize the body's CoM as it travels in a downward direction (Wikstrom et al., 2007). However, contrary to our hypothesis, increased RF activation decreased the likelihood of landing a jump successfully while increased VL activation increased the likelihood. Given that RF is a bi-articular muscle, this provides further evidence that recruitment of mono-articular muscles may be more effective for landing a jump successfully.

Increased RF activation would generate hip flexion moments and require relatively more hip extension moments to decelerate the trunk CoM. It appears that by generating knee extensor moments (VL activation), and less hip flexion moments (RF activation) participants are more effective at resisting the collapse of the lower extremity and are more likely to land the jump successfully (Zhang et al., 2000). Finally, although sex was included as a potential predictor, it was not selected in the eight variable model, indicating that the relation between the variables included in the model and the prediction for successful landing does not change based on sex.

7.3 Conclusion

Successfully performing an unanticipated landing requires a combination of feed-forward (implementing neuromuscular pattern from internal program) (Kandel, Schwartz, Jessell, Siegelbaum, & Hudspeth, 2000) and feed-back (modification of neuromuscular task) control (Seidler, Noll, & Thiers, 2004). During an unanticipated landing the ability of participants to implement neuromuscular programs to maintain optimal kinematic and kinetic control is reduced (Seidler et al., 2004). This may, at least partially, account for the observed differences during the preparatory phase of the landing between both males vs. females and successful vs. failed landings. Females tended to land the drop-jump with less trunk flexion and lower hip and knee flexion moments. Furthermore, immediately prior to landing from the drop-jump females tended to co-activate their quadriceps and gastrocnemius muscles. This indicates a strategy of increasing joint compressive forces, and therefore knee stiffness when preparing to land. In addition, males tended to activate their muscle sooner (i.e. for a longer duration), prior to landing the drop-jump. This indicates that males have an improved ability to prepare for the unanticipated landing and are therefore more effective at dissipating impact forces. Altered neuromuscular control patterns, in particular the timing of quadriceps and hamstring EMG activity, have been proposed as risk

factors for ACL injuries because it can result in suboptimal stabilization of the knee joint (Myer et al., 2009; Zebis, Andersen, Bencke, Kjær, & Aagaard, 2009). Furthermore, based on the findings presented in *Manuscript 2* greater pre-activation of certain muscles may have detrimental effect on jump landings. Greater pre-activation of a mono-articular knee extensor (VL) increased the likelihood of landing the jump successfully, while greater activation of a bi-articular knee extensor and hip flexor (RF) decreased the likelihood. Both Manuscripts also provided evidence for the role of the hip in controlling lower-limb biomechanics. When comparing male and female landings, less hip flexion moment was identified in the female participants. Alterations in hip mechanics and activation of the surrounding musculature were also strongly associated with an increased likelihood to land the jump successfully (for both sexes). This suggests the importance of hip joint control in response to altered trunk and CoM position. This may be a critical finding given that reduced trunk control (Zazulak, Hewett, Reeves, Goldberg, & Cholewicki, 2007) and hip strength (Khayambashi, Ghoddosi, Straub, & Powers, 2016) predict ACL injury. Finally, our findings indicate that sex does not affect the neuromechanical variables linked to successful landings (*Manuscript 2*) rather, it is the level of these variables which best describes the difference between males and females (*Manuscript 1*). Thus, intervention programs aimed at improving landing mechanics may benefit from targeting hip and trunk mechanics in both males and females.

We are hopeful that outcomes of this thesis will provide the impetus for ongoing research aimed at a more precise understanding of the non-contact ACL injury mechanism. The observed differences in hip mechanics and lower-limb muscle activation patterns may be useful for the design and development of interventions aimed at altering lower extremity biomechanics for safer landing positions. Several studies have already supported the effectiveness of dynamic

neuromuscular training in decreasing landing forces and ACL injury risk (Foss, Thomas, Khoury, Myer, & Hewett, 2018; Sugimoto et al., 2016). Furthermore, the implementation of unanticipated conditions within intervention and screening protocols may provide substantial improvements in the resultant movement response, particularly within the inherently random sporting environment.

REFERENCES

- Agel, J., & Klossner, D. (2014). Epidemiological Review of Collegiate ACL Injury Rates Across 14 Sports: National Collegiate Athletic Association Injury Surveillance System Data 2004-05 Through 2011. *British Journal of Sports Medicine*, *48*(7), 560.2-560.
- Agel, J., Rockwood, T., & Klossner, D. (2016). Collegiate ACL Injury Rates Across 15 Sports. *Clinical Journal of Sport Medicine*, *26*(6), 518–523.
- Ardern, C. L., Taylor, N. F., Feller, J. A., & Webster, K. E. (2014). Fifty-five per cent return to competitive sport following anterior cruciate ligament reconstruction surgery: an updated systematic review and meta-analysis including aspects of physical functioning and contextual factors. *British Journal of Sports Medicine*, *48*(21), 1543–1552.
- Arendt, E. A., Bershadsky, B., & Agel, J. (2002). Periodicity of noncontact anterior cruciate ligament injuries during the menstrual cycle. *The Journal of Gender-Specific Medicine : JGSM : The Official Journal of the Partnership for Women's Health at Columbia*, *5*(2), 19–26.
- Baratta, R., Solomonow, M., Zhou, B. H., Letson, D., Chuinard, R., & D'Ambrosia, R. (1988). Muscular coactivation. *The American Journal of Sports Medicine*, *16*(2), 113–122.
- Baumhauer, J. F., Alosa, D. M., Renström, P. A. F. H., Trevino, S., & Beynonn, B. (1995). A Prospective Study of Ankle Injury Risk Factors. *The American Journal of Sports Medicine*, *23*(5), 564–570.
- Beaulieu, M. L., Lamontagne, M., & Beaulé, P. E. (2010). Lower limb biomechanics during gait do not return to normal following total hip arthroplasty. *Gait and Posture*.
- Beaulieu, M. L., Lamontagne, M., & Xu, L. (2009). Lower limb muscle activity and kinematics of an unanticipated cutting manoeuvre: a gender comparison. *Knee Surgery, Sports*

- Traumatology, Arthroscopy*, 17(8), 968–976.
- Beck, N., Lawrence, J., Nordin, J., DeFor, T., & Tompkins, M. (2015). ACL Tears in School-Aged Children and Adolescents: Has There Been an Increased Incidence over the Last 20 Years? In *AAP National Conference and Exhibition*. American Academy of Pediatrics.
- Bell, D. G., & Jacobs, I. (1986). Electro-mechanical response times and rate of force development in males and females. *Medicine and Science in Sports and Exercise*, 18(1), 31–36.
- Benjamini, Y., & Hochberg, Y. (1995). *Controlling the False Discovery Rate: A Practical and Powerful Approach to Multiple*. Source: *Journal of the Royal Statistical Society. Series B (Methodological)* (Vol. 57).
- Besier, T. F., Lloyd, D. G., & Ackland, T. R. (2003). Muscle Activation Strategies at the Knee during Running and Cutting Maneuvers. *Med . Sci . Sports Exerc*, 35(1), 119–127.
- Bezodis, N. E., Salo, A. I. T., & Trewartha, G. (2013). Excessive fluctuations in knee joint moments during early stance in sprinting are caused by digital filtering procedures. *Gait & Posture*, 38(4), 653–657.
- Bisseling, R. W., & Hof, A. L. (2006). Handling of impact forces in inverse dynamics. *Journal of Biomechanics*, 39(13), 2438–2444.
- Blackburn, J. T., & Padua, D. A. (2009). Sagittal-Plane Trunk Position, Landing Forces, and Quadriceps Electromyographic Activity. *Journal of Athletic Training*, 44(2), 174–179.
- Boden, B. P., Dean, G. S., Feagin, J. A., & Garrett, W. E. (2000). Mechanisms of anterior cruciate ligament injury. *Orthopedics*, 23(6), 573–578.
- Borotikar, B. S., Newcomer, R., Koppes, R., & McLean, S. G. (2008). Combined effects of fatigue and decision making on female lower limb landing postures: Central and peripheral

