# EVALUATION OF KNEE STABILIZATION STRATEGIES IN ADOLESCENT MALES AND FEMALES WITH AND WITHOUT AN ACL INJURY DURING THE LUNGE AND DROP VERTICAL JUMP

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# Statement of Contributions

I, Joanna Geck, was responsible for the theory and experimental design of all studies, with input and guidance from Dr. Daniel L. Benoit (Supervisor), Dr. Teresa Flaxman, Nicholas Romanchuk and my thesis committee comprised of Dr. Sasha Carsen and Dr. Julie Nantel. My coworkers within the Clinical Biomechanics Research Unit assisted in participant recruitment, data collection and protocol set-up. Data and statistical analysis was performed primarily by me, with assistance from Nicholas Romanchuk and Blake Miller. Preparation of all manuscripts was completed by me, with contributions from Dr. Daniel L. Benoit, Michael Del Bel, Dr. Teresa Flaxman, Blake Miller, Nicholas Romanchuk, and Christine Smith.

# Glossary of Terms

| | |
|---|---|
| ACL | Anterior Cruciate Ligament |
| ACLd | Anterior Cruciate Ligament Deficient |
| ACLi | Anterior Cruciate Ligament Injury |
| BF | Biceps Femoris |
| BMI | Body Mass Index |
| CI | Coactivation Index |
| deg | Degree |
| DVJ | Drop-Vertical Jump |
| EMG | Electromyography |
| GMed | Gluteus Medius |
| GRF | Ground Reaction Force |
| HSS Pedi-FABS | Hospital for Special Surgery Pediatric Functional Activity Brief Scale |
| KOOS-Child | Knee Injury and Osteoarthritis Outcome Score Children |
| iBF | Integrated Biceps Femoris |
| iEMG | Integrated Electromyography |
| iGMed | Integrated Gluteus Medius |
| iKEXC | Integrated Knee Excursion |
| iKJP | Integrated Knee Joint Power |
| iLG | Integrated Lateral Gastrocnemius |
| iMG | Integrated Medial Gastrocnemius |
| iRF | Integrated Rectus Femoris |
| iST | Integrated Semitendinosus |
| iVL | Integrated Vastus Lateralis |
| iVM | Integrated Vastus Medialis |
| JP | Joint Power |
| KEXC | Knee Excursion |
| LG | Lateral Gastrocnemius |
| MG | Medial Gastrocnemius |
| MVIC | Maximum Voluntary Isometric Contraction |
| PKF | Peak Knee Flexion |
| RF | Rectus Femoris |
| RTA | Return-to-Activity |
| SnPM | Statistical Parametric Mapping |
| SPM | Statistical Non-Parametric Mapping |
| ST | Semitendinosus |
| VL | Vastus Lateralis |
| VM | Vastus Medialis |
| Q:H | Quadriceps to Hamstring Coactivation Index |
| Q:G | Quadriceps to Gastrocnemius Coactivation Index |

# General Abstract

***Purpose:*** Adolescents have significantly higher rates of diagnosed anterior cruciate ligament (ACL) injuries compared to adult cohorts. Approximately two-thirds of ACL injuries are non-contact scenarios that occur while performing "high-risk" maneuvers. Less than 50% of adolescents are able to return-to-activity, with females specifically having a lower activity level post-injury (Hewett, Di Stasi, & Myer, 2013; Schmale, Kweon, Larson, & Bompadre, 2014). Identifying the quantitative demand of a task used to assess return-to-activity will help establish its role in evaluating the knee stabilization strategies based on muscular coactivations and biomechanical outputs. Therefore, the aim of this study was to (1) assess the neuromuscular and biomechanical quantitative outputs of the lunge and drop-vertical jump (DVJ) in healthy adolescent male and females athletes and (2) to examine the muscular coactivation strategies of adolescent male and female athletes with and without an ACL injury.

***Methods:*** A total of 68 uninjured adolescent male and female athletes between the ages of 10 to-18 were used to identify the quantitative demand of the lunge and DVJ. Neuromuscular and biomechanical quantitative outputs included mean peak knee flexion (PKF), integrated knee excursion (iKEXC) in the sagittal and frontal planes, integrated knee joint power (iJP), and integrated electromyography (EMG) were used to assess the within (task) and between (sex) interactions. An additional 17 male and 37 female adolescents with an ACL injury were included to assess the impact of an ACL injury on the knee stabilization strategies (coactivations) used to maintain dynamic knee joint stability (frontal plane knee excursion). Ethics was approved by the University of Ottawa Research Ethics Board (uOttawa REB H09/17/10) (CHEO REB 17/74X).

***Results:*** Quantitative data for uninjured groups indicated that the lunge produced greater peak knee flexion, knee excursion, and quadriceps activation values than the DVJ. Conversely, the DVJ produced greater joint power, biceps femoris, gastrocnemii, and gluteus medius values. As for knee stabilization strategies, during the DVJ female ACL injured groups produced greater symmetry and higher muscular activations between anterior-posterior and medial-lateral muscular coactivations, which resulted in increased stability compared to uninjured female groups. Males with an ACL injury indicated similar knee stabilization strategies however decreased stability compared to males without an ACL injury.

***Conclusion:*** Results of this thesis identified differences in quantitative data between the lunge and DVJ, indicating differing demand requirements for each task. Results of the second study indicate that uninjured females use knee stabilization strategies that do not restrict their degrees of freedom through asymmetrical coactivations, while females with an ACL injury have increased coactivations in both anterior-posterior and medial-lateral muscle groups, resulting in increased dynamic knee joint stability as evidenced by reduced frontal plane knee excursion motion. Males, however, failed to show a difference between groups in dynamic knee stability, suggesting that those with an ACL injury compensated in a way to perform the DVJ efficiently and similarly to the uninjured group, while maintaining dynamic knee joint stability. In a clinical setting, these findings may help in understanding the direction of use of the lunge and DVJ tasks in a rehabilitation setting. As well as provide insight into the differing male and female adolescent knee stabilization strategies used to maintain dynamic knee joint stability during functional tasks.

# Chapter 1. Introduction

Children are now being introduced to the world of organized sport as early as three years of age (ParticipACTION Report, 2018). In Canada, an estimated 77% of children participate in some form of organized physical activity or sport (ParticipACTION Report, 2018). Not only is there a rise in participation rates but also in length and intensity of training at an earlier age (Werner, Yang, Looney, & Gwathmey, 2016). While increased physical activity and team sport participation has a positive influence on physical and psychological health (Eime, Young, Harvey, Charity, & Payne, 2013; ParticipACTION Report, 2018), this rise in participation has also led to an increase in injury rates (Dekker, Rush, & Schmitz, 2018; Werner et al., 2016). One of the more common and debilitating injuries found in the adolescent population (8-18 years) is an anterior cruciate ligament (ACL) tear. Adolescents now have a higher rate of diagnosed ACL tears than adults, with reconstruction rates growing at a rate of 924% from 1994 to 2006 (Dekker et al., 2018). More recently, Beck and colleagues (2017) reported a 2.3% yearly increase in the number of ACL injuries in patients between the ages of 6-18 years, with females showing to have a significantly higher injury rate (2-8 times) at a younger age compared to males (Beck, Lawrence, Nordin, DeFor, & Tompkins, 2017; Dekker et al., 2018).

An ACL injury is a life altering event for the adolescent due to a multitude of factors ranging from decreased physical activity, possible growth disturbances, increased risk of early onset osteoarthritis and secondary knee damage such as meniscal and chondral injury (Dekker et al., 2018; Noyes & Barber-Westin, 2018). Whether treated surgically, and/or with rehabilitation, this injury puts a large toll on the healthcare system. In the USA alone, annual costs have been estimated to reach upwards of $17 billion USD (Noyes and Barber-Westin, 2018; Paschos, 2017).

Despite the rise in injury rates and the fact that females between the ages of 10 and 18 have the highest risk of sustaining an ACL injury (Beck et al., 2017; Dekker et al., 2018; Werner et al., 2016), there is surprisingly little research that focuses on this population. For example, there is relatively little research exploring the causes of these sex differences in injury rates, in particular the interaction between sex and injury on neuromuscular function and how a change in function (compensation) can cause biomechanical alterations in knee joint stability in adolescent athletes (Otsuki, Del Bel, & Benoit, 2019). Previous research has identified that the body's ability to maintain dynamic knee joint stability is predominantly regulated through the use of neuromuscular strategies, such as muscular coactivations (Baratta et al., 1988; Flaxman, Speirs, & Benoit, 2012; Noyes & Barber-Westin, 2018; Solomonow et al., 1987). These strategies are the only active and modifiable regulators that can contribute to the manipulation of biomechanical movement patterns to enhance dynamic joint stability and load distribution (Hsieh & Walker, 1976; Noyes & Barber-Westin, 2018). These gaps in the literature are placing considerable limitations on our efforts to combat the rise in incidence rates and must be addressed to provide essential knowledge for developing optimal injury prevention and rehabilitation strategies.

To address these gaps, we must begin by examining the neuromuscular and biomechanical strategies of ACL injured and uninjured adolescent male and female athletes completing tasks that differ in movement pattern and loading demands, such as the lunge and drop-vertical jump (Noyes & Barber-Westin, 2018; Wild, Steele, & Munro, 2012). Only then can we gain a better understanding of when and where the differences occur and how it might influence the knee stabilisation strategies of what is considered a healthy or 'at-risk' knee. By incorporating tasks that challenge the body's neuromuscular and biomechanical control alternatively, we can assess the relevancy and appropriateness of the task that will help establish proper progressive programs and return-to-activity (RTA) guidelines associated with an ACL injury.

# Chapter 2. Defining Dynamic Knee Joint Stability

## 2.1 Dynamic Knee Joint Stability

Stability, in regard to a joint, cannot be solely expressed as a mechanical function. Therefore, for the purposes of this thesis, stability, defined by Reimann and Lephart (2002), is the "state of a joint remaining or promptly returning to proper alignment through an equalization of forces." (Riemann & Lephart, 2002). The knee's ability to efficiently support the loads is dependent on the integration of the articular geometry (size and shape of the cartilage, menisci, and tibial spines), soft tissue restraints, muscle action, and body mass of the individual (Flaxman et al., 2012; Johansson, Sjolander, & Sojka, 1991; Noyes & Barber-Westin, 2018; Sturnick et al., 2015). This combination helps resist potentially dangerous forces and external adduction moments which are commonly found in sporting maneuvers associated with ACL injury (Johansson et al., 1991; Noyes & Barber-Westin, 2018). The ability of the ligaments and soft tissues alone to provide joint stability is limited due to the geometry of the joint, tissue tolerance thresholds, and the insertion locations of the ligaments (Baratta et al., 1988; Johansson et al., 1991). Therefore, muscles, being the only active and modifiable regulators, can contribute to dynamic joint stability and load distribution (Frank R. Noyes & Barber-Westin, 2018). It is the dynamic ability of muscles to develop tensile forces across the knee joint throughout the range of motion that allows it to resist abnormal translations, distractions, or rotations that may induce injury (Baratta et al., 1988).

# Chapter 3. Literature Review

## 3.1 ACL Injury Mechanism

From a mechanical perspective, the primary function of the ACL is to help stabilize the knee by preventing excessive anterior translation of the tibia relative to the femur, and to secondarily resist tibial rotation (Takeda, Xerogeanes, Livesay, Fu, & Woo, 1994). The ACL provides sensory information to form the basis of proprioceptive feedback that recognizes movement patterns that can be deleterious (Cerulli & Benoit, 2001). However, even with the ACL's mechanical and sensory ability, it is still the most commonly injured ligament in the knee (Beck et al., 2017; Majewski, Susanne, & Ck Klaus, 2006), with the majority of these injuries occurring during so-called non-contact mechanisms (McNair, Marshall, & Matheson, 1990), defined as an event during which "forces applied to the knee at the time of injury resulted from the athlete's own movement and did not involve contact with another athlete or object" (Gianotti, Marshall, Hume, & Bunt, 2009). As such, it can be argued that many of the biomechanical and neuromuscular factors influencing a non-contact ACL injury are intrinsic and modifiable, thus opening the door for preventive intervention strategies (Pfeifer, Beattie, Sacko, & Hand, 2018). Approximately two-thirds of ACL injuries are non-contact scenarios (McNair et al., 1990) that involve multiplanar loadings that occur while in situations of high-risk maneuvers such as cutting, pivoting, decelerating, or landing from a jump (Joseph et al., 2013; Myer, Ford, & Hewett, 2005; Noyes & Barber-Westin, 2018).

A typical biomechanical loading pattern that results in an ACL injury includes landing in a relatively extended position about the hip and knee, with the hip and tibia internally rotated, the knee abducted, and the foot in a fixed position on the ground (Hewett, Zazulak, Myer, & Ford, 2005; Kaeding, Léger-St-Jean, & Magnussen, 2017; Myer, Sugimoto, Thomas, & Hewett, 2013;

Shin, Chaudhari, & Andriacchi, 2011). It has been hypothesised that this extended position causes the lower limb to absorb greater loads through passive joint restraints (ligaments, capsule) rather than the active musculo-tendon system (muscles, tendons) (Kaeding et al., 2017). It is in this extended position that the active components of the quadriceps muscles are shortened causing the cross-bridges to overlap and interference to occur which results in a reduction of tension and a need for passive restraints to compensate (Winter, 2009).

## 3.2 Injury Epidemiology

Historically, surgical intervention for adolescents have been avoided or delayed in order to avoid unnecessary physeal injury and/or growth disturbances (Dingel, Aoyama, Ganley, & Shea, 2019). Now, however, it is reported that adolescents are approximately three times more likely to undergo a primary ACL reconstruction as compared to 20 years ago (Dekker et al., 2018; Dodwell et al., 2014). Despite the continual development of ACL reconstruction techniques, approximately less than 50% of the adolescent population are able to return to their pre-injury level of activity (Dekker et al., 2018; Schmale et al., 2014). Females, specifically, are associated with a lower activity level post-surgery and are less likely to return to their previous level of sport (Dunn & Spindler, 2010; Hewett et al., 2013).

Although reconstructive surgery attempts to restore mechanical stability, adolescents are still undergoing an increase in reinjury rates which are, once again, higher in females (Dekker et al., 2018; Newman et al., 2015; Reid et al., 2017; Shelbourne, Gray, & Haro, 2009). This may, in part, be due to the long term consequences associated with neuromuscular function, because not only does the ACL injury itself lead to decreased neuromuscular function (Del Bel et al., 2018), but the surgery also further exacerbates this deficit by arthrogenic muscle inhibition (discussed below) (Gauffin 1992; Palmieri-Smith, Thomas, and Wojtys 2008). Therefore, it is critical to continue to develop an understanding of adolescent's neuromuscular function and how it is impacted once trauma to the ACL occurs. Only then can we improve our understanding of the current treatment standards for adolescent individuals with ACL injuries and further progress the current RTA guidelines.

### 3.3 Altered Neuromuscular Function in the ACL Deficient Population

One of the more persistent neuromuscular deficiencies that is associated with an ACL injury is quadriceps weakness (Hurley, Jones, & Newham, 1994; Palmieri-Smith et al., 2008; D. Urbach, Nebelung, Becker, & Awiszus, 2001). Current literature suggests that most individuals have a greater than 20% strength deficit at 6 months post reconstruction compared to controls and a continued deficit several years after in both limbs (Palmieri-Smith et al., 2008; Dietmar Urbach & Awiszus, 2002; Dietmar Urbach, Nebelung, Weiler, & Awiszus, 1999). Clinicians and scientists continue to make advances in improving intervention techniques that maximize quadriceps output and RTA guidelines that properly assess the athlete's readiness (Wright et al., 2015). However, there is still a gap in the knowledge that translates to the ability of restoring muscle strength to preinjury levels.

Two primary conditions have been linked to this issue: Arthrogenic muscle inhibition and muscle atrophy. Arthrogenic muscle inhibition, or voluntary activation failure, presents as a loss or reduction of mechanical and afferent feedback (Palmieri-Smith et al., 2008). In other words, when injured, the ACL and quadriceps ligamentous-muscular reflex is disrupted, which is caused mainly by joint effusion or a loss of mechanoreceptors (Iles, Stokes, & Young, 1990; Palmieri-Smith et al., 2008). This loss causes an interference with the patient's ability to actively recruit high-threshold motor units with the injured limb during a voluntary contraction (Hurley et al., 1994; Palmieri-Smith et al., 2008). Hopkins and Ingersoll (2000) highlighted arthrogenic muscle inhibition's influence in the injury cycle, indicating that it contributes to joint immobilization which further exasperates muscle wasting and weakness and thus, progressing muscle atrophy (Hopkins & Ingersoll, 2000). More recently, Lepley and colleagues (2020) proposed an article discussing two different types of muscle atrophy, which could help explain the impact that ACL injuries have on both the injured and the contralateral limb that many researchers have found (Hurley et al., 1994; Lepley, Davi, Burland, & Lepley, 2020; Palmieri-Smith et al., 2008; Snyder-Mackler, De Luca, Williams, Eastlack, & Bartolozzi, 1994; D. Urbach et al., 2001; Dietmar Urbach et al., 1999).

The two forms of muscle atrophy presented by Lepley and colleagues (2020) are muscle atrophy caused by a traumatic joint injury (ACL injured limb) and muscle atrophy due to disuse (contralateral limb). The two differ mostly in degree of influence, as muscle atrophy from a traumatic joint injury presents with a greater amount of muscle loss, fiber type transition, fatty tissue deposition, and reduction in satellite cells compared to the more common form caused from disuse (Lepley et al., 2020; Palmieri-Smith et al., 2008). Atrophy caused by a traumatic joint injury continues to progress despite muscle-strengthening interventions (Lepley, 2015; Palmieri-Smith et al., 2008). The degree to which muscle atrophy contributes to quadriceps weakness is still unclear. However, by using muscle morphology and electromyography (EMG) data, Williams and colleagues (2005) were able to distinguish diminished musculature and voluntary muscle control in the muscles of non-copers (those who do not compensate well/less likely to return to pre-injury level) compared to copers (those who compensate well/more likely to return to pre-injury level) (Alkjaer, Simonsen, Peter Magnusson, Aagaard, & Dyhre-Poulsen, 2002; Williams, Buchanan, Barrance, Axe, & Snyder-Mackler, 2005), suggesting that atrophy has the potential to contribute significantly in reducing quadriceps strength (Williams, Buchanan, et al., 2005; Williams, Snyder-

Mackler, Barrance, & Buchanan, 2005). Other more recent studies have confirmed the influence of muscle atrophy on strength deficits following knee joint injury and/or surgery, proposing that 38% of the variance in knee extension strength can be explained by this in combination with voluntary muscle activation (Mizner, Petterson, Stevens, Vandenborne, & Snyder-Mackler, 2005; Thomas, Wojtys, Brandon, & Palmieri-Smith, 2016; Williams, Buchanan, et al., 2005).

### 3.4 Muscular Contributions to Knee Joint Stability

Joint stability requires a collaboration of active (muscle groups) and passive (ligaments) components. Of these active components, the quadriceps are the primary extensors and the hamstrings and gastrocnemius are the primary flexors of the knee joint (Neumann, 2002), making them key regulators of knee joint stability. By generating greater activations of these muscles, joint stiffness is enhanced, which can then cause an increase in knee joint stabilization (Hewett, 2000; Johansson et al., 1991; McNair, Wood, & Marshall, 1992).

The coactivation index (CI) of the knee joint is a measure used to describe the muscular activation strategies of the antagonist and agonist muscles/muscle groups surrounding the knee joint. There are several means to describe muscle coactivations, such as a ratio or an average taken between the antagonist and agonist muscle activity that can be presented as an index or a root mean square (Hanson, Padua, Blackburn, Prentice, & Hirth, 2008; Madhavan & Shields, 2007; Myer et al., 2005; Palmieri-Smith, McLean, Ashton-Miller, & Wojtys, 2009). Lewek and colleagues (2005) and Rudolph and colleagues (2001) used a ratio but then multiplied this by the summed activation to better describe the relative importance of the muscle pairs along with the magnitude of the activation. In terms of a ratio, low CI values represent a lower activation of both muscle/muscle groups, or an asymmetrical activation pattern with one muscle/muscle group having a low-level activation and another muscle/muscle group having a high-level activation.

Larger CI values indicate a more symmetrical activation level of both muscles/muscle groups or both the antagonist and agonist having a high-level activation. Therefore, CIs are capable of providing descriptive relative muscle activation of the agonist and antagonist muscles along with the magnitude of the activation.

Baratta and colleagues (1988) used isokinetic knee flexion and extension maximal voluntary contractions of the quadriceps and hamstring muscles and compared the coactivations of three different population groups of differing athletic backgrounds (general population, varsity athletes, high performance athletes). Results indicated that the muscle's motor drive imbalance was the main cause of the diminished response of the hamstrings rather than their absolute strength (Baratta et al., 1988). This has been further studied during dynamic, weight-bearing tasks, leading to a unified agreement that muscular imbalance is correlated with an increased risk of injury ( Hewett, Lindenfeld, Riccobene, & Noyes, 1999; Hewett, Myer, & Ford, 2004; Hewett, Myer, Ford, Heidt, et al., 2005; Landry, McKean, Hubley-Kozey, Stanish, & Deluzio, 2007; Schmitt, Paterno, Ford, Myer, & Hewett, 2015). Because of these imbalances or deficits in dynamic neuromuscular control, athletes are more susceptible to develop poor biomechanical loading patterns that are known characteristics of increased risk of ACL injury or reinjury (Hewett et al., 2005; Hewett et al., 2013; Zazulak et al., 2005). Thus, these findings would suggest that balanced coactivation is critical in maintaining joint stability rather than an increase in overall strength (Baratta et al., 1988).

Muscle coactivations can help explain stabilization strategies of the joint during dynamic loading as it is hypothesized that an improved balance in strength and recruitment of the hamstring and gastrocnemii musculature relative to quadriceps, may help in protecting the knee ligaments during high-risk maneuvers (Morgan, Donnelly, & Reinbolt, 2014; Myer et al., 2005). The appropriate level of coactivation, in terms of decreasing one's risk of injury, is still up for debate, however, identifying their role in providing stability, stiffness, and proprioceptive control can provide valuable information (Myer et al., 2005; Sell et al., 2007).

There is a large amount of literature that has looked at the role that knee-spanning muscles, such as the hamstrings and quadriceps muscle groups, play in terms of assisting in knee joint stability (Del Bel et al., 2018; Flaxman et al., 2019; Morgan et al., 2014; Schmitt et al., 2015). However, most research has been done analyzing adult populations, and even within those studies few are looking at sex differences (Otsuki et al., 2019). The need to do so within adolescent populations is even more exaggerated as this is where the majority of development and growth takes place, and the physical divide between the two sexes are at its greatest (LaBella et al., 2014; Renstrom, Ljungqvist, Arendt, Beynnon, Fukubayashi, Garrett, Georgoulis, Hewett, Johnson, & Krosshaug, 2008).

### 3.5 Sex Differences in Neuromuscular Contribution to Knee Joint Stability

Physically active adult females have greater simultaneous quadriceps and hamstrings activation than their male counterparts (Padua et al., 2006), or coactivations. An increase in coactivation would cause an increase in joint compression and assist in knee stabilization, therefore, leading us to the assumption that females have an increased ability to maintain knee joint stability. However, this assumption of increased compression is relative, and one must consider that activation, as measured from EMG, is not directly proportional to muscle force. As such, given two individuals of the same mass doing the same movement, the individual with lower strength would require a higher activation level than an individual with higher strength to produce the muscle force required to perform the same task, and the resulting knee joint compression may end up the same as the stronger individual. This paradox might help us understand why injury rates would disagree with the assumption, as females, who are generally weaker than males, show a two to- eight times greater chance of sustaining an ACL injury (Beck et al., 2017; Dekker et al., 2018; Micheli, Metzl, Di Canzio, & Zurakowski, 1999). More recent studies have found that females produce increased quadriceps activation and decreased hamstring activation with a greater imbalance in medial-to-lateral coactivations than males (Palmieri-Smith et al., 2009; Wojtys, Ashton-Miller, & Huston, 2002). For example, when comparing between male and female high school basketball players, females tended to recruit activation strategies that promoted abduction loading, by preferentially activating the lateral quadriceps and hamstrings during a landing task (Ford, Myer, & Hewett, 2003). Similar results were found in older populations (college-aged), highlighting the tendency of female athletes to utilize neuromuscular activations that can contribute to abduction loading (Myer et al., 2005). Regardless of loading direction, females generate greater activation in the rectus femoris and lateral gastrocnemius compared males (Del Bel et al., 2018; Flaxman, Smith, & Benoit, 2014); thus, creating a medial-to-lateral imbalance. These studies underscore the importance of incorporating biomechanical and neuromuscular analysis.

Wojtys and colleagues (2002) compared sagittal plane knee stiffness and muscular strength between adult males and females, and revealed that both sexes exhibited similar mean anterior tibial translation values and average passive shear-stiffness values (Wojtys et al., 2002). When maximum coactivation of the knee musculature was performed, both sexes were able to significantly decrease the mean anterior tibial translation, however, males were able to generate significantly higher stiffness values than females even though muscular activation levels between sexes did not show significant differences (Wojtys et al., 2002). This finding would be in agreeance with the work done by da Fonesca and colleagues (2006) that compared the coactivations between sedentary and athletic males and females. Their results indicated that those who have lower work producing capabilities will have higher coactivation levels to compensate for the lack of strength (da Fonseca, Vaz, de Aquino, & Brício, 2006), which was evident when comparing between adult males and females. Findings from Häkkinen and colleagues (1983) also support this interpretation, as they concluded that the greater the muscular strength of an individual, the less amount of activation is required to achieve the same force output (Häkkinen & Komi, 1983). Therefore, because females have demonstrated lower force producing capabilities derived from strength, higher coactivation levels may be present about the knee joint, but the capacity to counteract the forces produced by the translation and rotation mechanism commonly seen in ACL injuries may still be reduced compared to stronger males. By this same argument, however, it can be surmised that increasing the strength in females would lead to improved mechanical stability, regardless of their sex.

Of note, is that the role of other muscles crossing the knee, such as the gastrocnemius, are commonly left unanalyzed and could help explain some of the imbalance found with the force and moment relationship (Fleming et al., 2001; Palmieri-Smith et al., 2009). Some studies observed ACL-deficient participants having lower gastrocnemii activity during gait (Benoit, Lamontagne, Cerulli, & Liti, 2003; Limbird, Shiavi, Frazer, & Borra, 1988), while others reported an increase (Del Bel et al., 2018; Klyne, Keays, Bullock-Saxton, & Newcombe, 2012; Lass et al., 2009) during a weight-bearing target match protocol, single-leg hop task and while walking respectively. Researchers have attributed the increase in amplitudes to be a compensatory mechanism of a ruptured ACL, which Fleming and colleagues (2001) has identified as a potential risk as it has the capability to increase ACL strain (Fleming et al., 2001). It is possible that the reduction in mechanical and afferent feedback due to the injury causes the central nervous system to use a more generalized knee stabilization strategy where muscles have similar activation levels in all loading directions (Flaxman et al., 2014), which could lead to greater ratios of activation (Del Bel et al., 2018). Since the degree to which muscular activation is involved in knee stabilization remains unclear, future work looking at muscle activations as it relates to injury mechanisms and rehabilitation is warranted.

The above statements are not necessarily arguing that a greater or altered coactivation signifies a 'better/worse' strategy, as highlighted by da Fonseca and colleague's (2006) work above (da Fonseca et al., 2006). A prolonged altered neuromuscular strategy motivated by an attempt to stabilize the knee joint will inevitably alter knee joint loads. For example, a compensatory mechanism of greater medial muscle coactivation positively correlates with a faster progression of medial knee osteoarthritis thus, playing a role in the detrimental decline of knee joint health (Griffin & Guilak, 2005; Hodges et al., 2016).

### 3.6 Adolescent Population

One of the major rationales for needing to address males and females in an adolescent population is the extent of development that occurs during this time period (8-18 years). The time of puberty causes rapid and complex changes at the hormonal, anatomical, and physiological level, which inevitably influences an individual's biomechanics and neuromuscular control (Buchanan & Vardaxis, 2003; Hewett et al., 2004; LaBella et al., 2014; Noyes & Barber-Westin, 2018; Shultz, Sander, Kirk, & Perrin, 2005). Based on the Tanner Stage, a widely used subjective classification, it was determined that the normal onset of puberty in North America ranges in females from 8 to 13 years old, and 9 to 14 years old in males (Bornstein, 2018; Marshall & Tanner, 1969). Extensive growth causing rapid increases in height, weight, and bone length all contribute to the disruption in the body's original movement pattern. Muscular control is challenged, balance is impaired, and joint loading increases as body weight increases (LaBella et al., 2014).

The divergence of neuromuscular patterns also becomes noticeable between males and females during puberty (Renstrom, Ljungqvist, Arendt, Beynnon, Fukubayashi, Garrett, Georgoulis, Hewett, Johnson, Krosshaug, et al., 2008; Shea, Pfeiffer, Jo, Curtin, & Apel, 2004). As testosterone levels increase in males so does their power, strength and coordination, whereas females demonstrate little change (Buchanan & Vardaxis, 2003; Hewett et al., 2004; Noyes & Barber-Westin, 2018). It is only in early adulthood when the sex disparity in ACL injury rates begins to decline (LaBella et al., 2014; Renstrom, Ljungqvist, Arendt, Beynnon, Fukubayashi, Garrett, Georgoulis, Hewett, Johnson, Krosshaug, et al., 2008). Since the nature of a dynamic task will determine the mechanical loads at the joint and the activation strategy needed to stabilize the joint, it is challenging to identify how and when the aforementioned differences between developing males and females might contribute to increased injury risk. In particular, it is still unclear how sex influences muscular coactivations of those surrounding the knee joint during athletic tasks (Wojtys et al., 2002). For example, not only is there a lack of research on adolescent male and female coactivations during athletic tasks (functional movements), neither the influence of the task difficulty nor the ACL injury on neuromuscular patterns, has been elucidated.

### 3.7 Functional Tasks

To elucidate some of the gaps identified in the literature above, we must study how young males and females respond during challenging and relevant functional activities. Both the lunge and drop-vertical jump (DVJ) are currently being used as clinical assessment tools to establish RTA readiness (Romanchuk, Livock, et al., 2020; Wright et al., 2015), with each task being an example of a multi-joint movement requiring different neuromuscular activations to establish joint stability. It is presumed that as the degree of loading demands increases so will the level of difficulty due to the increase in muscle recruitment, joint loads (ground reaction forces), and required joint stability (da Fonseca et al., 2006; Häkkinen & Komi, 1983). It has also been found that individuals that land with greater vertical ground reaction forces, knee abduction and extension angles, and greater knee abduction moments are at an increased risk of sustaining an ACL injury (Hewett, Myer, Ford, Heidt, et al., 2005; Mizner, 2008).

A recent study done by Alkjær and colleagues (2020) identified significantly slower movement times while performing a forward lunge in pre-operative participants who have sustained an ACL injury compared to matched controls and post-operative participants, alluding to the potential ability to differentiate this population group with respect to their functional performance (Alkjær, Henriksen, Dyhre-Poulsen, & Simonsen, 2009; Alkjær et al., 2020; Alkjaer et al., 2002). Others have established a difference between limbs in muscle symmetry (Kemp, Romanchuk, Del Bel, Girard, & Benoit, 2020) and peak hip and knee flexion angles while performing a DVJ that are representative by their muscular activity and sagittal and frontal plane moments (Pollard, Sigward, & Powers, 2010). A number of studies have alluded to the DVJ, or a task similar in nature, being a more demanding task compared to other "high-risk" maneuvers, as it requires the athlete to perform a landing technique requiring greater external work and achieving a maximum jump height (Nagano, Ida, Akai, & Fukubayashi, 2007). However, to our knowledge, no studies have compared the differences in biomechanics, neuromuscular control and demand of the lunge and DVJ in the context of RTA assessment.

# Chapter 4. Purpose and Hypothesis

## 4.1 Study Rationale

It is evident that there is a lack of specific research on the change in neuromuscular control when it comes to ACL injuries amongst adolescent males and females. Previous research has provided basic knowledge of the factors influencing knee joint stabilisation strategies of the adult knee, including strength (Failla et al., 2016; Lepley et al., 2020; Myer et al., 2009), hormonal (Hewett, 2000; Shultz et al., 2005), anatomical (Abulhasan & Grey, 2017), neuromuscular (Flaxman et al., 2012; Lephart, Abt, & Ferris, 2002; Palmieri-Smith et al., 2009), kinematic (Thomas P. Andriacchi & Dyrby, 2005; Oberländer, Brüggemann, Höher, & Karamanidis, 2014) and kinetic (Ambegaonkar, Shultz, & Perrin, 2011; Mohammadi Orangi et al., 2021) variables associated with injury mechanisms. However, research investigating how adolescent males and females differ in knee stabilization strategies through coactivations and how an ACL injury might impact the strategies and overall dynamic knee joint stability during periods of pubertal changes, is limited (Hewett, Myer, & Ford, 2004). Minimal, if yet any, evidence-based criteria exist specifically for RTA guidelines for adolescents, and in particular during two of the more commonly used functional assessment tests (lunge and DVJ). Research focusing on adolescents, specifically during tasks used to assess RTA, may help explain why the incidence of injuries is increasing substantially more in youth than in adults despite an overall greater public awareness and injury prevention campaigns. It is clear that greater attention on the knee stabilization strategies of this demographic and how it is influenced by an ACL injury is needed. Only then can we develop guidelines that are appropriate for the prevention and rehabilitation of adolescent ACL injuries.

## 4.2 Research Objectives and Hypothesis

The aim of this thesis was to fill the knowledge gap in adolescent research by evaluating the biomechanical and neuromuscular control of healthy adolescent male and female athlete’s during the lunge and DVJ, and to contrast these findings with an adolescent population with an ACL injury. To do so, this thesis (i) assessed the differences in kinematic, kinetic and neuromuscular control strategies between the lunge and DVJ (two functional tasks differing in movement performance and frequently used to assess RTA readiness (Wright et al., 2015)). This thesis then examined the muscular activation strategies of lower extremity muscle groups in male and female adolescent athletes with and without an ACL injury during the DVJ.