- contributions to ACL injury risk. *Clinical Biomechanics*, 23(1), 81–92.
- Brattström, H. (1964). Shape of the Intercondylar Groove Normally and in Recurrent Dislocation of Patella: A Clinical and X-Ray Anatomical Investigation. *Acta Orthopaedica Scandinavica*, 35(sup68), 1–148.
- Brooks, J. H. M., Fuller, C. W., Kemp, S. P. T., & Reddin, D. B. (2005). Epidemiology of injuries in English professional rugby union: part 1 match injuries. *British Journal of Sports Medicine*, 39(10), 757–766.
- Brown, T. N., Palmieri-Smith, R. M., & McLean, S. G. (2009). Sex and limb differences in hip and knee kinematics and kinetics during anticipated and unanticipated jump landings: implications for anterior cruciate ligament injury. *British Journal of Sports Medicine*, 43(13), 1049–1056.
- Burden, A. (2010). How should we normalize electromyograms obtained from healthy participants? What we have learned from over 25 years of research. *Journal of Electromyography and Kinesiology*, 20(6), 1023–1035.
- C.J.Donnely, D.G.Lloyd, B.C.Elliotta, & J.A.Reinbolt. (2012). Optimizing whole-body kinematics to minimize valgus knee loading during sidestepping: Implications for ACL injury risk. *Journal of Biomechanics*, 45(8), 1491–1497.
- Cavanagh, P. R., & Komi, P. V. (1979). Electromechanical delay in human skeletal muscle under concentric and eccentric contractions. *European Journal of Applied Physiology and Occupational Physiology*, 42(3), 159–163.
- Chandrashekar, N., Mansouri, H., Slauterbeck, J., & Hashemi, J. (2006). Sex-based differences in the tensile properties of the human anterior cruciate ligament. *Journal of Biomechanics*, 39(16), 2943–2950.

- Chapelle, O., Vapnik, V., Bousquet, O., & Mukherjee, S. (2002). Choosing Multiple Parameters for Support Vector Machines. *Machine Learning*, 46(1/3), 131–159.
- Chaudhari, A. M., & Andriacchi, T. P. (2006). The mechanical consequences of dynamic frontal plane limb alignment for non-contact ACL injury. *Journal of Biomechanics*, 39(2), 330–338.
- Chaudhari, A. M., Hearn, B. K., & Andriacchi, T. P. (2005). Sport-Dependent Variations in arm Position during Single-Limb Landing Influence Knee Loading. *The American Journal of Sports Medicine*, 33(6), 824–830.
- Clarys, J. P. (2000). Electromyography in sports and occupational settings: an update of its limits and possibilities. *Ergonomics*, 43(10), 1750–1762.
- Cleather, D. J., Goodwin, J. E., & Bull, A. M. J. (2011). An Optimization Approach to Inverse Dynamics Provides Insight as to the Function of the Biarticular Muscles During Vertical Jumping. *Annals of Biomedical Engineering*, 39(1), 147–160.
- Cohen, J. (2013). *Statistical power analysis for the behavioral sciences*. Academic.
- Coleman, W. H. (1969). Sex differences in the growth of the human bony pelvis. *American Journal of Physical Anthropology*, 31(2), 125–151.
- Cowley, H. R., Ford, K. R., Myer, G. D., Kernozek, T. W., & Hewett, T. E. (2006). Differences in neuromuscular strategies between landing and cutting tasks in female basketball and soccer athletes. *Journal of Athletic Training*, 41(1), 67–73.
- de Leva, P. (1996). Adjustments to Zatsiorsky-Seluyanov's segment inertia parameters. *Journal of Biomechanics*, 29(9), 1223–1230. [https://doi.org/10.1016/0021-9290\(95\)00178-6](https://doi.org/10.1016/0021-9290(95)00178-6)
- De Luca, C. J. (1993). The Use of Surface Electromyography in Biomechanics. *Journal of Applied Biomechanics*, 13(2), 135–163.

- Decker, M. J., Torry, M. R., Wyland, D. J., Sterett, W. I., & Richard Steadman, J. (2003). Gender differences in lower extremity kinematics, kinetics and energy absorption during landing. *Clinical Biomechanics*, *18*(7), 662–669.
- Dempsey, A. R., Lloyd, D. G., Elliott, B. C., Steele, J. R., & Munro, B. J. (2009). Changing Sidestep Cutting Technique Reduces Knee Valgus Loading. *The American Journal of Sports Medicine*, *37*(11), 2194–2200.
- Elias, L. J., Brydent, M. P., & Bulman-Fleming, M. B. (1998). *Footedness is a better predictor than is handedness of emotional lateralization. Neuropsychologia* (Vol. 36).
- Erickson, B. J., Harris, J. D., Cvetanovich, G. L., Bach, B. R., Bush-Joseph, C. A., Abrams, G. D., ... Cole, B. J. (2013). Performance and Return to Sport After Anterior Cruciate Ligament Reconstruction in Male Major League Soccer Players. *Orthopaedic Journal of Sports Medicine*, *1*(2), 232596711349718.
- Fabricant, P. D., Robles, A., Downey-Zayas, T., Do, H. T., Marx, R. G., Widmann, R. F., & Green, D. W. (2013). Development and Validation of a Pediatric Sports Activity Rating Scale. *The American Journal of Sports Medicine*, *41*(10), 2421–2429.
- Field, A. (2013). *Discovering statistics using IBM SPSS statistics* (4th ed.). London: SAGE Publications Ltd.
- Flaxman, T. E., Smith, A. J. J., & Benoit, D. L. (2014). Sex-related differences in neuromuscular control: Implications for injury mechanisms or healthy stabilisation strategies? *Journal of Orthopaedic Research*, *32*(2), 310–317.
- Flaxman, T. E., Speirs, A. D., & Benoit, D. L. (2012). Joint stabilisers or moment actuators: The role of knee joint muscles while weight-bearing. *Journal of Biomechanics*, *45*(15), 2570–2576.

- Fleming, B. C., Renstrom, P. A., Beynon, B. D., Engstrom, B., Peura, G. D., Badger, G. J., & Johnson, R. J. (2001). The effect of weightbearing and external loading on anterior cruciate ligament strain. *Journal of Biomechanics*, *34*(2), 163–170.
- Fong, D. T.-P., Lam, M.-H., Lai, P.-K., Yung, P. S.-H., Fung, K.-Y., & Chan, K.-M. (2014). Effect of anticipation on knee kinematics during a stop-jump task. *Gait & Posture*, *39*(1), 75–79.
- Ford, K. R., Myer, G. D., Toms, H. E., & Hewett, T. E. (2005). Gender differences in the kinematics of unanticipated cutting in young athletes. *Medicine and Science in Sports and Exercise*, *37*(1), 124–129.
- Foss, K. D. B., Thomas, S., Khoury, J. C., Myer, G. D., & Hewett, T. E. (2018). A School-Based Neuromuscular Training Program and Sport-Related Injury Incidence: A Prospective Randomized Controlled Clinical Trial. *Journal of Athletic Training*, *53*(1), 20–28.
- Fu, W., Liu, Y., Zhang, S., & Liu, Y. (2013). Personal pdf file for Effects of Footwear on Impact Forces and Soft Tissue Vibrations during Drop Jumps and Unanticipated Drop Landings Effects of Footwear on Impact Forces and Soft Tissue Vibrations during Drop Jumps and Unanticipated Drop Landings. *Int J Sports Med Orthopedics Int J Sports Med Int J Sports Med*, *34*(34), 477–483.
- Gornitzky, A. L., Lott, A., Yellin, J. L., Fabricant, P. D., Lawrence, J. T., & Ganley, T. J. (2016). Sport-Specific Yearly Risk and Incidence of Anterior Cruciate Ligament Tears in High School Athletes: A Systematic Review and Meta-analysis. *The American Journal of Sports Medicine*, *44*(10), 2716–2723.
- Gray, J., Taunton, J., McKenzie, D., Clement, D., McConkey, J., & Davidson, R. (1985). A Survey of Injuries to the Anterior Cruciate Ligament of the Knee in Female Basketball

- Players. *International Journal of Sports Medicine*, 06(06), 314–316.
- Gregoire, L., Veeger, H., Huijing, P., & van Ingen Schenau, G. (1984). Role of Mono- and Biarticular Muscles in Explosive Movements. *International Journal of Sports Medicine*, 05(06), 301–305.
- Griffin, L. Y., Albohm, M. J., Arendt, E. A., Bahr, R., Beynon, B. D., Demaio, M., ... Yu, B. (2006). Understanding and Preventing Noncontact Anterior Cruciate Ligament Injuries: A Review of the Hunt Valley II Meeting, January 2005. *American Journal of Sports Medicine*, 34(9), 1512–1532.
- Häkkinen, K., & Häkkinen, A. (1991). Muscle cross-sectional area, force production and relaxation characteristics in women at different ages. *European Journal of Applied Physiology and Occupational Physiology*, 62(6), 410–414.
- Hame, S. L., & Alexander, R. A. (2013). Knee osteoarthritis in women. *Current Reviews in Musculoskeletal Medicine*, 6(2), 182–187. <https://doi.org/10.1007/s12178-013-9164-0>
- Haycock, C. E., & Gillette, J. V. (1976). Susceptibility of women athletes to injury. Myths vs reality. *JAMA*, 236(2), 163–165.
- Heitkamp, H.-C., Horstmann, T., Mayer, F., Weller, J., & Dickhuth, H.-H. (2001). Gain in Strength and Muscular Balance After Balance Training. *International Journal of Sports Medicine*, 22(4), 285–290.
- Hermens, H. J., Freriks, B., Merletti, R., Stegeman, D., Blok, J., Rau, G., ... Hägg, G. (1999). European Recommendations for Surface ElectroMyoGraphy Results of the SENIAM project. *Roessingh Research and Development*, 8(2), 13–54.
- Herzog, M. M., Marshall, S. W., Lund, J. L., Pate, V., Mack, C. D., & Spang, J. T. (2017). Incidence of Anterior Cruciate Ligament Reconstruction Among Adolescent Females in the

- United States, 2002 Through 2014. *JAMA Pediatrics*, 171(8), 808.
- Hewett, T. E., Myer, G. D., & Ford, K. R. (2004). Decrease in neuromuscular control about the knee with maturation in female athletes. *The Journal of Bone and Joint Surgery. American Volume*, 86-A(8), 1601–1608.
- Hewett, T. E., Stroupe, A. L., Nance, T. A., & Noyes, F. R. (1996). Plyometric Training in Female Athletes. *The American Journal of Sports Medicine*, 24(6), 765–773.
- Hewett, T. E., Torg, J. S., & Boden, B. P. (2009a). Video analysis of trunk and knee motion during non-contact anterior cruciate ligament injury in female athletes: lateral trunk and knee abduction motion are combined components of the injury mechanism. *British Journal of Sports Medicine*, 43(6), 417–422.
- Hewett, T. E., Torg, J. S., & Boden, B. P. (2009b). Video analysis of trunk and knee motion during non-contact anterior cruciate ligament injury in female athletes: lateral trunk and knee abduction motion are combined components of the injury mechanism. *British Journal of Sports Medicine*, 43(6), 417–422.
- Hewett, T., Myer, G. D., Ford, K. R., Heidt, R. S., Colosimo, A. J., McLean, S. G., ... Succop, P. (2005). Biomechanical Measures of Neuromuscular Control and Valgus Loading of the Knee Predict Anterior Cruciate Ligament Injury Risk in Female Athletes: A Prospective Study. *American Journal of Sports Medicine*, 33(4), 492–501.
- Houck, J. R., Duncan, A., & Haven, K. E. De. (2006). Comparison of frontal plane trunk kinematics and hip and knee moments during anticipated and unanticipated walking and side step cutting tasks. *Gait & Posture*, 24(3), 314–322.
- Hubley-Kozey, C. L., Deluzio, K. J., Landry, S. C., McNutt, J. S., & Stanish, W. D. (2006). Neuromuscular alterations during walking in persons with moderate knee osteoarthritis.

- Journal of Electromyography and Kinesiology*, 16(4), 365–378.
- Huston, L. J., & Wojtys, E. M. (1996). Neuromuscular Performance Characteristics in Elite Female Athletes. *The American Journal of Sports Medicine*, 24(4), 427–436.
- Iguchi, J., Tateuchi, H., Taniguchi, M., & Ichihashi, N. (2014). The effect of sex and fatigue on lower limb kinematics, kinetics, and muscle activity during unanticipated side-step cutting. *Knee Surgery, Sports Traumatology, Arthroscopy*, 22(1), 41–48.
- Jacobs, R., Bobbert, M. F., & van Ingen Schenau, G. J. (1993). Function of mono- and biarticular muscles in running. *Medicine and Science in Sports and Exercise*, 25(10), 1163–1173.
- Jacobson, G. P., & Shepard, N. T. (2014). *Balance Function Assessment and Management Second Edition*.
- James, G., Witten, D., Hastie, T., & Tibshirani, R. (2013). *An Introduction to Statistical Learning with Applications in R*. London: Springer.
- Jensen, R. K., & Nassas, G. (1988). Growth of segment principal moments of inertia between four and twenty years. *Medicine and Science in Sports and Exercise*, 20(6), 594–604.
- Joseph, A. M., Collins, C. L., Henke, N. M., Yard, E. E., Fields, S. K., & Comstock, R. D. (2013). A Multisport Epidemiologic Comparison of Anterior Cruciate Ligament Injuries in High School Athletics. *Journal of Athletic Training*, 48(6), 810–817.
- Kandel, E., Schwartz, J., Jessell, T., Siegelbaum, S., & Hudspeth, A. J. (2000). *Principles of Neural Science* (5th ed.). New York: McGraw-Hill.
- Khayambashi, K., Ghoddosi, N., Straub, R. K., & Powers, C. M. (2016). Hip Muscle Strength Predicts Noncontact Anterior Cruciate Ligament Injury in Male and Female Athletes. *The American Journal of Sports Medicine*, 44(2), 355–361.
- Kim, J. H., Lee, K.-K., Kong, S. J., An, K. O., Jeong, J. H., & Lee, Y. S. (2014). Effect of