### Research Question

*Q1: Do two functional tasks that are frequently used to assess return-to-activity readiness post ACL reconstruction (lunge and drop-vertical jump) differ in neuromuscular and biomechanical demand in uninjured adolescent male and female athletes?*

In order to quantify the demand of a task, we evaluated the recruitment of muscles crossing the knee joint, as well as peak knee flexion angles, knee excursion values, and knee joint power. The effect of limb dominance was analysed prior to determining the demand of the lunge and DVJ to confirm whether both limbs, or the dominant limb, would be used to assessed task demand. It is presumed that as the degree of loading demands increases so will the level of difficulty as evidenced by increased muscle recruitment, joint loads (joint power), and joint stability (knee excursion) (da Fonseca et al., 2006; Häkkinen & Komi, 1983). Da Fonseca’s (2006) work, comparing muscular coactivations in sedentary and athletic population groups, found that sedentary women had greater muscular activity compared to athletic women (da Fonseca et al., 2006). This suggests that a way of compensating for higher demands and a lack of strength in relation to task difficulty is by increasing muscular activity in order to counterbalance the effects of external loads and increase joint compression (da Fonseca et al., 2006; Häkkinen & Komi, 1983). Previous research has also identified that an increase in joint compression could limit the range of motion of a task (Ford, Van Den Bogert, Myer, Shapiro, & Hewett, 2008), indicating a possible relationship between decreased knee flexion and knee excursion values with higher muscular amplitudes. Alkjær and colleagues work focusing on the forward lunge found that this task differentiated population groups as being copers and non-copers (defined above) with respect to their functional performance (Alkjær et al., 2009, 2020; Alkjaer et al., 2002). Other studies have discussed the DVJ as being a "high-risk" maneuver consistent with an ACL mechanism of injury (Hewett, Myer, & Ford, 2006; Hewett, Myer, Ford, Paterno, & Quatman, 2012; Yu & Garrett, 2007). Though sensitive to differing movements between copers and non-copers, we hypothesize that the lunge will only produce greater values in PKF and sagittal plane iKEXC variables while the DVJ will elicit greater iEMG and frontal plane iKEXC and iJP values.

*Q2: Do adolescent male and female athletes with an ACL-deficiency differ in knee stabilization strategies compared to uninjured controls while performing a drop-vertical jump?*

We hypothesized that females will have greater medial-to-lateral coactivation ratio asymmetries compared to males (Palmieri-Smith et al., 2009). Secondly, we hypothesized that both uninjured males and females will have lower coactivation levels in the medial musculature compared to the lateral musculature (Palmieri-Smith et al., 2009), and that an injury to the ACL will further decrease medial coactivations. Thirdly, we hypothesized that because of a quadriceps strength deficit present in those with ACL-deficiency (which was assessed), the unbalanced medial-to-lateral coactivations and the medial musculature weakness, females will achieve greater knee abduction angles contributing to greater knee excursion values (Palmieri-Smith et al., 2009, 2008). We postulated that this will lead to the ACL-deficient group having greater gastrocnemius contributions compared to the uninjured controls (Morgan et al., 2014; Palmieri-Smith et al., 2009) in an attempt to compensate for the lower muscular activations required to assist in knee stabilization.

# Chapter 5. Methodology

## 5.1 Study Design

The data obtained in this study was collected by the Clinical Biomechanics Research Unit at the University of Ottawa under the supervision of Dr. Daniel Benoit and in collaboration with Dr. Sasha Carsen from the Children's Hospital of Eastern Ontario (CHEO). This project contains only a portion of the data collected via a larger research project with the overall aim to better understand how sex and task selection influences the neuromuscular and biomechanical loading patterns of adolescent participants with and without an ACL injury. In the larger study, participants completed a series of hop, functional, and endurance tasks, however, this thesis will only focus on the lunge and DVJ tasks (See Appendix A: Table 1 for full protocol). A cross-sectional observational case control study design will be used to evaluate the muscular activation patterns of adolescent male and female athletes with and without an ACL injury during two functional tasks commonly used as a clinical assessment tool for RTA.

## 5.2 Participants

A power analysis using G*Power software (3.1.0, Dusseldorf, Germany) on pre-existing data that looked at the primary variable (EMG) of this study, investigated the different roles of the muscles crossing the knee in maintaining joint stability (Flaxman, AlkjÆr, Simonsen, Krogsgaard, & Benoit, 2017). Using the data from the vastus lateralis muscle revealed that in order to achieve an effect size of 0.48 an overall sample size of 52 is required to effectively test the research hypothesis and achieve a power of .80 with an $\alpha = 0.05$. Study one will be looking only at uninjured controls, which will include a total of 68 adolescent participants. The second study will be looking at both the uninjured (n=68; 29 males; 39 females) and ACL injured (n=54; 17 males; 37 females) population and will consist of a total of 122 participants.

Adolescent participants between and including the ages of 10-to 18 years who have a confirmed diagnosis of an ACL rupture by means of MRI were recruited by Orthopaedic Consultants at the Children's Hospital of Easter Ontario (CHEO). Patients received approval by their physician prior to participation in the study. Inclusion criteria required them to be currently participating in competitive organized sport. Exclusion criteria included: i) patients seeking an ACL reconstruction revision, ii) any recent injury or pain in the lower extremity within the past six months. Recruitment of uninjured controls occurred via convenience sampling of Ontario/Gatineau sport associations. Limb dominance will be defined as the leg they would kick a soccer ball with to achieve a maximum distance (van Melick, Meddeler, Hoogeboom, Nijhuis-van der Sanden, & van Cingel, 2017).

## 5.3 Experimental Protocol

### 5.3.1 Consent and Questionnaires

Each participant was asked to read and sign a consent form approved by the University of Ottawa Research Ethics Board (uOttawa REB H09/17/10) (CHEO REB 17/74X) prior to collecting data. Along with the consent form, they were each asked to complete several self-assessment forms assessing their puberty stage (Tanner Stages (Taylor et al., 2001)), sport exposure (Pedi-FABS (Fabricant et al., 2014)), subjective knee function (HSS Pedi-IKDC (Kocher et al., 2011) and ACL-RSI questionnaires (Webster, Feller, & Lambros, 2008)), and activity level (Tegner activity scale (Lysholm & Tegner, 2007)). Each participant was given a pair of tight fitted black spandex shorts and long sleeve shirt prior to completing anthropometric measurements that include: pelvis, knee, and ankle width (cm), height (cm), and weight (kg); leg and tibial length (cm), and thigh and shank circumference (cm).

### 5.3.2 Participant Preparation and Equipment

Once anthropometric measurements were taken, each participant was given standardized athletic footwear (KBS7FW3343; MS7F505027, Joe Fresh, ON, Canada) to reduce inter-participant variability. The participant then completed a 5-minute warm-up using a stationary bike with no resistance and was given an opportunity to stretch. Following SENIAM guidelines (De Luca, 1997; Hermens, Freriks, Disselhorst-Klug, & Rau, 2000), with some minor adjustments tailored towards individual anatomy, wireless bipolar surface EMG electrodes (16-channel Trigno, Delsys, Boston, USA) were placed on the midline of the muscle bellies between the myotendinous junction and the nearest innervation zone with the detection surface being perpendicular to the length of the muscle fibers on the gluteus medius (GMed), vastus lateralis (VL), rectus femoris (RF), vastus medialis (VM), biceps femoris (BF), semitendinosus (ST), medial gastrocnemius (MG), and lateral gastrocnemius (LG).

Full-body kinematic data was collected via 84 reflective markers 14mm in diameter and placed on various landmarks according to a hybrid cluster-marker set (See Appendix A: Figure 1.) (adapted from Mantovani and Lamontagne 2017). The marker trajectories were sampled at 200Hz using a 10-camera infrared motion analysis system (8 Vero and 2 Vantage; Vicon, Nexus, Oxford, UK). Simultaneously, the ground reaction forces (GRFs) were recorded using two force platforms (FP4060-08, Bertec Corp., Columbus, USA), and sampled at 1000Hz. EMG data was sampled at 2000Hz, amplified by a factor of 1000, and band-pass filtered at 20-450Hz.

### 5.3.3 Maximum Voluntary Isometric Contractions

Maximum voluntary isometric contractions (MVICs) were recorded using a Biodex isokinetic dynamometer (System 4 Pro, Biodex Medical Systems, New York, USA) (Benoit et al., 2003). Each participant went through a series of contractions including: i) knee flexion and ii) extension in a seated position with the knee flexed at 60 degrees, and iii) plantarflexion, recorded in a seated position with the knee at 0 degrees and the ankle in a neutral position; iv) hip abduction being recorded in a standing position with the hip at 10 degree abduction and 0 degree extension (Karst & Worrell, 2001; Romanchuk & Benoit, 2019). Participants were asked to generate their perceived maximal contraction over five seconds. Each participant performed each contraction three times with at least one minute of rest interval between attempts. Verbal encouragement and on-screen biofeedback was provided to each participant in order to help them achieve their maximal force (Mcnair, Depledge, Brettkelly, & Stanley, 1996).

### 5.3.4 Functional Movement Tasks

Participants performed five lunges per limb and five DVJs. During the lunge participants were asked to start with both feet on a single force plate while having their hands placed on their hips, then lunge forward as far as they felt comfortable onto a force plate in front of them and were instructed to lunge as low as possible without allowing the contralateral knee to touch the ground. The DVJ was performed by: i) stepping off a raised platform, ii) landing with two feet onto an in-ground force plate (one foot on each force plate; "drop landing"), iii) immediately performing a maximal vertical jump, and iv) landing back onto the force plates with one foot on each plate ("jump landing"). The height of the platform was aligned to the participant's tibial plateau. All movements, aside from the initial step off the platform, occurred while controlling and minimising momentum (Hewett, Myer, Ford, Heidt, et al., 2005). For both tasks, each participant was given two practice trials prior to the start of data collection. A trial was considered unsuccessful if either of the participant's feet were not entirely on the force plate, if they remove their hands from their hips (lunge), if they jumped off the platform instead of stepped (DVJ), or if they did not return properly to the starting upright position. After each trial, researchers asked the participants if they were experiencing any pain or discomfort and if so, recorded it.

## 5.4 Filtering and Data Reduction

### 5.4.1 Kinematics and Kinetics

Marker trajectories and GRFs were filtered with a 4th order zero-lag dual low-pass Butterworth filter with matching cut-off frequencies of 15Hz (Bisseling & Hof, 2006; Kristianslund, Krosshaug, & Van den Bogert, 2012) using custom pipelines in Vicon Nexus (v2.9, Vicon, UK). A Vicon Nexus model has been modified to be used for scaling purposes and to compute inverse kinematics with reference to a relative standing static trial. Lower limb inverse dynamics in the frontal and sagittal planes for the hip, knee, and ankle moments and angles were also calculated. Joint power was calculated using joint moments (Nm) and joint angular velocity (rad/s) (Equation 1; (Winter, 2009)).

$$P_m = M_j \omega_j \qquad W \tag{1}$$

Knee excursion was reported as the Euclidean distance of the knee joint center (Smale, Alkjaer, et al., 2019) as it traveled throughout the preparatory, deceleration, and acceleration phases of the two tasks (explained below). The knee joint center was defined as the midpoint between the lateral and medial femoral epicondyle markers (Smale, Alkjaer, et al., 2019).

### 5.4.2 Electromyography

All raw EMG signals were exported as .c3d files into MATLAB (2020a, Mathworks, Natick, USA), where they 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 a 2nd order dual-pass Butterworth filter. The mean of 50ms about the highest peak was used to identify the maximum EMG amplitude for each muscle during the MVICs which was used to amplitude-normalise the EMG data in the lunge and

DVJ tasks. The CI of the knee joint was defined as the ratio between the antagonists and agonists activation during the lunge and DVJ multiplied by the summed EMG from both muscles (Lewek, Ramsey, Snyder-Mackler, & Rudolph, 2005; Rudolph, Axe, Buchanan, Scholz, & Snyder-Mackler, 2001).

$$CI = \left(\frac{EMG_{lower}}{EMG_{higher}}\right) * \left(EMG_{lower} + EMG_{higher}\right) \qquad (2)$$

The CIs of interest were the antagonist and agonist muscle activity of the lateral quadriceps to hamstrings (Q:H) calculated using the VL and BF activity and the Q:G (VL:LG), and the medial Q:H (VM:ST) and Q:G (VM:MG). The ratio of medial-lateral coactivation was calculated by dividing the medial CI pairing by the lateral CI pairing to determine whether coactivation was imbalanced between the medial and lateral sides (Palmieri-Smith et al., 2009).

### 5.4.3 Time Normalization

Waveform data from the lunge and DVJ data was time normalized prior to statistical analysis with the preparatory phase occurring 100ms prior to initial contact (IC; (GRF > 10 N)) (Cavanagh & Komi, 1979; Kipp et al., 2014; Palmieri-Smith, Wojtys, & Ashton-Miller, 2007; Russell, Croce, Swartz, & Decoster, 2007; Smale, Flaxman, et al., 2019). Each phase was separated by a 1-100% phase with the *deceleration phase* being identified as IC until maximum knee flexion and the *acceleration phase* being maximum knee flexion until take-off (GRF < 10N). Only the drop landing of the DVJ was analyzed (Bencke, Naesborg, Simonsen, & Klausen, 2000; Myer, Ford, McLean, & Hewett, 2006).

## 5.5 Data Analysis

### 5.5.1 Statistical Analysis

The primary variables of interest are the integrated EMG or coactivations of the muscles crossing the knee joint with the secondary variables being kinetic and kinematic data that include peak knee joint angles, knee joint power, and knee excursion. All statistical analysis was done using Matlab (2020a, Mathworks, Natick, USA) or SPSS Statistics 26.0 (IBM Corp., Armonk, NY, USA) with the level of significance set at $p = 0.05$. Cohen's *d* effect sizes was calculated for each statistically significant result using these parameters: small effect size $d < 0.5$, medium effect size $0.5 < d < 0.8$, large effect size $d > 0.8$ (Field, 2013). All variables were assessed for normality to determine whether a parametric or non-parametric test was needed to analyze the data. Other appropriate assumption tests were conducted for the tests described below.

### 5.5.2 Study 1 Statistical Analysis

Prior to the primary analysis, paired samples *t*-tests were used to determine if there was an effect of limb dominance on the uninjured population using kinematic and kinetic data. A two-way mixed model analysis of variance (ANOVA) was used for primary analysis to determine if there was a difference or interaction within task (Lunge x DVJ) and between sex (Male x Female) using the discrete variables of peak knee flexion, integrated knee excursion (sagittal and frontal planes), integrated joint power, and integrated EMG of all eight muscles. Analyses was only done during the *deceleration phase* of each task . If a significant effect or interaction is observed, a post hoc dependent *t-test* was used to determine where the differences exist in the pairwise comparisons along with a Bonferroni test to correct for multiple comparisons.

### 5.5.3 Study 2 Statistical Analysis

Independent two-sample *t*-test's using statistical parametric mapping (SPM) or statistical non-parametric mapping (SnPM) was used to evaluate the mean differences of the dominant/injured limb between the uninjured controls and those with an ACL injury. SPM is a technique that uses random field theory (RFT) to perform comparisons between entire time-dependent data sets (i.e., the whole acceleration phase of a DVJ or deceleration phase of a lunge). It included all data within the tasks waveforms and was used to determine the time-varying differences throughout the phases identified above (Pataky, Robinson, & Vanrenterghem, 2013; Sole, Pataky, Tengman, & Häger, 2017). The assumption of normality for the discrete variable of frontal plane knee excursion was evaluated through Shapiro-Wilk tests. Normally distributed data used independent *t*-tests, whereas data that rejected the assumption of normality used Mann-Whitney U tests.

If significance was observed, a Benjamini-Hochberg correction for multiple comparisons was performed with a set false discovery rate (FDR) of 0.05. Post hoc analogue of an independent *t-test* was used to determine where the significance exists. This form of correction was selected based on its ability to preserve greater statistical power while also limiting the familywise *Type I* error rate (Benjamini & Hochberg, 1995). This procedure uses individual rankings from smallest to largest (smallest *p*-value has a rank of 1) and then compares them to their respective Benjamini-Hochberg critical values calculated as:

$$Critical\ Value = \left(\frac{i}{m}\right)Q \tag{3}$$

The variables *i* is the rank, *m* is the total number of statistical tests, and *Q* is the false discovery rate (Benjamini & Hochberg, 1995). The largest *p*-value that is less than the *critical value* is significant along with all other values of lower rank (Benjamini & Hochberg, 1995). Knee stability was interpreted using the variable of knee excursion, with higher values indicating reduced stability. Knee stabilisation strategies were interpreted using co-contraction index (CI).

# Chapter 6. Manuscript 1

## Comparing biomechanical and neuromuscular demands using the lunge and drop-vertical jump performed by healthy adolescent male and female athletes

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## Abstract

***Background:*** Task selection for strength, hopping, and quality movement tests are designed to challenge the functional capacity of an individual. Identifying the demand of a task will help translate its ability to effectively compare neuromuscular and biomechanical outputs of each task based on the evaluation criteria. The purpose of this study is to quantify the biomechanical and neuromuscular demands of the lunge and drop-vertical jump (DVJ) for its use in a return-to-activity (RTA) assessment.

***Methods:*** Sixty-eight adolescent male (n=29) and female (n=39) athletes aged 10 to18 performed five trials of a lunge and DVJ task. Kinematics, kinetics, and surface electromyography (EMG) were recorded. Discrete variables of mean peak knee flexion (PKF), integrated knee excursion (iKEXC) in the sagittal and frontal planes, integrated knee joint power (iJP) and integrated EMG during the deceleration phase of the task were used in the data analysis. A two-way mixed model analysis of variance analyzed the interaction within task (lunge x DVJ) and between sex (male x female).