- Anticipation on Lower Extremity Biomechanics During Side- and Cross-Cutting Maneuvers in Young Soccer Players. *The American Journal of Sports Medicine*, 42(8), 1985–1992.
- Kipp, K., Brown, T. N., McLean, S. G., & Palmieri-Smith, R. M. (2013). Decision making and experience level influence frontal plane knee joint biomechanics during a cutting maneuver. *Journal of Applied Biomechanics*, 29(6), 756–762.
- Knapik, J. J., Bauman, C. L., Jones, B. H., Harris, J. M., & Vaughan, L. (1991). Preseason strength and flexibility imbalances associated with athletic injuries in female collegiate athletes. *The American Journal of Sports Medicine*, 19(1), 76–81.
- Koga, H., Nakamae, A., Shima, Y., Iwasa, J., Myklebust, G., Engebretsen, L., ... Krosshaug, T. (2010). Mechanisms for Noncontact Anterior Cruciate Ligament Injuries: Knee Joint Kinematics in 10 Injury Situations From Female Team Handball and Basketball. *The American Journal of Sports Medicine*, 38(11), 2218–2225.
- Koga, H., Nakamae, A., Shima, Y., Iwasa, J., Myklebust, G., Engebretsen, L., ... Krosshaug, T. (2010). Mechanisms for Noncontact Anterior Cruciate Ligament Injuries: Knee Joint Kinematics in 10 Injury Situations From Female Team Handball and Basketball. *The American Journal of Sports Medicine*, 38(11), 2218–2225.
- Komi, P. V., & Karlsson, J. (1978). Skeletal muscle fibre types, enzyme activities and physical performance in young males and females. *Acta Physiologica Scandinavica*, 103(2), 210–218.
- Krishnan, C., & Williams, G. N. (2009). Sex differences in quadriceps and hamstrings EMG-moment relationships. *Medicine and Science in Sports and Exercise*, 41(8), 1652–1660.
- Kristianslund, E., Krosshaug, T., & van den Bogert, A. J. (2012). Effect of low pass filtering on joint moments from inverse dynamics: Implications for injury prevention. *Journal of*

Biomechanics, 45(4), 666–671.

Krosshaug, T., Nakamae, A., Boden, B. P., Engebretsen, L., Smith, G., Slauterbeck, J. R., ...

Bahr, R. (2007). Mechanisms of Anterior Cruciate Ligament Injury in Basketball. *The American Journal of Sports Medicine*, 35(3), 359–367.

LaBella, C. R., Hennrikus, W., Hewett, T. E., Council on Sports Medicine and Fitness, and

Section on Orthopaedics, J. S., Brooks, A., Demorest, R. A., ... Alexander, S. N. (2014).

Anterior cruciate ligament injuries: diagnosis, treatment, and prevention. *Pediatrics*, 133(5), e1437-50.

Landry, S. C., McKean, K. A., Hubble-Kozey, C. L., Stanish, W. D., & Deluzio, K. J. (2009).

Gender differences exist in neuromuscular control patterns during the pre-contact and early stance phase of an unanticipated side-cut and cross-cut maneuver in 15–18 years old adolescent soccer players. *Journal of Electromyography and Kinesiology*, 19(5), e370–e379.

LaPrade, R. F., & Burnett, Q. M. (1994). Femoral Intercondylar Notch Stenosis and Correlation

to Anterior Cruciate Ligament Injuries. *The American Journal of Sports Medicine*, 22(2), 198–203.

Lephart, S. M., Ferris, C. M., Riemann, B. L., Myers, J. B., & Fu, F. H. (2002). Gender

differences in strength and lower extremity kinematics during landing. *Clinical Orthopaedics and Related Research*, (401), 162–169.

Lewek, M. D., Ramsey, D. K., Snyder-Mackler, L., & Rudolph, K. S. (2005). Knee stabilization

in patients with medial compartment knee osteoarthritis. *Arthritis & Rheumatism*, 52(9), 2845–2853.

Llewellyn, M., Yang, J. F., & Prochazka, A. (1990). Human H-reflexes are smaller in difficult

- beam walking than in normal treadmill walking. *Experimental Brain Research*, 83(1), 22–28.
- Lloyd, D. G., & Buchanan, T. S. (2001). Strategies of muscular support of varus and valgus isometric loads at the human knee. *Journal of Biomechanics*, 34(10), 1257–1267.
- Lohmander, L. S., Englund, P. M., Dahl, L. L., & Roos, E. M. (2007). The Long-term Consequence of Anterior Cruciate Ligament and Meniscus Injuries: Osteoarthritis. *The American Journal of Sports Medicine*, 35(10), 1756–1769.
- Louie, J. K., & Mote, C. D. (1987). Contribution of the musculature to rotatory laxity and torsional stiffness at the knee. *Journal of Biomechanics*, 20(3), 281–300.
- Majewski, M., Susanne, H., & Klaus, S. (2006). Epidemiology of athletic knee injuries: A 10-year study. *The Knee*, 13(3), 184–188.
- Mall, N. A., Chalmers, P. N., Moric, M., Tanaka, M. J., Cole, B. J., Bach, B. R., & Paletta, G. A. (2014). Incidence and Trends of Anterior Cruciate Ligament Reconstruction in the United States. *The American Journal of Sports Medicine*, 42(10), 2363–2370.
- Malloy, P. J., Morgan, A. M., Meinerz, C. M., Geiser, C. F., & Kipp, K. (2016). Hip External Rotator Strength Is Associated With Better Dynamic Control of the Lower Extremity During Landing Tasks. *Journal of Strength and Conditioning Research*, 30(1), 282–291.
- Mandelbaum, B. R., Silvers, H. J., Watanabe, D. S., Knarr, J. F., Thomas, S. D., Griffin, L. Y., ... Garrett, W. (2005). Effectiveness of a Neuromuscular and Proprioceptive Training Program in Preventing Anterior Cruciate Ligament Injuries in Female Athletes: 2-Year Follow-up. *American Journal of Sports Medicine*, 33(7), 1003–1010.
- Mantovani, G., & Lamontagne, M. (2017). How Different Marker Sets Affect Joint Angles in Inverse Kinematics Framework. *Journal of Biomechanical Engineering*, 139(4), 044503.