***Results:*** Significant differences were found within task and between sex in all but two discrete variables (integrated semitendinosus and rectus femoris). The lunge task produced significantly greater demands in the PKF (p=0.001), iKEXC (p=0.001), and vastus lateralis (VL; p=<0.001), vastus medialis (VM; p=0.002) integrated EMG (iEMG) discrete variables than the DVJ. The DVJ elicited greater demands in iJP (p<0.001) and iEMG in the lateral gastrocnemius (LG; p=0.005), medial gastrocnemius (MG; p<0.001) and gluteus medius (GMed; p=0.039). Significant differences were found in the iJP in both males (p<0.001) and females (p<0.001) with a positive interaction only present during the DVJ (p=0.002). In females, the DVJ elicited significantly greater iLG activity (*p*=0.040) that was not present during the lunge (*p*=0.282). Integrated biceps femoris (iBF) variable revealed a significant effect of sex (p=0.010) indicating greater contributions in iBF in females than in males during both the lunge and DVJ.

***Conclusion:*** The lunge elicited greater demands in peak knee flexion, knee excursion, and quadriceps values. While the DVJ challenged the BF, gastrocnemii, and GMed to a greater degree than the lunge, while also eliciting greater iJP demands.

## *1. Introduction*

The adolescent age group (10-18 years; inclusive) now has a higher rate of diagnosed anterior cruciate ligament (ACL) tears compared to adult groups, exhibiting an increase in reconstruction rates growing 924% from 1994 to 2006 (Dekker et al., 2018). Following ACL reconstruction the typical return-to-activity (RTA) time period ranges from 9-12 months, yet, despite the continuous development of ACL rehabilitation techniques, less than 50% of adolescent populations return to their pre-injury level of activity (Dekker et al., 2018; Schmale et al., 2014), with females showing decreased rates of RTA (Dunn & Spindler, 2010; Hewett et al., 2013). Recent literature has recognized that muscular and biomechanical deficits, such as joint power and rate of force development, are still present up to 18 months post-op (Jordan et al., 2020), which could contribute to the lack of RTA success. A systematic review by Webster and Hewett (2019) identified that passing a RTA testing battery did not significantly reduce the risk of sustaining another ACL injury or other form of knee injury (Webster & Hewett, 2019).

Return-to-activity criteria has taken many forms to reduce the overall risk of sustaining an initial, and subsequent ACL injury. A systematic review and multidisciplinary consensus conducted by van Melick et al. (2016), indicated that a testing battery for RTA should include a series of strength, hopping, and quality movement tests. Currently, there are a significant number of differing protocols, assessments, and testing batteries that have been implemented to reduce the risk of ACL injuries. However, it is often hard to apply the current RTA testing batteries in a clinical setting, as the testing battery can take up to several hours to complete the full assessment and can require equipment that is not commonly found in a clinical setting (Webster & Hewett, 2019).

The ability of a task to challenge the functional capacity of the individual is commonly done through strength, hopping, and cutting tasks using biomechanical and neuromuscular quantitative data. Identifying the demand of the task will help translate its ability to effectively compare the neuromuscular and biomechanical outputs of each task, and thus, identify the appropriateness of the task in RTA assessment. Most RTA assessments have been developed based on comparisons between adult men and women performing high-risk maneuvers, such as landing, jumping, and cutting (Paterno et al., 2010; van Melick et al., 2016), with limited attention being put into adolescent populations. Given the developmental differences between sexes, more studies are necessary to investigate the demands of a task and the relevance of those tasks in RTA assessments that assess quality of movement in adolescent males and females. This first needs to be done in healthy cohorts to assess the demands of the neuromuscular and biomechanical factors (Chappell, Creighton, Giuliani, Yu, & Garrett, 2007; Colby et al., 2000; K. Ford, Myer, Toms, & Exerc, 2005; Hewett, Stroupe, Nance, & R., 1996).

Both the lunge and drop-vertical jump (DVJ) are currently being used as clinical assessment tools to establish RTA readiness (Romanchuk, Livock, et al., 2020; Wright et al., 2015), with each task being an example of a multi-joint movement requiring different neuromuscular activations to establish joint stability. It is presumed that as the degree of loading demands increases so will the level of difficulty due to the increase in muscle recruitment, joint loads, and required joint stability (da Fonseca et al., 2006; Häkkinen & Komi, 1983). It has also been found that individuals that land with greater vertical ground reaction forces, knee abduction and extension angles, and greater knee abduction moments are at an increased risk of sustaining an ACL injury (Hewett, Myer, Ford, Heidt, et al., 2005; Mizner, 2008).

The overall goal of a RTA assessment is to demonstrate that an individual can perform sport specific maneuvers that have the potential to mimic injury inducing biomechanical patterns while still maintaining knee joint stability. Therefore, the purpose of this study is to compare the kinematic, kinetic and neuromuscular characteristics of these tasks to quantify their demand and identify their suitability in a RTA assessment. More specifically, this study will look at discrete variables such as integrated electromyography (iEMG) to assess muscular activity, peak knee flexion (PKF), integrated knee excursion (iKEXC), and integrated knee joint power (iJP) to assess kinematic and kinetic load. We hypothesize that the lunge will produce greater PKF and sagittal plane iKEXC values while the DVJ will elicit greater iEMG, frontal plane iKEXC, and iJP values.

## ***2. Methods***

### ***2.1 Participants***

Sixty-eight uninjured male (n=29) and female (n=39) adolescent athletes aged 10-18 years were recruited from the Ottawa/Gatineau area (see Table 2). Inclusion criteria required each participant to be actively participating in organized sport, which was assessed via the HSS Pedi-FABS activity level questionnaire (Fabricant et al., 2014). All participants were screened prior to inclusion for any previous lower extremity injury and pain in the past six months or prior traumatic knee injury (i.e., meniscal tear, ligament rupture/tear) including any diseases/illnesses that would impact the neuromuscular function.

### ***2.2 Participant Preparation***

Prior to collecting participant data, each individual was required to read and sign a consent form approved by the University of Ottawa Research Ethics Board (uOttawa REB H09/17/10) (CHEO REB 17/74X), as well as complete a series of self-assessment forms that estimated their

Tanner stage of pubertal development (Taylor et al., 2001), sport exposure (Fabricant et al., 2014), and activity level (Tegner activity scale (Lysholm & Tegner, 2007)).

**Table 2**

*Demographic group means (SD) for uninjured males and females*

| **Variable** | **Female Control** ***Mean±SD*** | **Male Control** ***Mean±SD*** | ***p*-value** |
|---|---|---|---|
| **Age** (years) | 13.2 ± 1.6 | 13.2 ± 1.7 | 0.890 |
| **Height** (cm) | 161.7 ± 8.1 | 164.4 ± 13.9 | 0.332 |
| **Weight** (kg) | 50.8 ± 11.1 | 51.7 ± 13.1 | 0.747 |
| **BMI** (kg/m$^2$) | 19.2 ± 2.8 | 18.9 ± 2.9 | 0.643 |
| **Tegner Activity Level** | 8.3 ± 1.3 | 8.4 ± 1.2 | 0.984 |
| **Tanner Stage** | 3.2 ± 1.1 | 3.1 ± 1.2 | 0.816 |

*Note.* p-values corrected using the Bonferroni method. * indicated a statistical difference of $p < 0.05$

### *2.3 Protocol*

Anthropometric measurements of the pelvis, knee, and ankle widths (cm); participant height (cm) and weight (kg); leg and tibial length (cm); and thigh and shank circumference (cm) were collected. Following measurements, the participants were given standardized athletic footwear (KBS7FW3343; MS7F505027, Joe Fresh, ON, Canada) to reduce inter-participant variability.

Prior to testing, each participant was required to warm-up for a minimum of five-minutes using a stationary bike with little to no resistance. Adhering to SENIAM guidelines (De Luca, 1997; Hermens et al., 2000) with some minor adjustments tailored to the individual, wireless bipolar surface electromyography (sEMG) electrodes (16-channel Trigno, Delsys, Boston, USA) were placed on the right and left limbs over the gluteus medius (GMed), vastus lateralis (VL), rectus femoris (RF), vastus medialis (VM), biceps femoris (BF), semitendinosus (ST), medial gastrocnemius (MG), and lateral gastrocnemius (LG). Proper electrode-skin preparation was achieved by shaving each location, cleaning with an alcohol swab, and allowing to dry prior to electrode placement. Each sensor was then secured via tape and pre-wrap to reduce noise generated from movement artifacts (De Luca, 1997; Hermens et al., 2000).

Following sEMG setup, maximum voluntary isometric contractions (MVICs) were recorded using a Biodex isokinetic dynamometer (System 4 Pro, Biodex Medical Systems, New York, USA) (Benoit et al., 2003) with the torque and position data output to an analog to digital converter (Lock Sync Box, Level One) and recorded through Vicon Nexus software (8 Vero and 2 Vantage; Vicon, Nexus, Oxford, UK V 2.10.0) on a separate computer. Each participant performed: *i)* knee flexion and *ii)* extension, while in a seated position with the hip at 90 degrees and the knee flexed at 60 degrees (Lanie, Beaulieu, Lamontagne, & Beaulé, 2010); *iii)* plantarflexion, while in a seated position with the knee slightly bent and the ankle in a neutral position; and *iv)* hip abduction while in a standing position with the hip at 10 degree abduction and 0 degree extension (Karst & Worrell, 2001; Romanchuk & Benoit, 2019). Each participant performed three MVICs, each with a minimum of one-minute of rest between attempts. Verbal encouragement and on-screen biofeedback was provided to assist in achieving their maximal force at each contraction (Mcnair et al., 1996).

The participants were then instrumented with 84 retro-reflective markers (14mm diameter) placed on various landmarks according to a hybrid cluster-marker set (Mantovani & Lamontagne, 2017). Kinematic data was sampled at 200Hz using a 10-camera infrared motion analysis system (8 Vero and 2 Vantage; Vicon, Nexus, Oxford, UK). In combination with full-body kinematic data, ground reaction forces (GRFs) were recorded using two force platforms (FP4060-08, Bertec Corp., Columbus, USA), and sampled at 1000Hz. Electromyography data was sampled at 2000Hz, amplified by a factor of 1000, and band-pass filtered at 20-450Hz.

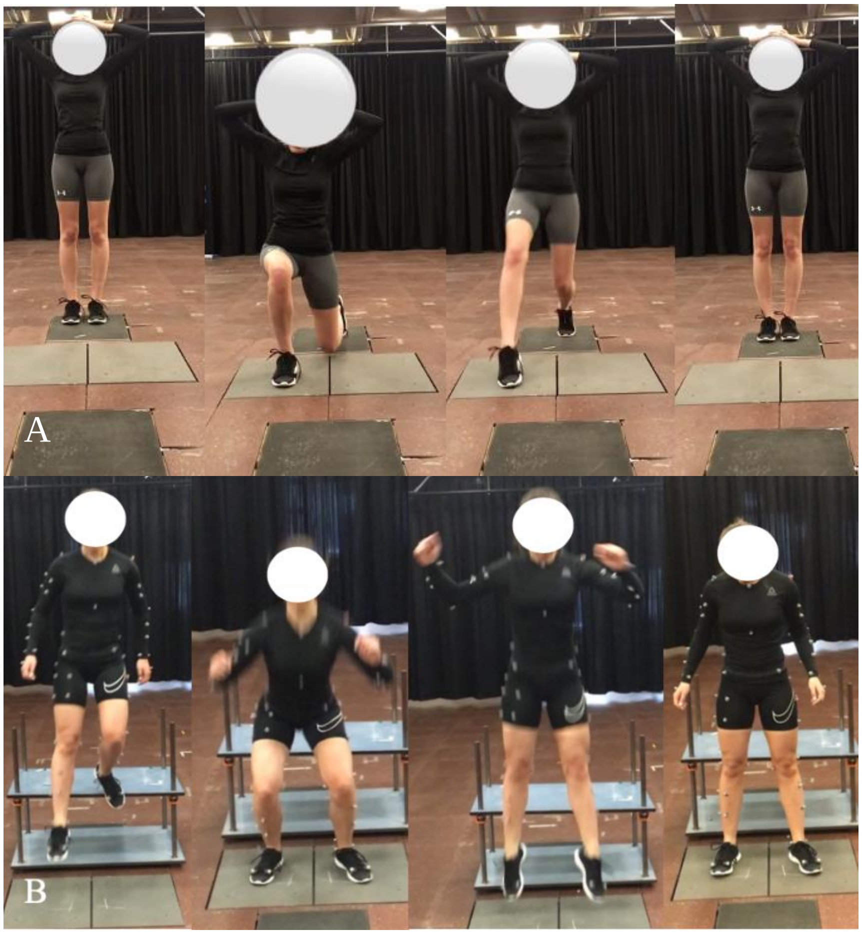

*Figure 2.1.* Lunge (A) and DVJ (B) tasks.

Following a series of practice trials, participants were asked to perform five successful attempts at both the DVJ and the lunge. A successful DVJ consisted of stepping off a raised platform, landing with one foot on each force plate installed flush with the underlying ground, and immediately taking off to perform a maximal vertical jump with the same landing protocol as the initial contact. The platform height was set to the height of the participants tibial plateau and placed behind the two force plates. A lunge was considered successful if participants kept their hands on both their hips while performing a forward lunge to a self-selected pace onto the force plate in front of them. The participant was instructed to achieve their maximal depth without allowing their supporting limb to touch the ground and finished the movement by returning to the original starting position (lunge Figure 1A and DVJ Figure 1B).

### *2.4 Data Processing*

#### Kinematics

Both the marker trajectories and GRFs were filtered using a 4th order zero-lag low-pass Butterworth filter with a matching cut off frequency of 15Hz (Bisseling & Hof, 2006; Kristianslund et al., 2012). Filter order and cut-off frequency were selected based on visual inspection of filter performance and previous studies (Romanchuk, Smale, Del Bel, & Benoit, 2020). Hip, knee, and ankle angles were collected in the sagittal and frontal planes along with knee excursion. Knee excursion is reported as the Euclidean distance of the knee joint center (Smale, Alkjaer, et al., 2019) as it traveled throughout the deceleration phase of each task (explained below). The knee joint center is defined as the midpoint between the lateral and medial femoral epicondyle markers (Smale, Alkjaer, et al., 2019). Joint moments were then calculated through inverse dynamics, as well as integrated knee joint power (iJP) in the sagittal and frontal plane on each successful trial.

#### Electromyography

Electromyography (EMG) data was high-pass filtered at 20Hz with a 2nd order dual-pass Butterworth filter, full-wave rectified, and low-pass filtered at 6Hz with a 2nd order dual-pass Butterworth filter. Using the participants MVIC, the mean of 50ms about the highest peak identified the maximum EMG amplitude for each muscle, which was then used to amplitude-normalise the EMG data in the lunge and DVJ. All data was visually inspected pre and post filtering to confirm validity of sEMG signal.

### Time Normalization

All discrete data for the lunge and DVJ was trimmed using unfiltered data to establish the *deceleration phase,* identified as the initial contact (IC (GRF < 10 N)) (Navacchia et al., 2019; Romanchuk & Benoit, 2019) until peak knee flexion.

### *2.5 Statistical Analysis*

Prior to the primary analysis, paired samples *t*-tests were used to determine if there was an effect of limb dominance on the uninjured population using kinematic data. If a significant effect was identified, limbs were compared separately. However, if the dependent *t*-tests failed to identify an effect of limb dominance, the dominant limb of each participant was used. Subjective data consisting of a self-perceived exertion/effort scale and level of difficult (Appendix A) was analyzed separately using dependent *t*-tests and used to establish task demand (Table 3.1).

A two-way mixed model analysis of variance (ANOVA) was used to analyze the interaction within task (Lunge x DVJ) and between sex (Male x Female) for each discrete variable presented in Table 3.3 and Table 3.4. All variables were assessed for normality through Shapiro-Wilk's tests. If data rejected the assumption of normality the central limit theorem was assumed. This states that due to the overall robustness of a two-way ANOVA and the large sampling size, we can conclude that the data is approximately normally distributed (Field, 2013). Equality of variance was tested through Levene's tests (Levene, 1961). If a significant result was found, the Hartley $F_{max}$ value (variance ratio) was used in order to compare the critical values based on sample size (David, Hartley, & Pearson, 1954). With a large sample size (~30-60), a ratio value of about 2-3 was deemed as acceptable (Field, 2013). Due to the high level of comparisons, a Bonferroni post-hoc was used to correct for multiple comparisons.

If a significant effect or interaction was observed, a post hoc dependent *t-test* was used to determine where the differences existed in the pairwise comparisons. Outliers were identified as those exceeding 1.5 times the interquartile range and were inspected to determine the appropriate action. If an outlier was a result of an error in the data collection it was excluded (ex. EMG electrodes losing contact with the skin). Those that reflected accurate data were included in the subsequent analysis. Outliers were further inspected and confirmed by members of the co-authors. Cohen's *d* effect sizes were calculated for each statistically significant result in the pairwise comparisons using these parameters: small effect size $d < 0.5$, medium effect size $0.5 < d < 0.8$, large effect size $d > 0.8$ (Field, 2013; Lakens, 2013). All statistical analysis was completed using a combination of MATLAB (2020a, Mathworks, Natick, USA), SPSS Statistics 26.0 (IBM Corp., Armonk, NY, USA), and Excel (2021, Microsoft, Washington, USA) with the level of significance of $\alpha=0.05$. Means and standard deviations were reported for each variable (Table 3.3 and Table 3.4).

### *3. Results*

The initial dependent *t*-tests identified that seven out of the eight analyses failed to identify an effect of limb dominance ($p>0.05$ for 88% of analyses); therefore, the dominant limb was selected for further analysis (Table 3.2). No differences were found in age ($p = 0.890$), height ($p = 0.332$), weight ($p = 0.747$), BMI ($p = 0.643$), activity level ($p = 0.984$), or puberty level ($p = 0.816$) (Table 2). Post hoc analyses for all kinematic variables revealed significant differences between the lunge and DVJ tasks. Results from the ANOVA revealed a positive interaction between sex and task with iJP, identifying that task affected JP, although, differently between males and females. Integrated EMG outputs were significantly different between the lunge and the DVJ in all but three muscles (RF, BF and ST). The BF was the only muscle that showed a significant difference between males and females but not between the lunge and DVJ. The LG was the only muscle to show a positive interaction between sex and task. Analysis of variance main effects are shown in Table 3.3 and Table 3.4.

**Table 3.1**

*Effect of limb dominance using kinematic and kinetic variables*

| ***Kinematic & Kinetic Variables*** | **Lunge *p*-value** | **DVJ *p*-value** |
|---|---|---|
| **PKF Mean (°)** | 0.142 | 0.346 |
| **iKEXC Sagittal** (cm) | 0.385 | 0.004 |
| **iKEXC Frontal** (cm) | 0.374 | 0.566 |
| **iKJP (Watt/kg)** | 0.519 | 0.472 |

*Note.* Test between dominant and non-dominant limbs in the lunge and drop-vertical jump. Significance set at a p-value of 0.05

**Table 3.2**

*Group means (SD) for uninjured males and females subjective measure scores*

| **Variable** | **Female Control** *Mean±SD* | **Male Control** *Mean±SD* | ***p*-value** |
|---|---|---|---|
| **Difficulty for Lunges** | 1.7 ± 0.74 | 1.6 ± 0.71 | 0.601 |
| **Borg Scale for Lunges** | 12.0 ± 4.6 | 11.1 ± 4.1 | 0.452 |
| **Difficulty for DVJ** | 2.03 ± 0.72 | 1.89 ± 0.83 | 0.487 |
| **Borg Scale for DVJ** | 13.3 ± 4.0 | 13.1 ± 4.3 | 0.847 |

*Note.* Difficulty and Borg scales for the lunge and drop-vertical jump (DVJ) are attached in Appendix A. p-values corrected using the Bonferroni method. * indicated a statistical difference of $p < 0.05$

### *3.1 Perceived Difficulty and Exertion*

Self-perceived level of difficulty was consistently higher in the DVJ (Females: 2.03±0.72; Males: 1.89±0.83) compared to the lunge (Females: 1.74±0.74; Males: 1.6±0.71) in both the males and females, however not significantly different. Similar trends occurred with the Borg scale exertion level (Female DVJ: 13.3±4.0, Male DVJ: 13.1±4.3; Female Lunge: 12.0±4.6, Male Lunge: 11.1±4.1).

### *3.2 Kinematic Variables*

Mean peak knee flexion values indicated a significant main effect within task (F(1,66)= 179.94, p=0.001, Cohen's d=0.422) indicating that the lunge produced greater peak knee flexion angles with no significance found between sex (p=0.227) and no interaction (p=0.766). A significant main effect within task was found in integrated knee excursion in both the sagittal (F(1,66)= 685.227, p=0.001, Cohen's d=3.174) and frontal (F(1,66)= 27.757, p=0.001, Cohen's d = 0.639) planes indicating greater distances travelled during the lunge (Table 3.3). No significance was found between sex in the sagittal (p=0.076) or frontal (p=0.680) planes, along with no positive interactions (p=0.117; p=0.411).

### *3.3 Kinetic Variable*

A significant main effect of task (F (1,66) = 128.355, p<0.001, *d* = 1.374), indicated greater iJP values in the DVJ. A significant main effect of sex (F (1,66) = 9.377, p=0.003, *d*=0.371) indicating overall greater iJP in males than in females, regardless of task selection. Positive interactions (F (1,66) = 4.759, p = 0.033) revealed significant differences between tasks in both males (Male lunge vs Male DVJ; p<0.001) and females (Female lunge vs Female DVJ; p<0.001), and between sexes only in the DVJ (Female DVJ vs Male DVJ; p = 0.002) but not during the lunge (Female lunge vs Male lunge; p = 0.654).

### *3.4 Electromyography Variables*

Analysis of variance results indicated a significant main effect of task for iVL, iVM, iLG, iMG, and iGMed. Significantly greater iVL (F (1,66) = 23.964, p<0.001, *d* = 0.594) and iVM (F (1,64) = 10.707, p=0.002, *d* = 0.403) values were found in the lunge compared to the DVJ. Integrated lateral (F (1,66) = 29.247, p=0.005, *d* = 0.656) and medial (F (1,66) = 71.831, p<0.001, *d* = 1.028) gastrocnemius and iGMed (F (1,65) = 4.428, p=0.039, *d* = 0.257) results, however, indicated greater values produced during the DVJ than during the lunge.

A positive interaction between sex and task for iLG (F (1,66) = 8.295, p = 0.005) was found revealing greater activity in females (Female Lunge vs Female DVJ, p < 0.001) during the DVJ (p=0.040) but not in the lunge (p=0.282). No significant differences were found between sex (p=0.507).

No significance differences were found between sexes for all iEMG (p>0.05) variables except for the iBF. There was no main effect of task in the iBF (p = 0.386), however, a significant main effect of sex was present (F (1,59) = 7.178, p=0.010, *d* = 0.343). Post hoc testing indicated an overall greater contribution in BF in females than in males, which was present in both tasks.

No main effect for task or differences between sexes were found in the iRF (p=0.952) and iST (p=0.589) variables. All significant task and sex differences can be found in (Table 3.4)

### *3.5 Outliers*

Further analyses on outliers revealed several cases that reflected accurate, but highly variable data. A separate analysis was conducted that excluded the initial outliers to determine if there were any notable differences in significant outcomes. For the majority of variables, excluding outliers increased significance and power of comparisons that were already significant. Significant main effects were found in addition to the already significant group differences in the PKF, VL, LG, and Gmed variables. The RF variable revealed a significant main effect present in task, and the ST indicated a positive interaction between sex and task (Appendix A; Table 2). All interpretations in this study will be based off data that included the outliers, as they were extreme representations of this populations. Even though the data without outliers yielded different results we made the decision to include the outliers as they are extreme representations of the population and are worth discussing.

**Table 3.3**

*Group means (SD) for uninjured males and females using kinematic and kinetic variables during the lunge and DVJ.*

| Variables | Uninjured Females Mean ± SD Lunge | DVJ | Uninjured Males Mean ± SD Lunge | DVJ | Effect Size Cohen's *d* | ***p*-value** |
|---|---|---|---|---|---|---|
| ***Kinematics*** | | | | | | |
| **PKF Mean** (°) | 105.30 ± 7.3 | 99.0 ± 14.5 | 108.70 ± 6.9 | 101.60 ± 17.9 | T: 0.422 | 0.001** |
| **iKEXC Sag** (cm) | 34.24 ± 4.9 | 17.24 ± 2.0 | 36.91 ± 7.0 | 17.72 ± 3.2 | T: 3.174 | < 0.001*** |
| **iKEXC Fro** (cm) | 6.11 ± 1.9 | 4.82 ± 1.4 | 6.47 ± 2.0 | 4.71 ± 1.3 | T: 0.639 | < 0.001*** |
| ***Kinetics*** | | | | | | |
| **iKJP** (Watt/kg) | 81.13 ± 33.0 | 146.64 ± 67.1 | 105.00 ± 44.9 | 201.71 ± 86.2 | T: 1.374<br>S: 0.371 | < 0.001***<br>0.003** |

*Note.* Peak knee flexion (PKF) mean, integrated knee excursion (iKEXC) in the sagittal and frontal planes, and integrated knee joint power (iKJP) are presented in this table for the lunge and drop-vertical jump (DVJ) tasks. Cohen's *d* effect size presented for significant main effects of task (T) and sex (S). p-values corrected using the Bonferroni test and indicated by * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

**Table 3.4**

*Group means (SD) for uninjured males and females using integrated EMG variables during the lunge and DVJ.*

| | **Uninjured Females Mean ± SD** | | **Uninjured Males Mean ± SD** | | **Effect Size** Cohen's *d* | ***p*-value** |
|---|---|---|---|---|---|---|
| ***Variables*** | **Lunge** | **DVJ** | **Lunge** | **DVJ** | | |
| ***Muscles*** (Normalized EMG*s) | | | | | | |
| **RF iEMG** | 234.0 ± 177.8 | 238.7 ± 94.2 | 210.9 ± 133.7 | 208.3 ± 104.4 | - | 0.952 |
| **VL iEMG** | 365.6 ± 163.3 | 293.5 ± 98.3 | 331.6 ± 168.7 | 232.8 ± 99.4 | T: 0.594 | < 0.001*** |
| **VM iEMG** | 322.7 ± 191.5 | 289.8 ± 101.1 | 326.9 ± 167.5 | 244.8 ± 109.1 | T: 0.403 | 0.002** |
| **BF iEMG** | 232.1 ± 170.9 | 254.1 ± 164.2 | 143.6 ± 118.6 | 142.8 ± 140.5 | S: 0.343 | 0.010* |
| **ST iEMG** | 105.1 ± 199.9 | 133.9 ± 202.6 | 96.0 ± 78.6 | 80.2 ± 75.7 | - | 0.589 |
| **LG iEMG** | 94.6 ± 46.0 | 174.0 ± 79.4 | 112.7 ± 89.6 | 136.9 ± 61.4 | T: 0.656 | 0.005** |
| **MG iEMG** | 76.2 ± 35.2 | 184.7 ± 85.9 | 97.3 ± 63.5 | 165.9 ± 66.4 | T: 1.028 | < 0.001*** |
| **GMed iEMG** | 116.0 ± 62.2 | 140.4 ± 86.4 | 95.0 ± 68.4 | 116.9 ± 63.5 | T: 0.257 | 0.039* |

*Note*. Integrated electromyography (iEMG) for rectus femoris (RF), vastus lateralis (VL), vastus medialis (VM), biceps femoris (BF), semitendinosus (ST), lateral gastrocnemius (LG), medial gastrocnemius (MG), and gluteus medius (GMed) are presented in this table for the lunge and drop-vertical jump (DVJ) tasks. Cohen's *d* effect size presented for significant main effects of task (T) and sex (S). p-values corrected using the Bonferroni test and indicated by * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

## *4. Discussion*

The purpose of this study was to contrast the demand of the DVJ and lunge using discrete kinematic, kinetic, and neuromuscular variables in in the context of assessing RTA following an injury in adolescent athletes. We found that *1)* all kinematic variables showed a significant difference between task, however, failed to identify an effect of limb dominance, *2)* the DVJ produced greater iEMG activations posteriorly and the lunge produced greater iEMG activations anteriorly and ,*3)* the DVJ produced significant kinetic differences in iJP values while the lunge produced significant kinematic differences in iKEXC and PKF.

### *4.1 Kinematics*

Significant differences were present between tasks in all kinematic data. Participants achieved greater PKF angles during the lunge task compared to the DVJ. This could be due to several reasons. Lower PKF values could be caused by a reduction in movement time that has been associated with increased joint power. This could limit duration of the task, as higher joint power can drive quicker movement (Alkjaer et al., 2002). Decreased PKF values could also be attributed to an increase in joint stiffness, which would impact knee excursion and iEMG results as well (Rozzi, Lephart, Gear, & Fu, 1999; Sell et al., 2006). Previous research has also distinguished differing neuromuscular responses depending on the intent of the task. A study comparing a drop-jump to a drop-landing highlighted significant differences in biomechanical and neuromuscular response. A slight change in task focus (drop landings: energy absorption; drop jump: energy absorption and subsequent maximal vertical jump) altered landing mechanics (Ambegaonkar et al., 2011). In a drop landing alone, the focus is to decelerate the body and absorb the impact forces while stabilising the body, similar to the lunge. For a drop jump, the goal of the task shifts from absorbing impact to transferring the energy into a propulsive vertical force. This shift in focus could further explain the higher iJP and iEMG results found in the DVJ (Ambegaonkar et al., 2011).

### *4.2 Electromyography*

Analysis of EMG activations provided insight into muscular contributions towards joint torque. Overall, the DVJ produced greater demands in iEMG in the posterior musculature compared to the lunge which showed increased iEMG in the anterior musculature, with the lateral hamstring muscles providing the greatest differences between tasks. As indicated by previous work, the hamstring, being a biarticulate muscle, depends on both the knee and hip joint angles, with majority of length change coming from the hip (Hawkins & Hull, 1990). Thus, an increase in hamstring activity could indicate greater hip angles as a means of compensating for an increase in knee joint angle (Jönhagen, Halvorsen, & Benoit, 2009).

When comparing between males and females, females exhibited higher iBF and iST demands during both the lunge and DVJ compared to males. Considering the measure of integration, the variable of time needs to be considered. Females showing higher hamstring iEMG values in the lunge could be in relation to the duration of task. For example, a longer duration of a task requires longer muscular activation, as the sum of the activation is larger. Thus, concluding that females performed both tasks more slowly than males. A study done by Alkjær et al. (2002) looking at differences in lunge performance between three groups (copers, non-copers, controls), indicated significantly higher ST amplitudes in copers than in non-copers and controls (Alkjaer et al., 2002). A similar study analyzed movement time of the lunge, indicating that ACL-deficient participants performed the lunge 28% more slowly than the ACL-deficient and controls (Alkjær et al., 2020). Similar assumptions can be made with respect to all other iEMG variables.

Independent of task, female athletes required greater hamstring contribution than males. A greater need for muscular contribution could be related back to the efficiency of muscular usage. Previous work has indicated that those who have lower work producing capabilities can achieve higher activations as a means to compensate for the lack of overall strength. Therefore, the higher iEMG demands could be an indication of an increased need for longer and greater muscular contractions (da Fonseca et al., 2006; Häkkinen & Komi, 1983). Increased hamstring activity has also been identified as a means of reducing stress on the knee and has been suggested that it is an attempt by female athletes to prevent anterior tibial translation (Rozzi et al., 1999; Sell et al., 2007), which could help explain the sex differences found in this study.

Increased gastrocnemius values in the DVJ compared to the lunge could suggest a greater involvement of the ankle during the deceleration phase of the movement. Similar results were found in previous studies comparing muscular amplitudes in a variety of drop jumps (Ambegaonkar et al., 2011; Noyes & Barber-Westin, 2018; Rozzi et al., 1999), showing periods of higher gastrocnemius demands during the deceleration phase of a movement. Additionally, differences were found between sexes in gastrocnemius contributions. Males demonstrated greater iLG and iMG values during the lunge, whereas females showed greater iLG and iMG values during the DVJ. This could be due to muscular weakness, which is what Häkkinen and Komi (1983) distinguished when comparing between sexes during an isometric strength test and training program, indicating a greater requirement of the musculature in order to meet similar demands of the muscle to achieve a similar outcome (Häkkinen & Komi, 1983).

Higher demands in EMG values for quadriceps muscles compared to the hamstrings was also evident in both males and females, with the lunge attaining overall greater values. This might suggest that the lunge is a task that is more sensitive to anterior muscular differences rather than the DVJ, which might be more sensitive to posterior muscular differences. Regardless of the duration of movement, quadriceps muscles produced greater iEMG results in both males and females. This has been associated with increased anterior tibial translation and has the potential to load the ACL during the landing phase of a movement, thus, potentially increasing the risk of ACL injury (Hanson et al., 2008; McLean et al., 2005). However, quadriceps activation has also been identified as a protective mechanism serving as a shock absorber that has the capability of decreasing the mechanical load of an activity (Palmieri-Smith & Thomas, 2009). For example, quadriceps avoidance alters knee joint mechanics during landing, with subjects producing larger ground reaction forces and in higher knee extension (Palmieri-Smith, Kreinbrink, Ashton-Miller, & Wojtys, 2007).

The lunge and DVJ are tasks that are commonly found in sporting situations and produce distinct demands on the participants. The lunge challenged the participants peak knee flexion, knee excursion, and quadriceps values to a greater degree than the DVJ. The DVJ challenged the BF, gastrocnemii, and GMed to a greater degree than the lunge, while also contributing to greater iJP demands. These differences in task demands support their ability to distinguish between differing movement patterns, which is synonymous to the findings of Alkjær et al. (2002) and Padua et al. (2015) (Alkjaer et al., 2002; Padua et al., 2015).

### *4.3 Limitations*

Initially, this study included 68 participants (male: n=29; female: n=39), however, several participants EMG (VM-2; GMed-1; BF-7; ST-10) was excluded due to signal noise or technical issues with electrodes. When considering EMG, some authors have cautioned the use of MVICs to normalize muscle activation (Clarys, 2010), however, for the purposes of this study, MVICs was deemed as the most appropriate solution as it provides a reference to the muscular activations collected during the dynamic tasks (Benoit et al., 2003). Other procedures have been established to collect MVICs, such as during a dynamic task, however, more movement, whether that is by the dynamic task itself or by the lengthening/shortening of a muscle, allows for the potential of more noise (Benoit et al., 2003). Finally, due to the unbalanced sample size with differing maturation levels, this study was unable to take the influence of pubertal development into account. Previous studies have identified large differences in more mature populations, especially in females (Hewett et al., 2004; Ithurburn et al., 2019). This could explain the high number of outliers present in this and should be considered in future studies.