- Markolf, K. L., Burchfield, D. M., Shapiro, M. M., Shepard, M. F., Finerman, G. A. M., & Slauterbeck, J. L. (1995). Combined knee loading states that generate high anterior cruciate ligament forces. *Journal of Orthopaedic Research*, *13*(6), 930–935.
- Matava, M. J., Freehill, A. K., Grutzner, S., & Shannon, W. (2002). Limb dominance as a potential etiologic factor in noncontact anterior cruciate ligament tears. *The Journal of Knee Surgery*, *15*(1), 11–16.
- McKay, M. J., Baldwin, J. N., Ferreira, P., Simic, M., Vanicek, N., Burns, J., & 1000 Norms Project Consortium. (2017). Normative reference values for strength and flexibility of 1,000 children and adults. *Neurology*, *88*(1), 36–43.
- McLean, S. G. (2008). The ACL injury enigma: we can't prevent what we don't understand. *Journal of Athletic Training*, *43*(5), 538–540. <https://doi.org/10.4085/1062-6050-43.5.538>
- McLean, S. G., Borotikar, B., & Lucey, S. M. (2010). Lower limb muscle pre-motor time measures during a choice reaction task associate with knee abduction loads during dynamic single leg landings. *Clinical Biomechanics*, *25*(6), 563–569.
- McLean, S. G., Huang, X., & van den Bogert, A. J. (2005). Association between lower extremity posture at contact and peak knee valgus moment during sidestepping: Implications for ACL injury. *Clinical Biomechanics*, *20*(8), 863–870.
- Mclena, S. G., & Samorezov, J. E. (2009). Fatigue-Induced ACL Injury Risk Stems from a Degradation in Central Control. *Medicine & Science in Sports & Exercise*, *41*(8), 1662–1673.
- Metz, C. E. (1978). Basic principles of ROC analysis. *Seminars in Nuclear Medicine*, *8*(4), 283–298.
- Meyer, D. E., Abrams, R. A., Kornblum, S., Wright, C. E., & Smith, J. E. (1988). Optimality in

- human motor performance: ideal control of rapid aimed movements. *Psychological Review*, 95(3), 340–370.
- More, R. C., Karras, B. T., Neiman, R., Fritschy, D., Woo, S. L.-Y., & Daniel, D. M. (1993). Hamstrings—an anterior cruciate ligament protagonist. *The American Journal of Sports Medicine*, 21(2), 231–237.
- Mornieux, G., Gehring, D., Fürst, P., & Gollhofer, A. (2014). Anticipatory postural adjustments during cutting manoeuvres in football and their consequences for knee injury risk. *Journal of Sports Sciences*, 32(13), 1255–1262.
- Myer, G. D., Ford, K. R., Barber Foss, K. D., Liu, C., Nick, T. G., & Hewett, T. E. (2009). The Relationship of Hamstrings and Quadriceps Strength to Anterior Cruciate Ligament Injury in Female Athletes. *Clinical Journal of Sport Medicine*, 19(1), 3–8.
- Myer, G. D., Ford, K. R., & Hewett, T. E. (2004). Methodological approaches and rationale for training to prevent anterior cruciate ligament injuries in female athletes. *Scandinavian Journal of Medicine and Science in Sports*, 14(5), 275–285.
- Myer, G. D., Ford, K. R., & Hewett, T. E. (2005). The effects of gender on quadriceps muscle activation strategies during a maneuver that mimics a high ACL injury risk position. *Journal of Electromyography and Kinesiology*, 15(2), 181–189.
- Myer, G. D., Ford, K. R., Paterno, M. V., Nick, T. G., & Hewett, T. E. (2008). The Effects of Generalized Joint Laxity on Risk of Anterior Cruciate Ligament Injury in Young Female Athletes. *The American Journal of Sports Medicine*, 36(6), 1073–1080.
- Myklebust, G., Holm, I., Mæhlum, S., Engebretsen, L., & Bahr, R. (2003). Clinical, Functional, and Radiologic Outcome in Team Handball Players 6 to 11 Years after Anterior Cruciate Ligament Injury. *The American Journal of Sports Medicine*, 31(6), 981–989.

- Myklebust, G., Maehlum, S., Engebretsen, L., Strand, T., & Solheim, E. (1997). Registration of cruciate ligament injuries in Norwegian top level team handball. A prospective study covering two seasons. *Scandinavian Journal of Medicine & Science in Sports*, 7(5), 289–292.
- Negrete, R. J. ;, Schick, E. A. ;, & Cooper, J. P. (2007). *LOWER-LIMB DOMINANCE AS A POSSIBLE ETIOLOGIC FACTOR IN NONCONTACT ANTERIOR CRU*. *Journal of Strength and Conditioning Research* (Vol. 21).
- Niu, W., Wang, Y., He, Y., Fan, Y., & Zhao, Q. (2011). Kinematics, kinetics, and electromyogram of ankle during drop landing: A comparison between dominant and non-dominant limb. *Human Movement Science*, 30(3), 614–623.
- Noyes, F. R., & Grood, E. S. (1976). The strength of the anterior cruciate ligament in humans and Rhesus monkeys. *The Journal of Bone and Joint Surgery. American Volume*, 58(8), 1074–1082.
- Oberländer, K. D., Brüggemann, G.-P., Höher, J., & Karamanidis, K. (2014). Knee mechanics during landing in anterior cruciate ligament patients: A longitudinal study from pre- to 12months post-reconstruction. *Clinical Biomechanics*, 29(5), 512–517.
- Oiestad, B. E., Holm, I., Engebretsen, L., & Risberg, M. A. (2011). The association between radiographic knee osteoarthritis and knee symptoms, function and quality of life 10-15 years after anterior cruciate ligament reconstruction. *British Journal of Sports Medicine*, 45(7), 583–588.
- Olsen, O.-E., Myklebust, G., Engebretsen, L., & Bahr, R. (2004). Injury Mechanisms for Anterior Cruciate Ligament Injuries in Team Handball: A Systematic Video Analysis. *American Journal of Sports Medicine*, 32(4), 1002–1012.

- Örtqvist, M., Roos, E. M., Broström, E. W., Janarv, P.-M., & Iversen, M. D. (2012). Development of the Knee Injury and Osteoarthritis Outcome Score for Children (KOOS-Child). *Acta Orthopaedica*, 83(6), 666–673.
- P.W. Hodges, B. H. B. (1996). A comparison of computer-based methods for the determination of onset of muscle contraction using electromyography. *Electroencephalography and Clinical Neurophysiology/Electromyography and Motor Control*, 101(6), 511–519.
- Padua, D. A., Marshall, S. W., Boling, M. C., Thigpen, C. A., Garrett, W. E., & Beutler, A. I. (2009). The Landing Error Scoring System (LESS) Is a Valid and Reliable Clinical Assessment Tool of Jump-Landing Biomechanics. *The American Journal of Sports Medicine*, 37(10), 1996–2002.
- Pappas, E., Hagins, M., Sheikhzadeh, A., Nordin, M., & Rose, D. (2007). Biomechanical Differences Between Unilateral and Bilateral Landings From a Jump: Gender Differences. *Clinical Journal of Sport Medicine*, 17(4), 263–268.
- Park, E.-J., Lee, J.-H., Ryue, J.-J., Sohn, J.-H., & Lee, K.-K. (2011). Influence of Anticipation on Landing Patterns during Side-Cutting Maneuver in Female Collegiate Soccer Players. *Korean Journal of Sport Biomechanics*, 21(4), 391–395.
- Pataky, T. C., Robinson, M. A., & Vanrenterghem, J. (2013). Vector field statistical analysis of kinematic and force trajectories. *Journal of Biomechanics*, 46(14), 2394–2401.
- Paterno, M. V., Myer, G. D., Ford, K. R., & Hewett, T. E. (2004). Neuromuscular Training Improves Single-Limb Stability in Young Female Athletes. *Journal of Orthopaedic & Sports Physical Therapy*, 34(6), 305–316.
- Piasecki, D. P., Spindler, K. P., Warren, T. A., Andrish, J. T., & Parker, R. D. (2003). Intraarticular injuries associated with anterior cruciate ligament tear: findings at ligament

- reconstruction in high school and recreational athletes. An analysis of sex-based differences. *The American Journal of Sports Medicine*, 31(4), 601–605.
- Pollard, C. D., Sigward, S. M., & Powers, C. M. (2010). Limited hip and knee flexion during landing is associated with increased frontal plane knee motion and moments. *Clinical Biomechanics*, 25(2), 142–146.
- Pope, M. H., Johnson, R. J., Brown, D. W., & Tighe, C. (1979). The role of the musculature in injuries to the medial collateral ligament. *The Journal of Bone and Joint Surgery. American Volume*, 61(3), 398–402.
- Powers, C. M. (2010). The Influence of Abnormal Hip Mechanics on Knee Injury: A Biomechanical Perspective. *Journal of Orthopaedic & Sports Physical Therapy*, 40(2), 42–51.
- Renström, P., Arms, S. W., Stanwyck, T. S., Johnson, R. J., & Pope, M. H. (1986). Strain within the anterior cruciate ligament during hamstring and quadriceps activity*. *The American Journal of Sports Medicine*, 14(1), 83–87.
- Rozzi, S. L., Lephart, S. M., Gear, W. S., & Fu, F. H. (1999). Knee Joint Laxity and Neuromuscular Characteristics of Male and Female Soccer and Basketball Players. *The American Journal of Sports Medicine*, 27(3), 312–319.
- Rudolph, K. S., Axe, M. J., Buchanan, T. S., Scholz, J. P., & Snyder-Mackler, L. (2001). Dynamic stability in the anterior cruciate ligament deficient knee. *Knee Surgery, Sports Traumatology, Arthroscopy*, 9(2), 62–71.
- Sale, D., Quinlan, J., Marsh, E., McComas, A. J., & Belanger, A. Y. (1982). Influence of joint position on ankle plantarflexion in humans. *Journal of Applied Physiology: Respiratory, Environmental and Exercise Physiology*, 52(6), 1636–1642.

- Schmitz, R. J., Kulas, A. S., Perrin, D. H., Riemann, B. L., & Shultz, S. J. (2007). Sex differences in lower extremity biomechanics during single leg landings. *Clinical Biomechanics*, 22(6), 681–688.
- Seidler, R. ., Noll, D. ., & Thiers, G. (2004). Feedforward and feedback processes in motor control. *NeuroImage*, 22(4), 1775–1783.
- Sell, Ferris, C. M., Abt, J. P., Tsai, Y.-S., Myers, J. B., Fu, F. H., & Lephart, S. M. (2005). The Effect of Direction and Reaction on the Neuromuscular and Biomechanical Characteristics of the Knee During Tasks That Simulate the Noncontact Anterior Cruciate Ligament Injury Mechanism. *American Journal of Sports Medicine*, 34(1), 43–54.
- Sell, T. C., Ferris, C. M., Abt, J. P., Tsai, Y.-S., Myers, J. B., Fu, F. H., & Lephart, S. M. (2007). Predictors of proximal tibia anterior shear force during a vertical stop-jump. *Journal of Orthopaedic Research*, 25(12), 1589–1597.
- Shin, C. S., Chaudhari, A. M., & Andriacchi, T. P. (2009). The effect of isolated valgus moments on ACL strain during single-leg landing: A simulation study. *Journal of Biomechanics*, 42(3), 280–285.
- Shin, C. S., Chaudhari, A. M., & Andriacchi, T. P. (2011). Valgus Plus Internal Rotation Moments Increase Anterior Cruciate Ligament Strain More Than Either Alone. *Medicine & Science in Sports & Exercise*, 43(8), 1484–1491.
- Sigward, S. M., & Powers, C. M. (2006). The influence of gender on knee kinematics, kinetics and muscle activation patterns during side-step cutting. *Clinical Biomechanics*, 21(1), 41–48.
- Sigward, S., & Powers, C. M. (2006). The influence of experience on knee mechanics during side-step cutting in females. *Clinical Biomechanics*, 21(7), 740–747.

Simon, D., Mascarenhas, R., Saltzman, B. M., Rollins, M., Bach, B. R., & MacDonald, P.

(2015). The Relationship between Anterior Cruciate Ligament Injury and Osteoarthritis of the Knee. *Advances in Orthopedics*, 2015, 928301.

Sugimoto, D., Myer, G. D., Barber Foss, K. D., Pepin, M. J., Micheli, L. J., & Hewett, T. E.

(2016). Critical components of neuromuscular training to reduce ACL injury risk in female athletes: meta-regression analysis. *British Journal of Sports Medicine*, 50(20), 1259–1266.

Swenson, D. M., Collins, C. L., Best, T. M., Flanigan, D. C., Fields, S. K., & Comstock, R. D.

(2013). Epidemiology of knee injuries among U.S. high school athletes, 2005/2006–2010/2011. *Medicine and Science in Sports and Exercise*, 45(3), 462–469.

Taylor, S. J., Whincup, P. H., Hindmarsh, P. C., Lampe, F., Odoki, K., & Cook, D. G. (2001).

Performance of a new pubertal self-assessment questionnaire: a preliminary study. *Paediatric and Perinatal Epidemiology*, 15(1), 88–94.

Thissen, D., Steinberg, L., & Kuang, D. (2002). Quick and Easy Implementation of the

Benjamini-Hochberg Procedure for Controlling the False Positive Rate in Multiple Comparisons. *Journal of Educational and Behavioral Statistics*, 27(1), 77–83.

Tillman, M. D., Bauer, J. A., Cauraugh, J. H., & Trimble, M. H. (2005). Differences in lower

extremity alignment between males and females. Potential predisposing factors for knee injury. *The Journal of Sports Medicine and Physical Fitness*, 45(3), 355–359.

Tsai, L.-C., McLean, S., Colletti, P. M., & Powers, C. M. (2012). Greater muscle co-contraction

results in increased tibiofemoral compressive forces in females who have undergone anterior cruciate ligament reconstruction. *Journal of Orthopaedic Research*, 30(12), 2007–2014.

van Deursen, R. W. M., Cavanagh, P. R., van Ingen Schenau, G. J., Becker, M. B., & Ulbrecht,