## *5. Conclusion*

This study is the first to compare neuromuscular and biomechanical discrete variables of the lunge and DVJ to quantify the demand of each task. Both tasks have been researched independent from one another and have indicated their ability to measure movement performance. In this study the lunge elicited greater demands in peak knee flexion, knee excursion, and quadriceps values. While the DVJ challenged the BF, gastrocnemii, and GMed to a greater degree than the lunge, while also eliciting greater iJP demands. These differences found between tasks allows us to evaluate specific characteristics of functional movements that are commonly found in sporting environments that involve high-risk maneuvers such as single leg loading, cutting, and landing from a jump, and thus making each task a valid form of measurement for functional capacity (Alkjaer et al., 2002; Padua et al., 2015).

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# Chapter 7. Manuscript 2

## The effects of an ACL injury on knee stabilization strategies in adolescent males and females during a drop-vertical jump

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## Abstract

***Background:*** Adolescents have significantly higher rates of diagnosed anterior cruciate ligament (ACL) injuries compared to adult cohorts. Approximately two-thirds of ACL injuries are non-contact scenarios while performing "high-risk" maneuvers. The purpose of this study was to examine the knee stabilization strategies of adolescent male and female athletes with and without an ACL injury using medial-lateral coactivations and measures of dynamic knee joint stability assessed via frontal plane knee excursion.

***Methods:*** Fifty-four males (n=17) and females (n=37) with an ACL injury and 68 uninjured males (n=29) and females (n=39) performed a drop-vertical jump (DVJ) time-normalized into three phases: preparatory, deceleration, and acceleration. Two-sample *t*-tests using statistical parametric mapping (SPM) determined time-varying statistically significant differences in coactivation indices (CI) and medial-lateral ratios. Independent samples *t*-tests were used to analyze discrete integrated frontal plane knee excursion values.

***Results:*** Males and females with an ACL injury produced higher CI values compared to the uninjured groups. Significant differences were found in the females between the lateral Q:H (p=0.01) during 48-70% of the preparatory phase and between the lateral Q:G (p<0.001) during 1-63% of the preparatory phase, indicating higher coactivations in females with an ACL injury. Medial Q:H coactivations were significantly different in females during the entire preparatory phase (p<0.001) and 80-88% of the acceleration phase (p=0.021), whereas males were significantly different during 5-32% (p=0.040) of the deceleration phase and 44-75% (p=0.010) of the acceleration phase. Females also had significant differences in medial Q:G during all of the preparatory phase (p<0.001), 1-2% (p<0.001) of the deceleration phase and 66-76% (p=0.012) of the acceleration phase. Frontal plane knee excursion values indicated significant differences between females during the preparatory (p=0.011) and acceleration phase (p=0.031), whereas males indicated no significant differences.

***Conclusion:*** Our results indicate that females with an ACL injury increase dynamic knee joint stability through greater medial-lateral symmetry, greater generalised coactivation levels, and greater preparatory medial quadriceps and hamstring activation during the DVJ.

## *1. Introduction*

Adolescent (10- to 18: inclusive) enrollment in sport has increased exponentially in Canada with an estimated 77% of five- to nineteen-year-olds and 46% of three- to four-year-old's participating in organized sport (ParticipACTION Report, 2018). This rise in sport participation along with early specialization and better injury detection has caused an influx of anterior cruciate ligament (ACL) injuries (Beck et al., 2017; Frank & Gambacorta, 2013; LaBella et al., 2014). Adolescent athletes also have significantly higher rates of ACL injuries compared to adults (Werner et al., 2016), with rates continuing to rise 2.3% annually in patients between the ages of six- to eighteen (Beck et al., 2017). Furthermore, females who participate in athletics that involve "high-risk" movements such as cutting, pivoting or landing from a jump are two- to eight times more likely to suffer an ACL injury compared to their male counterparts (Beck et al., 2017; Dekker et al., 2018; Werner et al., 2016). It is also worth noting that the disparity of ACL injury rates between males and females become apparent as early as 12- years-old and continues to diverge well into maturation (Ford, Shapiro, Robert., Myer, Gregory D., Van Den Bogert, Antonie J., Hewett, 2011; Ford et al., 2003; Renstrom, Ljungqvist, Arendt, Beynnon, Fukubayashi, Garrett, Georgoulis, Hewett, Johnson, & Krosshaug, 2008).

Approximately two-thirds of these ACL injuries occur during noncontact scenarios (McNair et al., 1990) while performing a "high-risk" maneuver involving multiplanar loading of the knee (Joseph et al., 2013; Myer et al., 2005; Noyes & Barber-Westin, 2018). It is believed that these "high-risk" maneuvers elicit biomechanical movement patterns that increase loading on the ACL (Hewett, Myer, Ford, Heidt, et al., 2005; Myer et al., 2005). Research suggests that landing or absorbing force in a relatively extended position about the hip and knee, with the hip and tibia internally rotated, can place excessive amounts of strain on the ACL (Hewett et al., 2006, 2012;

Yu & Garrett, 2007). This position, in combination with the knee abducted and the foot fixed on the ground, is a likely cause for sustaining an ACL injury (Hewett et al., 2005; Kaeding et al., 2017; Myer et al., 2013; Shin et al., 2011). Avoiding these “high-risk” positions requires both passive ligament restraint and active muscle force (Hewett, Myer, Ford, Heidt, et al., 2005). Once the passive structure involved in joint stability is injured, such as the ACL, the active structures are thought to offset the disruption. However, research has yet to identify what a proper way of maintaining dynamic knee joint stability is once damage to the passive structure is sustained.

Thus, neuromuscular control deficits present in dynamic movements are theorized to be a likely contributing factor for ACL injury and re-injury. In “high-risk” maneuvers, such as a drop-vertical jump, a combination of dynamic joint stability and movement efficiency are required to achieve a maximum performance (Ford et al., 2008; Ford et al., 2003; Paterno et al., 2010). A potential strategy used to dynamically stabilize a joint through active structures is to coactivate the muscles surrounding the joint by simultaneously contracting the agonist and antagonist muscles (Winter, 2009). Mechanically, higher levels of agonist and antagonist muscle recruitment can result in increased levels of joint compression (Baratta et al., 1988; Wojtys, Huston, Schock, Boylan, & Ashton-Miller, 2018; Yack, Washco, & Whieldon, 1994). Increasing joint compression by increasing coactivation has been indicated as a knee stabilization strategy of those who are low-skilled/sedentary (da Fonseca et al., 2006; Ford et al., 2008; Frost, Bar-Or, Dowling, & Dyson, 2002; Hamstra-Wright et al., 2006; Withrow, Huston, Wojtys, & Ashton-Miller, 2008), and could be a compensatory mechanism of those with an ACL injury. In those who are higher-skilled/active, it has been found that inhibiting the antagonist muscle could be an effective adaptation to maintain movement efficiency, as increased joint compression may lead to a reduction of the system’s ‘degrees of freedom’ (Bernstein, 1967; Keith L. Markolf, O’Neill, Jackson, & McAllister, 2004).

The imbalance of musculature as a means of knee stabilization may also influence neuromuscular control and potentially increase the risk of sustaining an ACL injury (Hewett et al., 1999; Hewett, Myer, Ford, Heidt, et al., 2005; Landry et al., 2007; Schmitt et al., 2015). An imbalance in extensor (quadriceps) and flexor (hamstrings and gastrocnemii) activation, medial-laterally or anterior-posteriorly, can influence neuromuscular control about the knee potentially increasing risk of ACL injury (Hewett, Myer, Ford, Robert S. Heidt, et al., 2005). Baratta and colleagues (1988) initially discovered that muscular imbalance was the main cause of a diminished muscular response rather than absolute strength (Baratta et al., 1988). Others, looking at adult populations during weight-bearing tasks, agreed with this finding proposing that medial-lateral and anterior-posterior muscular imbalance can lead to an increased risk of injury (Hewett et al., 1999, 2004; Hewett, Myer, Ford, Heidt, et al., 2005; Landry et al., 2007; Schmitt et al., 2015). Additionally, research has indicated that maintaining medial-lateral neuromuscular control about the knee can reduce knee abduction and adduction angles, and decrease the risk of femoral condylar lift-off from the tibial plateau, thus, decreasing potential excessive loading on the ACL (Hewett et al., 2004; K. Markolf, Graff-Radford, & Amstutz H.C, 1978).

Not only has research identified muscle activation-based differences in coactivation strategies, but also sex-differences as well. Females demonstrate general joint stabilization strategies in neuromuscular control with greater quadriceps and lateral musculature involvement compared to males (Dedinsky, Baker, Imbus, Bowman, & Murray, 2020; Flaxman et al., 2014; Landry et al., 2007; Rudolph et al., 2001; Sigward & Powers, 2006). Landry et al. (2007) identified a gastrocnemius medial-lateral imbalance in females indicating greater lateral activation strategies compared to males at initial contact during a side-cut (Landry et al., 2007). This combination of high lateral musculature involvement and dominant quadriceps muscle activity has been speculated to cause a decrease in generalized dynamic knee joint stability with higher lateral joint compression and increased anterior tibial translation (Andriacchi, Andersson, Örtengren, & Mikosz, 1983; Lloyd & Buchanan, 2001; K L Markolf, Mensch, Amstutz, & Quantitative, 1976; Tibone, Antich, Fanton, Moynes, & Perry, 1986). Given the importance of neuromuscular control for dynamic stability, more research is needed to understand how an ACL injury might impact the neuromuscular control of the knee joint. This is especially relevant for adolescents, considering that females exhibit decreased neuromuscular control about the knee from early to late puberty as established through valgus angle, whereas males demonstrate increased control through decreased valgus angles throughout maturation (Hewett et al., 2004). This research could lead to the development of rehabilitations guidelines designed for adolescents and in turn, combat the rise in ACL injury rates in this demographic.

Thus, the purpose of this study was to examine the knee stabilization strategies of adolescent male and female athletes with and without an ACL injury through medial-lateral coactivations and measures of dynamic knee joint stability assessed via knee excursion. To achieve this purpose we tested three hypotheses: (1) both uninjured males and females would have lower coactivation levels in the medial musculature, and an injury to the ACL would further decrease medial coactivation (Palmieri-Smith et al., 2009); (2) females would have an imbalanced medial-lateral quadriceps-hamstrings (Q:H) coactivations, however, those with an ACL injury would demonstrate a significantly greater imbalance; (3) due to a quadriceps strength deficit present in those with an ACL-deficiency (Thomas et al., 2016; D. Urbach et al., 2001; Dietmar Urbach & Awiszus, 2002; Dietmar Urbach et al., 1999), the unbalanced medial-lateral coactivations and the medial musculature weakness predominantly found in females (Palmieri-Smith et al., 2009) will contribute to greater knee abduction angles leading to greater frontal plane knee excursion (Hewett, Myer, Ford, Heidt, et al., 2005; Palmieri-Smith, Wojtys, et al., 2007; Paterno et al., 2010).

## *2. Methods*

### *2.1 Participants*

A total of 122 adolescent athletes (37 ACL injured (ACLi) females; 17 ACLi males; 39 uninjured females; 29 uninjured males) aged 10-to 18 were recruited for participation in the study. Uninjured adolescent athletes were recruited from sporting associations within the Ottawa/Gatineau area (Table 2.1.1). Those with an ACLi were recruited by Orthopaedic Consultants at the Children's Hospital of Easter Ontario (CHEO) and received approval by their physician prior to participation in the study. Confirmation of a positive ACL rupture was done by means of MRI. All uninjured participants were screened prior to collection of any prior knee injury, lower extremity pain (within 6 months), or any disease/illness that would impact the neuromuscular function. Only the dominant (uninjured participants) and injured (ACLi participants) limbs were used in this study. Limb dominance was defined as the preferred leg to kick a soccer ball to achieve a maximum distance (van Melick et al., 2017). Prior to data collection, each participant provided informed consent, approved by the University of Ottawa Research Ethics Board (uOttawa REB H09/17/10) (CHEO REB 17/74X).

**Table 1**

*Uninjured and ACL injured male and female characteristics presented as means and standard deviations*

| **Variable** | **Females** |  | **Males** |  |
|---|---|---|---|---|
|  | ***Mean±SD*** |  | ***Mean±SD*** |  |
|  | **Uninjured** | **ACL Injured** | **Uninjured** | **ACL Injured** |
| **Age** (years) | 13.2 ± 1.6 | 15.2 ± 1.4 | 13.2 ± 1.7 | 15.4 ± 1.2 |
| **Height** (cm) | 161.7 ± 8.1 | 164.8 ± 6.1 | 164.4 ± 13.9 | 174.5 ± 9.5 |
| **Weight** (kg) | 50.8 ± 11.1 | 64.1 ± 9.8 | 51.7 ± 13.1 | 69.4 ±16.1 |
| **BMI** ($kg/m^2$) | 19.2 ± 2.8 | 23.6 ± 3.5 | 18.9 ± 2.9 | 22.7 ± 4.6 |
| **Tegner Activity Level** | 8.3 ± 1.3 | 8.7 ± 1.0 | 8.4 ± 1.2 | 8.4 ± 1.2 |
| **Tanner Stage** | 3.2 ± 1.1 | 3.8 ± 1.8 | 3.1 ± 1.2 | 4.1 ± 1.0 |

*Note:* Values closer to 10 indicate higher Tegner activity level

### *2.2 Protocol*

Each participant was given a pair of tight fitted black spandex shorts and a long sleeve shirt. Anthropometric measurements of the pelvis, knee, and ankle widths (cm); height (cm) and weight (kg); leg and tibial length (cm); and thigh and shank circumference (cm) were collected. Following these measurements, the participants were given standardized athletic footwear (KBS7FW3343; MS7F505027, Joe Fresh, ON, Canada) to reduce inter-participant variability. Each participant completed a five-minute warm-up using a stationary bike with little to no resistance. Adhering to SENIAM guidelines (De Luca, 1997; Hermens et al., 2000), with minor adjustments tailored to the individual, wireless bipolar surface EMG (sEMG) electrodes (16-channel Trigno, Delsys, Boston, USA) were placed on the gluteus medius (GMed), vastus lateralis (VL), rectus femoris (RF), vastus medialis (VM), biceps femoris (BF), semitendinosus (ST), medial gastrocnemius (MG), and lateral gastrocnemius (LG) on each limb. Electromyography data was sampled at 2000Hz, amplified by a factor of 1000, and band-pass filtered at 20-450Hz. To reduce the amount of noise generated from crosstalk each sensor was placed on the midline of the muscle bellies between the myotendinous junction and the nearest innervation zone with the detection surface being perpendicular to the length of the muscle fibers. The skin was shaved and cleaned with an alcohol swab and allowed to dry prior to electrode placement. Each sensor was then checked for signal quality prior to securing each device onto the muscles via tape and pre-wrap to reduce movement artifacts (De Luca, 1997; Hermens et al., 2000).

Following sEMG setup, maximum voluntary isometric contractions (MVICs) were recorded using a Biodex isokinetic dynamometer (System 4 Pro, Biodex Medical Systems, New York, USA) (Benoit et al., 2003). Each participant went through a series of contractions highlighting the primary actions of each muscle. These included: i) knee flexion and ii) extension placed in a seated position with the hip at 90 degrees and the knee flexed at 60 degrees (Beaulieu, Lamontagne, & Beaulé, 2010); and iii) plantarflexion, recorded in a seated position with the knee at 0 degrees and the ankle in a neutral position (Romanchuk & Benoit, 2019; Sale et al., 1982). Each participant recorded three MVICs each with a minimum of one minute of rest between attempts. Verbal encouragement and on-screen biofeedback was provided to assist in achieving their maximal force (Mcnair et al., 1996).

Eighty four reflective markers (14mm diameter) were then positioned on anatomical landmarks according to a hybrid cluster-marker set (Mantovani & Lamontagne, 2017; Romanchuk & Benoit, 2019). All kinematic data was sampled at 200Hz using a 10-camera infrared motion analysis system (8 Vero and 2 Vantage; Vicon, Nexus, Oxford, UK). Ground reaction forces (GRFs) were recorded using two force platforms (FP4060-08, Bertec Corp., Columbus, USA), and sampled at 1000Hz.

Participants were then asked to perform five successful attempts of a drop-vertical jump task (DVJ). A successful DVJ consisted of stepping off an adjustable raised platform set to the height of the participant’s tibial plateau, landing with each foot on the embedded force platforms, immediately performing a maximal vertical jump, and landing again with each foot on a force platform. *Notes: this thesis was part of a larger dataset; however, only the tasks relevant to this thesis will be discussed (Appendix A).*

### *2.3 Data Processing*

#### Kinematics

Both the marker trajectories and GRFs were filtered using a 4th order zero-lag low-pass Butterworth filter with a matching cut off frequency of 15Hz (Bisseling & Hof, 2006; Kristianslund et al., 2012). Filter order and cut-off frequency were selected based on a residual analysis and visual inspection of filter performance. Hip, knee, and ankle moments and angles were collected in the sagittal and frontal planes during the DVJ. Knee excursion was collected in the frontal plane and is reported as the Euclidean distance of the knee joint center (Smale, Alkjaer, et al., 2019) as it traveled throughout the three phases of interest during the DVJ (explained below). The knee joint center is defined as the midpoint between the lateral and medial femoral epicondyle markers (Smale, Alkjaer, et al., 2019).

#### Electromyography

Electromyography data was high-pass filtered at 20Hz with a 2nd order dual-pass Butterworth filter to attenuate movement artifact, full-wave rectified to obtain an absolute value, and low-pass filtered at 6Hz with a 2nd order dual-pass Butterworth filter to smooth the signal. Using the participants MVIC, the mean of 50ms about the highest peak identified the maximum amplitude for each muscle which was then used to amplitude-normalise the EMG data to the DVJ.