- J. S. (1998). The role of cutaneous information in a contact control task of the leg in humans. *Human Movement Science*, *17*(1), 95–120.
- van Ingen Schenau, G. J., Bobbert, M. F., & Rozendal, R. H. (1987). The unique action of bi-articular muscles in complex movements. *Journal of Anatomy*, *155*, 1–5.
- van Ingen Schenau, G. J., Boots, P. J. M., de Groot, G., Snackers, R. J., & van Woensel, W. W. L. M. (1992). The constrained control of force and position in multi-joint movements. *Neuroscience*, *46*(1), 197–207.
- Vapnik, V., & Chapelle, O. (2000). Bounds on error expectation for support vector machines. *Neural Computation*, *12*(9), 2013–2036.
- Wagner H, B. R. (1999). Stabilizing Function of Skeletal Muscles: an Analytical Investigation. *Journal of Theoretical Biology*, *199*(2), 163–179.
- Wang, X., Malik, A., Bartel, D. L., Wright, T. M., & Padgett, D. E. (2016). Load Sharing Among Collateral Ligaments, Articular Surfaces, and the Tibial Post in Constrained Condylar Knee Arthroplasty. *Journal of Biomechanical Engineering*, *138*(8), 081002.
- Werner, B. C., Yang, S., Looney, A. M., & Gwathmey, F. W. (2016). Trends in Pediatric and Adolescent Anterior Cruciate Ligament Injury and Reconstruction. *Journal of Pediatric Orthopaedics*, *36*(5), 447–452.
- Whittaker, J. L., Woodhouse, L. J., Nettel-Aguirre, A., & Emery, C. A. (2015). Outcomes associated with early post-traumatic osteoarthritis and other negative health consequences 3–10 years following knee joint injury in youth sport. *Osteoarthritis and Cartilage*, *23*(7), 1122–1129.
- Wikstrom, E. A., Tillman, M. D., Schenker, S. M., & Borsa, P. A. (2008). Jump-landing direction influences dynamic postural stability scores. *Journal of Science and Medicine in*

Sport, 11(2), 106–111.

Wikstrom, Tillman, M. D., Schenker, S., & Borsa, P. A. (2007). Failed jump landing trials:

deficits in neuromuscular control. *Scandinavian Journal of Medicine & Science in Sports, 18(1)*, 55–61.

Winter, D. A. (2009). *Biomechanics and motor control of human movement*. Wiley.

Winter, E. M., & Brookes, F. B. C. (1991). Electromechanical response times and muscle

elasticity in men and women. *Eur J Appl Physiol Eump~n , Ou...o, Applied Physiology and Occupational Physiology, 63*, 124–128.

Wojtys, E. M., Huston, L. J., Lindenfeld, T. N., Hewett, T. E., & Greenfield, M. L. V. H. (1998).

Association Between the Menstrual Cycle and Anterior Cruciate Ligament Injuries in Female Athletes. *The American Journal of Sports Medicine, 26(5)*, 614–619.

Woo, S. L.-Y., Hollis, J. M., Adams, D. J., Lyon, R. M., & Takai, S. (1991). Tensile properties

of the human femur-anterior cruciate ligament-tibia complex. *The American Journal of Sports Medicine, 19(3)*, 217–225.

Yeow, C. H., Lee, P. V. S., & Goh, J. C. H. (2011). An investigation of lower extremity energy

dissipation strategies during single-leg and double-leg landing based on sagittal and frontal plane biomechanics. *Human Movement Science, 30(3)*, 624–635.

Zatsiorsky, V., Seluyanov, V., & Chugunova, L. (1990). In vivo body segment inertial

parameters determination using a gamma-scanner method. *Contemporasy Problems of Biomechnics*.

Zazulak, B. T., Hewett, T. E., Reeves, N. P., Goldberg, B., & Cholewicki, J. (2007). Deficits in

Neuromuscular Control of the Trunk Predict Knee Injury Risk. *The American Journal of Sports Medicine, 35(7)*, 1123–1130.

- Zebis, M. K., Andersen, L. L., Bencke, J., Kjær, M., & Aagaard, P. (2009). Identification of Athletes at Future Risk of Anterior Cruciate Ligament Ruptures by Neuromuscular Screening. *The American Journal of Sports Medicine*, *37*(10), 1967–1973.
- Zelisko, J. A., Noble, H. B., & Porter, M. (1982). A comparison of men's and women's professional basketball injuries. *The American Journal of Sports Medicine*, *10*(5), 297–299.
- Zeni, J. A., Rudolph, K., & Higginson, J. S. (2010). Alterations in quadriceps and hamstrings coordination in persons with medial compartment knee osteoarthritis. *Journal of Electromyography and Kinesiology*, *20*(1), 148–154.
- Zhang, S. N., Bates, B. T., & Dufek, J. S. (2000). Contributions of lower extremity joints to energy dissipation during landings. *Medicine and Science in Sports and Exercise*, *32*(4), 812–819.

APPENDIX

Table A.1

Summary of all tasks performed by participants during each data collection

Task	Description
Unanticipated Drop-Jump	Left leg Two Leg Right Leg
Anticipated Drop-Jump	Left leg Two Leg Right Leg
Dynamic Strength	Knee Extension Knee Flexion
Isometric Strength	Knee Extension Knee Flexion
Muscular Endurance	Quadriceps Deficit Hamstrings Deficit

Table A.2

Participant characteristics and subjective functional scores. Healthy male and female means and standard deviations

	Male (n=16)	Female (n=16)
Age (yrs.)	15.8±1.87	15.7±1.7
BMI (kg/m ²)	21.1±2.66	21.1±2.9
Waterloo Footedness Questionnaire (R=+20; L=-20)	9.62 ±6.78	9.37±6.84
HSS Pedi-FABS (0-30)	22.6±5.95	20±3.98
KOOS Child – Symptoms (%)	95.5±5.76	95.3±4.65
KOOS Child – Pain (%)	93.7±10.8	96.5±4.55
KOOS Child – Daily Living (%)	96.7±8.34	99.1±2.01
KOOS Child – Sport and Recreation (%)	94.6±8.45	96.6±7.87
KOOS Child – Quality of Life (%)	93±12.7	97.4 ±4.27
Tanner Stage (1-5)	4.12±1.09	4.06±1.12
Primary Sport	Rowing <i>n</i> =7 Soccer <i>n</i> =4 Basketball <i>n</i> =3 Ultimate Frisbee <i>n</i> =1 Karate <i>n</i> =1	Rowing <i>n</i> =8 Soccer <i>n</i> =3 Swimming <i>n</i> =3 Ringette <i>n</i> =2

Note. 27 of 32 participants competed in multiple competitive sports, only primary sports shown