The coactivation index (CI) used to measure the muscular coactivations, describes the relative and overall magnitude of the muscular activation strategies in the antagonist and agonist muscles/muscle groups of interest (Lewek et al., 2005; Rudolph et al., 2001). The CI is defined as the ratio between the antagonists and agonists activation during the DVJ multiplied by the summed EMG from both muscles (Equation 2; Lewek et al., 2005; Rudolph et al., 2001).

$$CI = \left(\frac{EMG_{lower}}{EMG_{higher}}\right) * (EMG_{lower} + EMG_{higher}) \qquad (2)$$

The CIs of interest are the antagonist and agonist muscle activity of the lateral quadriceps to hamstring (Q:H) calculated using the VL and BF activity and the Q:G (VL:LG), and the medial Q:H (VM:ST) and Q:G (VM:MG). Anterior-posterior coactivations compare anterior muscles to posterior muscles, where medial-lateral ratios compares medial muscles to lateral muscles. A medial-to-lateral ratio was then calculated by dividing the medial Q:H CI by the lateral Q:H CI and the medial Q:G CI by the lateral Q:G CI to determine whether coactivation was imbalanced between the medial and lateral sides (Palmieri-Smith et al., 2009).

### Time Normalization

All waveform data for the DVJ was trimmed using unfiltered data to establish the three phases of interest: *preparatory*, *deceleration*, and *acceleration phase*. Each phase was then adjusted to fit the time normalized scale prior to extracting variables with each phase totaling 1-100%. The *preparatory phase* was identified as 100ms prior to initial contact (IC: GRF > 10 N) (Cavanagh & Komi, 1979; Kipp et al., 2014; Palmieri-Smith, Wojtys, et al., 2007; Russell et al., 2007; Smale, Flaxman, et al., 2019). The *deceleration phase* was established as the point of IC until peak knee flexion, and the *acceleration phase* as peak knee flexion until take-off (GRF < 10 N). Only the first contact on the force plates were analyzed (Bencke et al., 2000; Myer et al., 2006). All continuous variables such as the coactivations and knee excursions were time-normalized, while discrete data points that were collected to help interpret the primary findings were not.

### *2.4 Statistical Analysis*

The primary variables of this study are muscular coactivations and knee excursion. The secondary variables, such as hip, knee, and ankle moments and angles will be used to help interpret the findings of the primary variables. The assumption of normality for continuous group means of the coactivations were evaluated through a Shapiro-Wilk test within the statistical parametric mapping (SPM) software. Normally distributed data was compared between groups (Female ACL vs Uninjured Female; Male ACL vs Uninjured Male) using SPMs independent two-sample *t*-tests, whereas statistical non-parametric mapping (SnPM) independent two-samples *t*-tests was used for data that rejected the assumption of normality. All data failed to assumption of normality, thus, the non-parametric test was used. Statistical parametric mapping is a technique that uses random field theory to perform comparisons between entire time-dependent data sets, which includes all data within the tasks waveforms as a reductionist approach to determine the time-varying differences throughout the phases identified above (Pataky et al., 2013; Sole et al., 2017). The assumption of normality for the discrete variable of frontal plane knee excursion was evaluated through Shapiro-Wilk tests. Normally distributed data used independent *t*-tests, whereas data that rejected the assumption of normality used Mann-Whitney U tests.

For all statistically significant results, a Benjamini-Hochberg correction for multiple comparisons was performed with a false discovery rate of 0.05 (Benjamini & Hochberg, 1995). Outliers were identified as those exceeding 1.5 times the interquartile range and were inspected to determine the appropriate action. If an outlier was a result of an error in the data collection it was excluded (ex. EMG electrodes losing contact with the skin). Those that reflected accurate data were included in the subsequent analysis. Effect sizes were calculated for continuous variables using the critical threshold (*t**) and discrete variables used Cohen's *d* effect sizes with these parameters: small effect size $d < 0.5$, medium effect size $0.5 < d < 0.8$, large effect size $d > 0.8$ (Field, 2013). All statistical analysis was done using a combination of MATLAB (2020a, MathWorks, Natick, USA) and SPSS Statistics 26.0 (IBM Corp., Armonk, NY, USA) with the level of significance set at $p= 0.05$.

## ***3. Results***

All 122 participants completed five trials of the DVJ, however one male subject with an ACL injury presented as an outlier and was removed due to their high BMI (59.3) and the implications it has towards influencing EMG data (Nordander et al., 2003). Results from the Benjamini-Hochberg correction can be found in Table 3.1. For events in the preparatory, deceleration, or acceleration phases where SnPM achieved periods of significance, effect sizes were reported for within phase differences (Figure 3.1-3.4; Table 3.2 and 3.3). Two-tailed two-samples *t* tests revealed statistically significant CI, sagittal and frontal knee excursion, and medial-to-lateral ratios. Location of significance, critical threshold value and coactivation description can be found in Table 3.2 and Table 3.4 for frontal plane knee excursion data.

**Table 3.1**

Results from Benjamini-Hochberg on statistically significant values from the SPM analysis. Process done to correct for multiple comparisons with a false discovery rate of 0.05 for a total of 22 comparisons.

| Variable | *p*-value | *Rank* | Benjamini-Hochberg Critical Value | *Significance* |
|---|---|---|---|---|
| Female Medial Q:H | < 0.001 | 1 | 0.0023 | * |
| Female Medial Q:G | < 0.001 | 1 | 0.0023 | * |
| Female Lateral Q:G | < 0.001 | 1 | 0.0023 | * |
| Female Medial Q:G | < 0.001 | 1 | 0.0023 | * |
| Female Uninjured M-L Q:H Ratio | < 0.001 | 1 | 0.0023 | * |
| Male Uninjured M-L Q:H Ratio | < 0.001 | 1 | 0.023 | * |
| Male Uninjured M-L Q:H Ratio | 0.002 | 7 | 0.016 | * |
| Female ACL Injured M-L Q:G Ratio | 0.003 | 8 | 0.018 | * |
| Male Medial Q:H | 0.010 | 9 | 0.021 | * |
| Female Uninjured M-L Q:H Ratio | 0.011 | 10 | 0.023 | * |
| Female Preparatory Knee Excursion | 0.011 | 10 | 0.023 | * |
| Female Medial Q:G | 0.012 | 12 | 0.027 | * |
| Female Lateral Q:H | 0.014 | 13 | 0.030 | * |
| Female Uninjured M-L Q:H Ratio | 0.021 | 14 | 0.032 | * |
| Female Medial Q:H | 0.021 | 14 | 0.032 | * |
| Female Acceleration Knee Excursion | 0.031 | 16 | 0.036 | * |
| Male Medial Q:H | 0.040 | 17 | 0.039 | |

*Note.* Total of 22 comparisons (males and females and 11 variables) with some comparisons providing multiple statistically significant clusters, ordered chronologically, within one SPM test.

### 3.1. Lateral Coactivation Indices

The mean CIs during the lateral Q:H CI were similar for the majority of the task (Figure 3.1A and Figure 3.2A; Table 3.2). However, during 48-70% of the preparatory phase females with an ACL injury produced higher coactivations than the uninjured females ($p$= 0.01). Males presented no statistically significant differences during the DVJ between groups (Figure 3.2A).

Females with ACL injury had higher lateral Q:G ratios ($p < 0.001$) during 1-63% of the preparatory phase (Figure 3.1C; Table 3.2). Males group means showed no significant difference throughout the DVJ between those with and without an ACL injury (Figure 3.2C).

### *3.2. Medial Coactivation Indices*

Group means for the medial Q:H were significantly different throughout 1-100% of the preparatory phase ($p < 0.001$) and 80-88% ($p = 0.021$) of the acceleration phase when comparing between female groups (Figure 3.1B; Table 3.2). Those with an ACL injury presented with significantly higher coactivations compared to the uninjured controls. Medial Q:H CI were the only coactivations to produce significant differences between groups. Males with an ACL injury produced significantly higher CI during 44-75% ($p = 0.010$) of the acceleration phase (Figure 3.2B; Table 3.2).

Medial Q:G showed similar trends presenting with significant differences during all 1-100% of the preparatory phase ($p < 0.001$), 1-2% ($p < 0.001$) of the deceleration phase and 66-76% ($p = 0.012$) of the acceleration phase of the DVJ (Figure 3.1D; Table 3.2). Males indicated no statistically significant differences between groups (Figure 3.2D).

**Table 3.2**

Description of statistically significant coactivation indices during the drop-vertical jump using SPM for male and female groups.

| Variables | Location of Sig. | t* | *p*-value | Coactivation Index: Uninjured | Coactivation Index: ACL |
|---|---|---|---|---|---|
| ***Females*** | | | | | |
| **Lateral Q:H** | 48-70% P | 2.757 | 0.014 | Hamstring dominant<br>Overall lower VL and BF<br>More asymmetrical | Quadriceps dominant<br>Greater VL and BF<br>More symmetrical |
| **Medial Q:H** | 1-100% P<br>80-88% A | 2.819 | < 0.001<br>0.021 | Overall lower VM and ST<br>More symmetrical (Ant/Ag) | Quadriceps dominant<br>~2x VM, ~3x ST than uninjured |
| **Lateral Q:G** | 1-63% P | 3.004 | < 0.001 | Gastrocnemius dominant<br>Similar symmetry | Quadriceps dominant<br>Similar symmetry |
| **Medial Q:G** | 1-100% P<br>1-2% D<br>66-76% A | 3.027 | < 0.001<br>< 0.001<br>0.012 | Gastrocnemius dominant<br>Utilized MG more on initial impact | Higher amplitudes (~2x)<br>Gastrocnemius dominant |
| ***Males*** | | | | | |
| **Medial Q:H** | 44-75% A | 2.654 | 0.019 | Hamstring dominant<br>More symmetrical (Ant/Ag) | Hamstring dominant<br>Greater amplitudes for Ant/Ag (~1.5x) |

*Note.* Only significant preparatory (P), deceleration (E), and acceleration (C) locations are present in table. Coactivation index indicates variability in antagonist and agonist (Ant/Ag) muscular activations. Included coactivation variables are lateral Q:H (VL:BF), medial Q:H (VM:ST), lateral Q:G (VL:LG), and medial Q:G (VM:MG) respectively. Dividing lower EMG to higher EMG indicated coactivation symmetry. Values closer to 1.0 indicated greater symmetry.

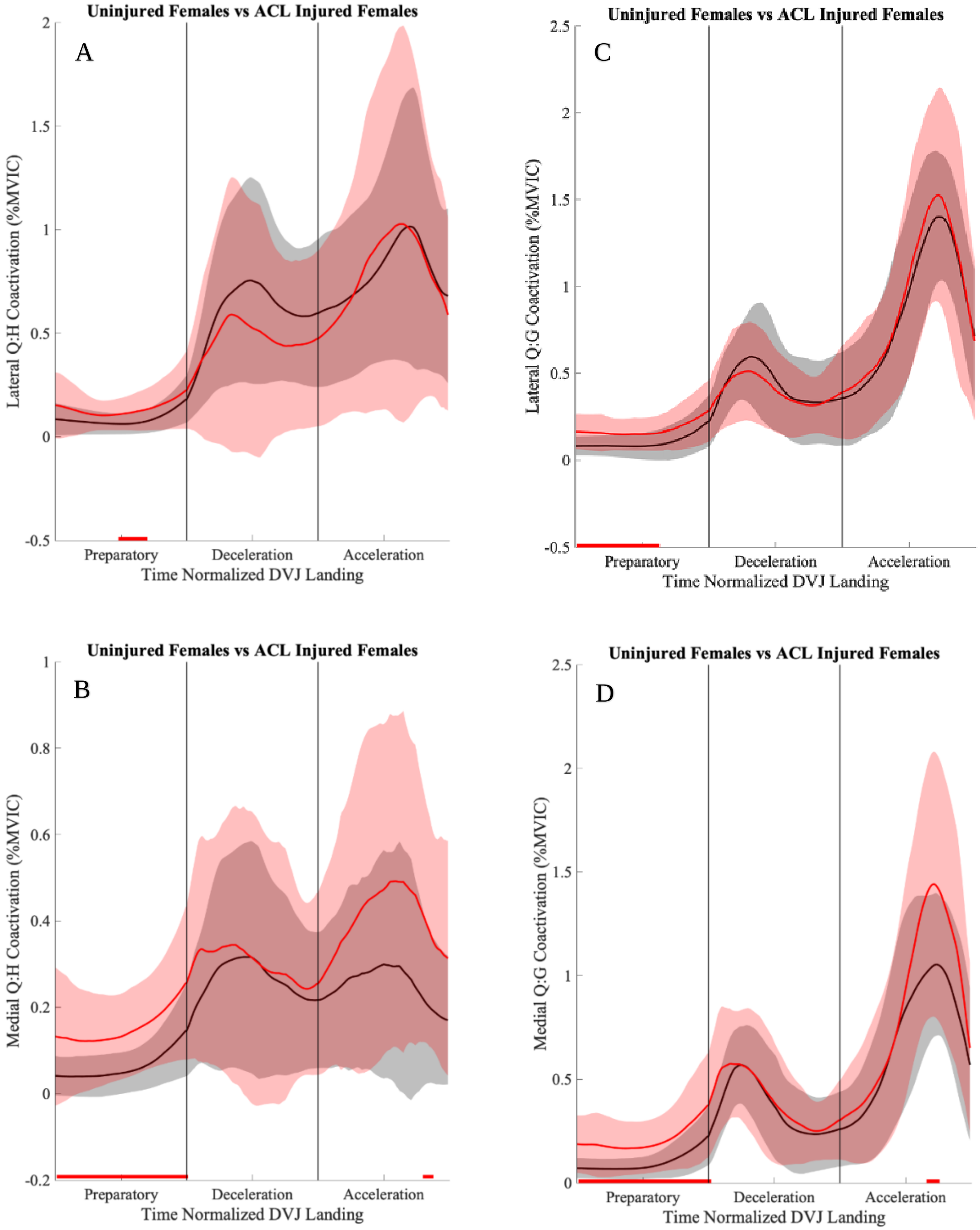

*Figure 3.1.* Time-normalized EMG coactivation waveforms for the lateral Q:H (A) and Q:G (C) and medial Q:H (B) and Q:G (D) muscles during the drop-vertical jump task. Red horizontal bar on x-axis indicates statistical significance between uninjured (black) and ACL injured (red) females.

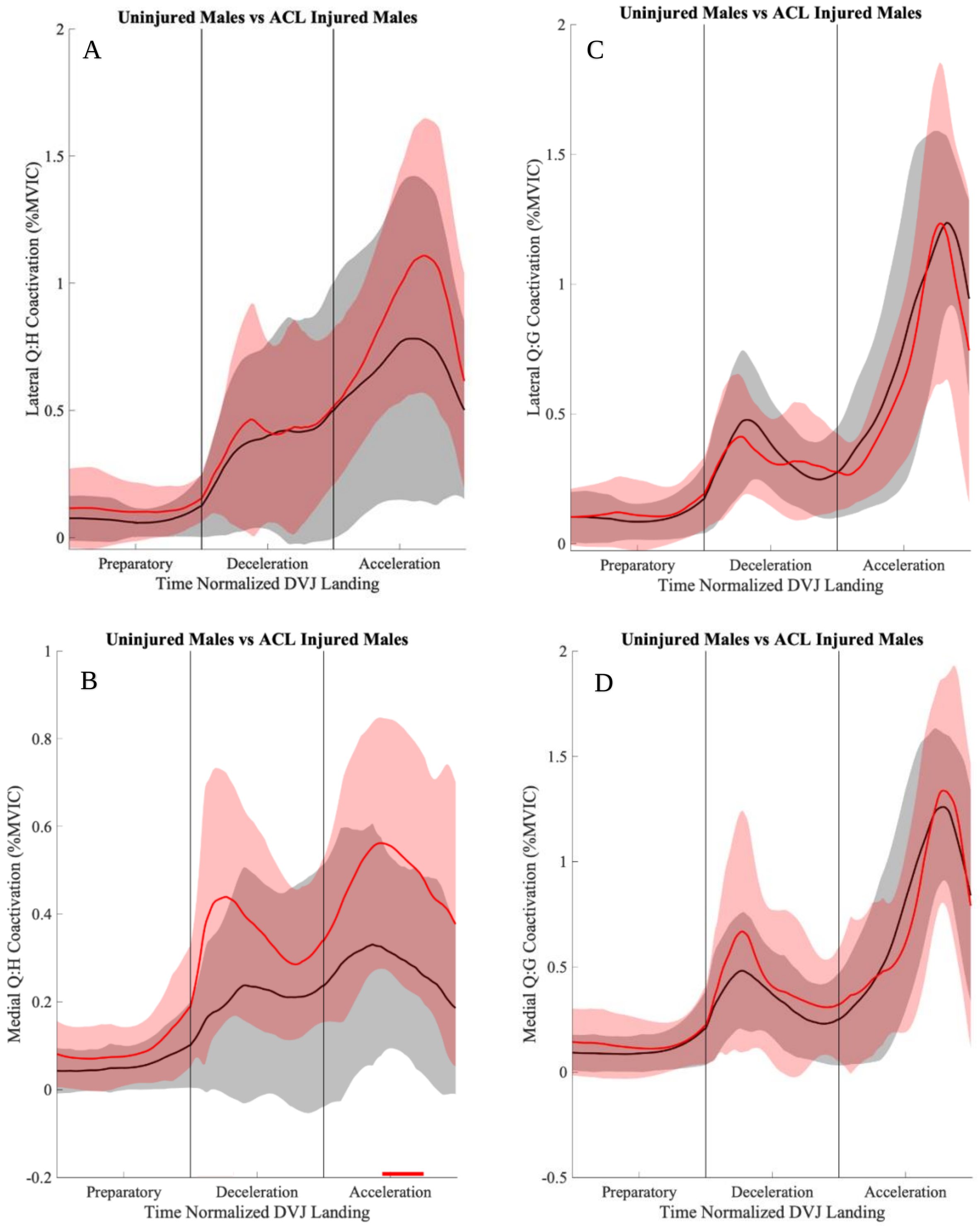

*Figure 3.2.* Time-normalized EMG coactivation waveforms for the lateral Q:H (A) and Q:G (C) and medial Q:H (B) and Q:G (D) muscles during the drop-vertical jump task. Red horizontal bar on x-axis indicates statistical significance between uninjured (black) and ACL injured (red) males.