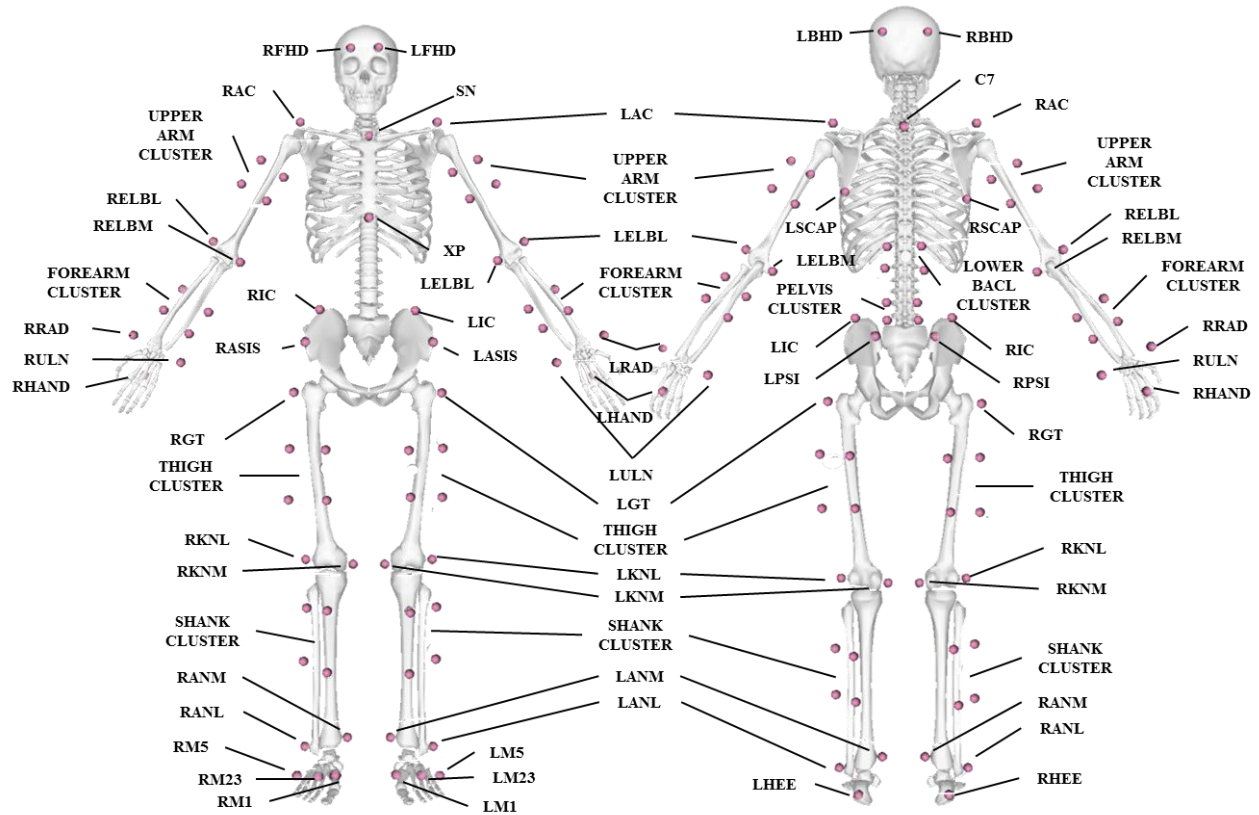


Figure A.1. Clinical Biomechanics Research Unit (CBRU) cluster marker set, adapted from the Human Movement Biomechanics Laboratory cluster marker set. Plug-in-Gait marker set acted as the basis with the additions of medial knee, ankle and elbow markers (LMKN, RMKN, LMAN, RMAN, LELBM, RELBM), three thigh, tibial, upperarm and forearm markers (THIGH CLUSTER, SHANK CLUSTER, UPPERARM CLUSTER, FOREARM CLUSTER), two iliac crest markers (LIC, RIC), four lower back markers (LOWER BACK CLUSTER), two pelvis markers (PELVIS CLUSTER) and two metatarsal markers (RMT1, RMT5, LMT1, LMT5) (figure adapted from Mantovani and Lamontagne, 2016)

Table A.3

Body segment parameter data from Zatsiorsky et al. (1990), as modified by deLeva (1996). Segment masses are relative to body mass; segment CM positions are referenced either to proximal or cranial endpoints (origin). Both segment CM positions and radii of gyration (r) are relative to the respective segment lengths.

Segment	Endpoint		Mass (%)		CoM (%)		Sagittal r (%)		Transverse r (%)		Longitudinal r (%)	
	Proximal	Distal	Female	Male	Female	Male	Female	Male	Female	Male	Female	Male
Head	VERT	CERV	6.68	6.94	58.94	59.76	27.1	30.3	29.5	31.5	26.1	26.1
Trunk	CERV	MIDH	42.57	43.46	41.51	44.86	30.7	32.8	29.2	30.6	14.7	16.9
Upper Arm	SJC	EJC	2.55	2.71	57.54	57.72	27.8	28.5	26	26.9	14.8	15.8
Forearm	EJC	WJC	1.38	1.62	45.59	45.74	26.1	27.6	25.7	26.5	9.4	12.1
Thigh	HJC	KJC	14.78	14.16	36.12	40.95	36.9	32.9	36.4	32.9	16.2	14.9
Shank	KJC	AJC	4.81	4.33	44.16	44.59	26.7	25.1	26.3	24.6	9.2	10.2
Foot	HEEL	TTIP	1.29	1.37	40.14	44.15	29.9	25.7	27.9	24.5	13.9	12.4

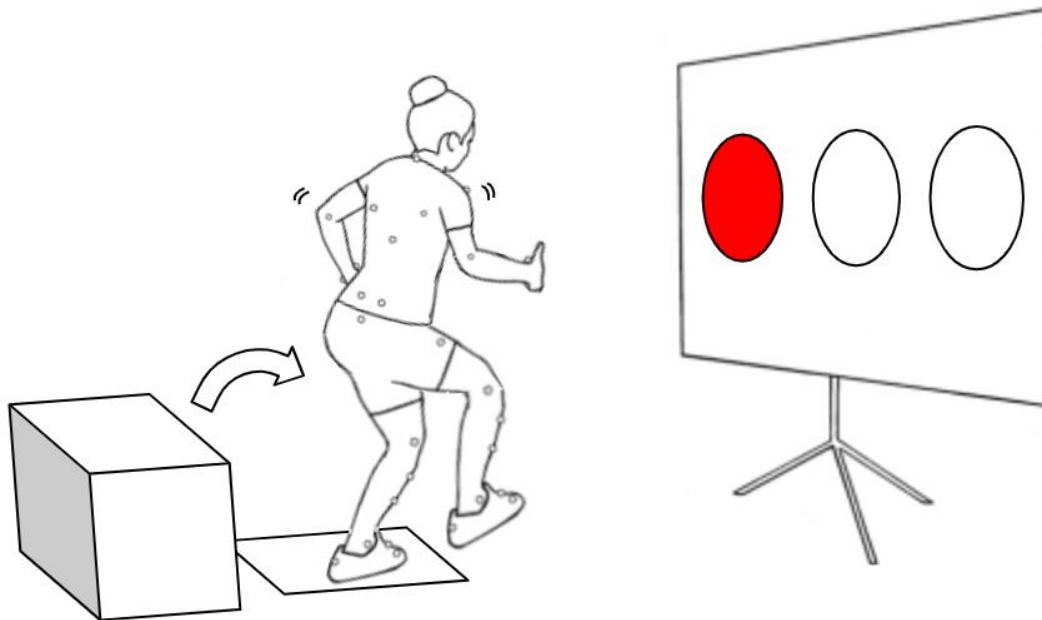


Figure A.2. Participants performed drop-jumps from a raised platform aligned to their tibial plateau. Projector in front of participants displayed a visual cue for the required landing leg (left leg landing shown). Visual cue was shown during the *flight phase* of the drop-jump task (~500ms before landing).

Table A.4

Isometric strength data for the dominant limb of male and female participants during the MVIC trials

	Knee Extension (Nm/kg)	Knee Flexion (Nm/kg)	Plantar Flexion (Nm/kg)	Hip Abduction (Nm/kg)	Hip Extension (Nm/kg)
Male	3.34±0.63	1.71±0.33	3.11±0.51	1.79±0.42	2.41±0.58
Female	2.79±0.4	1.49±0.27	2.72±0.45	1.45±0.48	1.79±0.44