**Table 3.3**

Description of statistically significant medial-lateral ratio values using SnPM for male and female groups.

| Medial-Lateral Ratio | Location of Sig. | t* | *p*-value | Muscular Dominance |
|---|---|---|---|---|
| ***Uninjured Females*** | | | | |
| **Q:H** | 1-8% P<br>11-100% D<br>1-100% A | 2.686 | 0.021<br>< 0.001 | Lateral Q:H |
| **Q:G** | 64-88% A | 3.041 | 0.003 | Lateral Q:G |
| ***ACLi Females*** | | | | |
| **Q:H** | 76-97% A | 2.829 | 0.011 | Lateral Q:H |
| ***Uninjured Males*** | | | | |
| **Q:H** | 34-100% A | 2.759 | < 0.001 | Lateral Q:H |
| ***ACLi Males*** | | | | |
| **Q:H** | 47-91% A | 2.801 | 0.002 | Lateral Q:H |

*Note.* Time-normalized medial-lateral ratio for the three phases of drop-vertical jump. Only significant preparatory (P), deceleration (D), and acceleration (A) locations are present in table. Muscular Dominance indicates which aspect of the ratio presented with greater musculature involvement

### *3.3. Medial-to-Lateral Ratio*

Females with an ACL injury indicated greater lateral Q:H (p = 0.011) during 76-97% of the acceleration phase (Figure 3.3C; Table 3.3). Whereas uninjured females indicated significant medial-to-lateral asymmetries during the preparatory and deceleration phase (p=0.021, <0.001), indicating significantly greater lateral Q:H values than medial (Figure 3.3A; Table 3.3). Similar trends were shown in the Q:G medial-to-lateral ratio for the uninjured females, revealing greater lateral Q:G values in the acceleration phase (Figure 3.3B; Table 3.3), with no significant differences in females with an ACL injury. The ratio of medial-to-lateral Q:H in males revealed significant asymmetries in the uninjured group during 34-100% of the acceleration phase (p<0.001) and in 47-91% of the acceleration phase in those with an ACL injury, favouring the lateral Q:H as well (Figure 3.4A&C; Table 3.3). No significant differences in Q:G asymmetries were found in the male groups.

### *3.4. Frontal Plane Knee Excursion*

Group means for frontal plane knee excursion indicated significant differences in the preparatory (p=0.011) and acceleration phases (p=0.031) but not in the deceleration phase (p=0.263) between female groups. Males indicated no significant differences in frontal knee excursion values in any of the phases (Table 3.4; Figure 3.5).

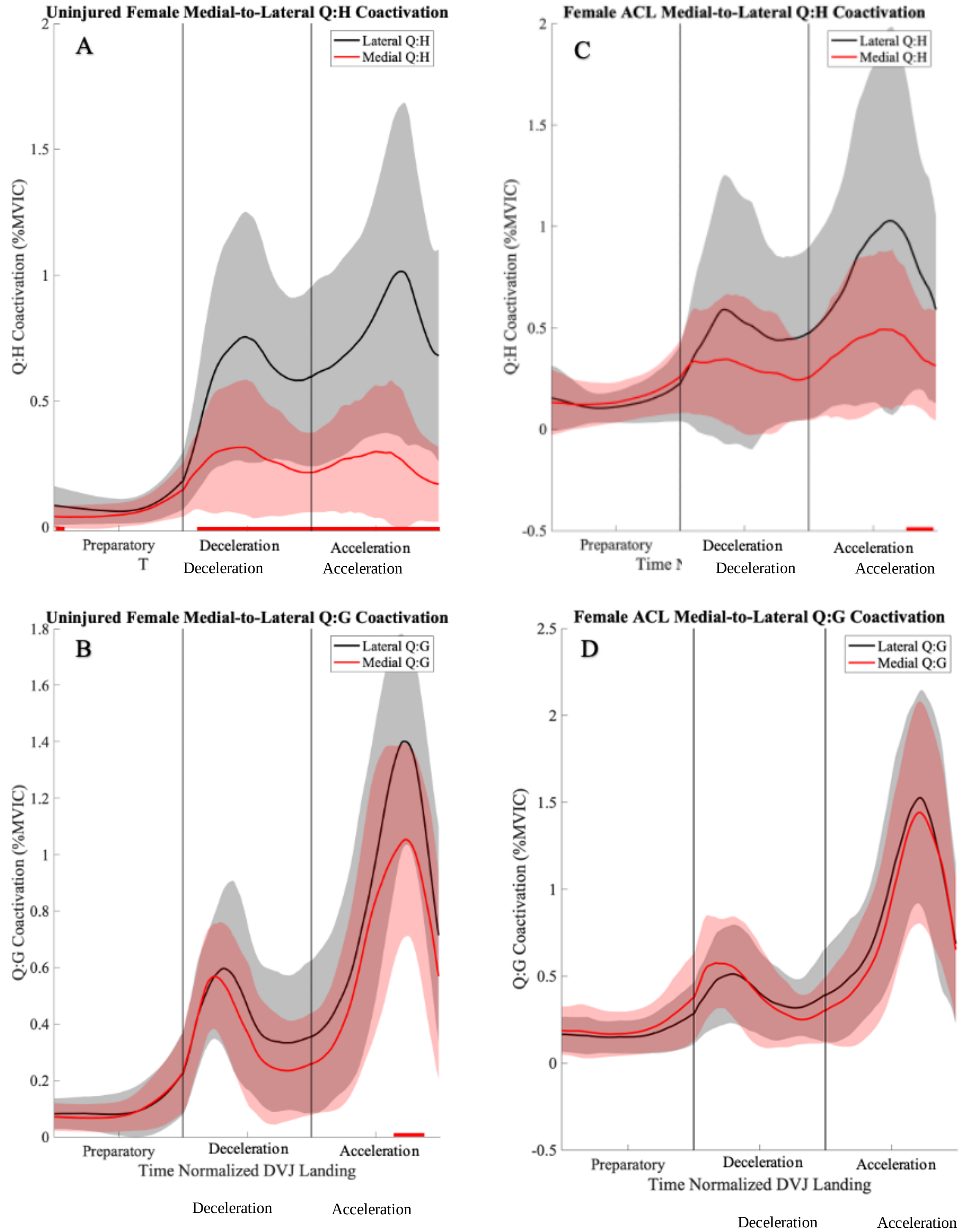

*Figure 3.3.* Time-normalized EMG medial-to-lateral Q:H (A, C) and Q:G (B, D) coactivation waveforms during the drop-vertical jump task for uninjured (A, B) and ACL injured (C, D) females. Red horizontal bar on x-axis indicates statistical significance between lateral (black) and medial (red) CI.

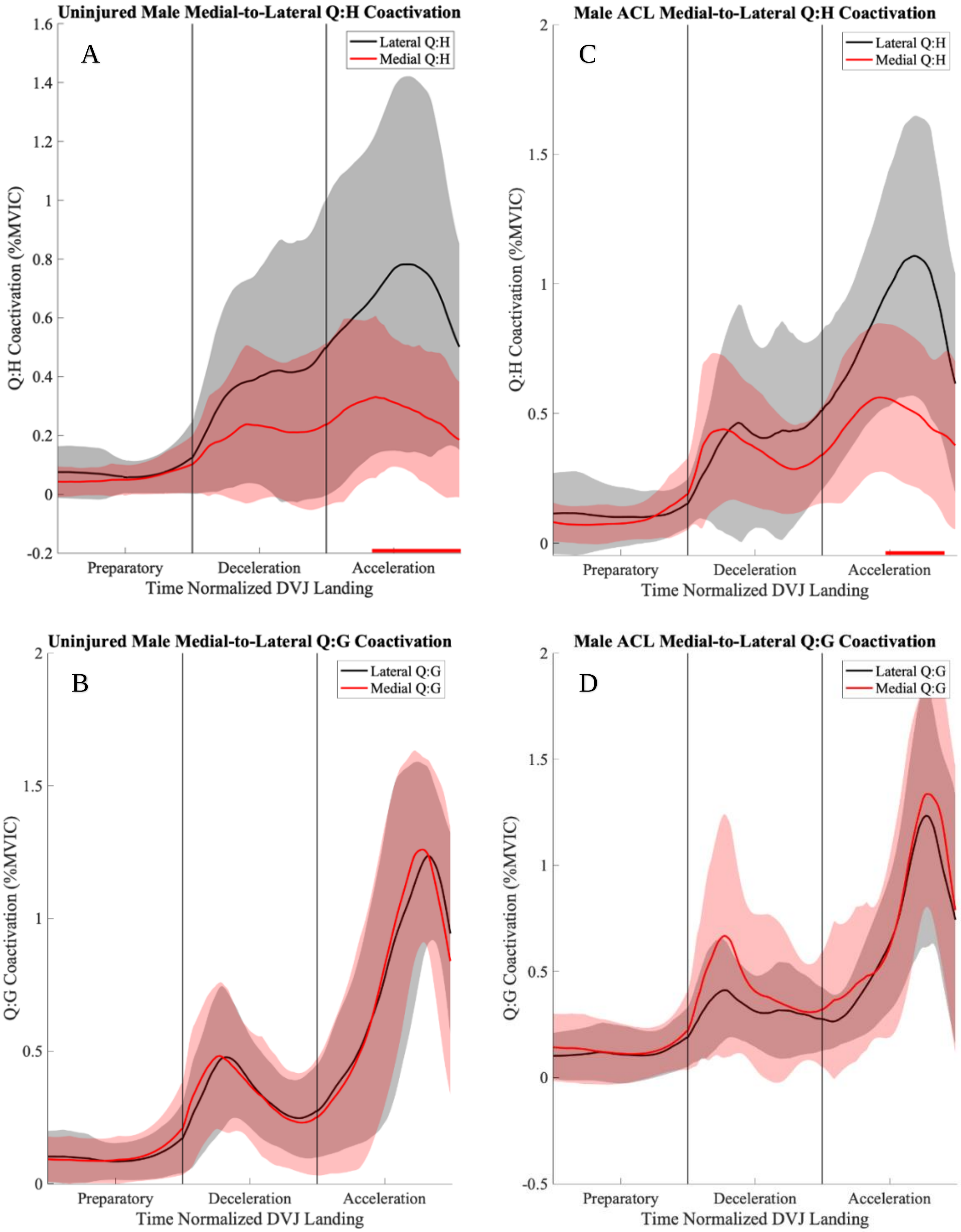

*Figure 3.4.* Time-normalized EMG medial-to-lateral Q:H (A, C) and Q:G (B, D) coactivation waveforms during the drop-vertical jump task for uninjured (A, B) and ACL injured (C, D) males. Red horizontal bar on x-axis indicates statistical significance between lateral (black) and medial (red) CI.

**Table 3.4**

Mean and standard deviations of coactivation indices and knee excursion in the sagittal and frontal plane for uninjured and ACL injured males and females

| **Variable** | **Females** *Mean±SD* | | | **Males** *Mean±SD* | | |
|---|---|---|---|---|---|---|
| | **Uninjured** | **ACL Injured** | ***p*-value** | **Uninjured** | **ACL Injured** | ***p*-value** |
| **Preparatory Phase** | | | | | | |
| Frontal Plane KEXC (cm) | 1.6 ± 0.6 | 1.2 ± 0.5 | 0.011* | 1.5 ± 0.7 | 1.3 ±0.7 | 0.848 |
| **Deceleration Phase** | | | | | | |
| Frontal Plane KEXC (cm) | 4.8 ± 1.3 | 4.5 ± 1.3 | 0.263 | 4.7 ± 1.3 | 5.2 ± 2.3 | 0.539 |
| **Acceleration Phase** | | | | | | |
| Frontal Plane KEXC (cm) | 5.8 ± 1.9 | 4.9 ± 1.4 | 0.031* | 6.0 ± 2.0 | 5.5 ± 2.1 | 0.914 |

*Note*. Time-normalized EMG for the three phases of drop-vertical jump. Coactivations shown as group means.

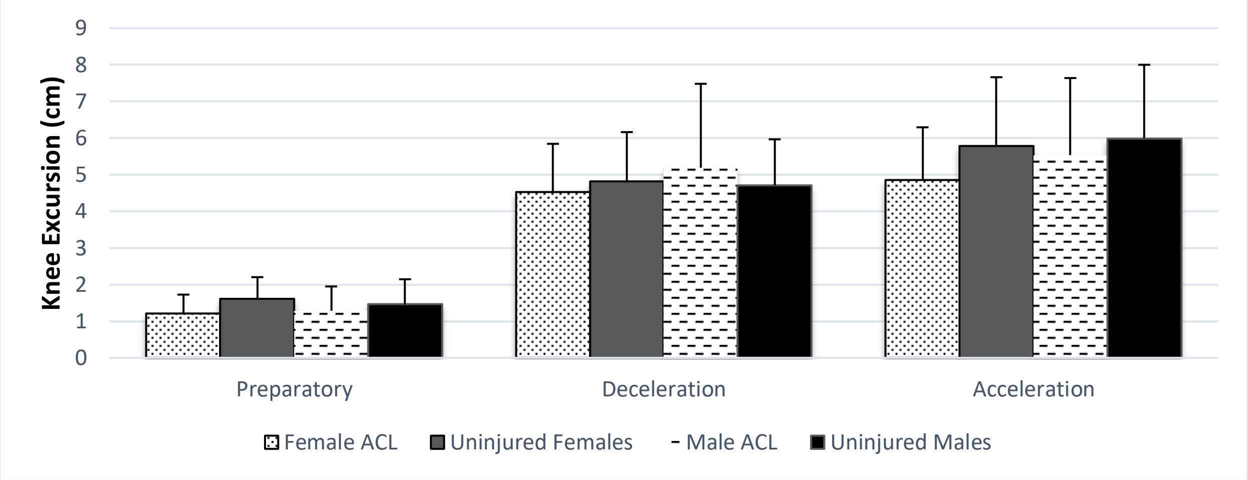

*Figure 3.5*. Integrated frontal plane knee excursion total distance travelled throughout the three phases of the drop-vertical jump for males and females with and without an ACL injury.

## *4. Discussion*

The purpose of this study was to evaluate how an ACL injury impacts the knee stabilization strategies and knee joint stability of both male and female athletes during a DVJ. Knee stabilization strategies were identified as the coactivations in the medial and lateral Q:H and Q:G musculature. Low CI values indicated lower total activation of both antagonist and agonist muscles, or an asymmetrical activation pattern with one group presenting higher or lower activations comparatively. Statistical non-parametric mapping was used to analyze the CI throughout the entire three phases of the waveform (preparatory: 1-100%, deceleration: 101-200%, acceleration: 201-300%). The results of this study support our original hypotheses that females elicit greater medial-to-lateral imbalances and that those with an ACL injury will produce greater CIs. However, the hypothesis of females with an ACL injury producing greater imbalances than uninjured controls was rejected, as the uninjured female controls presented with greater imbalances in the medial-to-lateral ratio.

Specifically, we found that *1)* uninjured female controls presented with greater medial-to-lateral imbalances than those with an ACL injury and relied heavily on the lateral coactivations, *2)* males and females with an ACL injury presented with higher CI than the uninjured controls, *3)* the preparatory phase elicited greater values of statistical significance between females with and without an ACL injury, *4)* gastrocnemius involvement was significantly different between female groups, which was not present in male comparisons, and lastly *5)* frontal-plane knee excursions were significantly different in female groups during the preparatory and acceleration phases and not in males, which indicates reduced frontal plane motion.

### *4.1. Interpretation of Coactivation Index*

Overall, males and females with an ACL injury indicated greater CI than the uninjured controls. In general, both female groups represented a coactivation pattern that was quadriceps and gastrocnemii dominant with less hamstring activation. However uninjured females had higher quadriceps activation than females with an ACL injury, thus contributing to the asymmetries and lower CI values. Males demonstrated differing strategies of coactivation by using higher levels of hamstring activation compared to quadriceps activation.

This suggests that those with an ACL injury require a more generalized coactivation strategy in order to stabilize the knee joint and increase joint compression. This type of compensatory mechanism has been found in previous research, highlighting increased hamstring and quadriceps activity to resist external loads and increase joint compression to compensate for a lack of a passive restraint or lower work-producing capabilities (da Fonseca et al., 2006; Swanik, Lephart, Giraldo, DeMont, & Fu, 1999; Wojtys & Huston, 1994). Others have found similar results in adult ACL-deficient populations indicating that females utilize a more general (symmetrical) coactivation strategy while males utilize more adaptable load-specific coactivations (Chmielewski, Hurd, & Snyder-Mackler, 2005; Del Bel et al., 2018). These differing functional roles of the knee joint muscles can improve joint compression, however, prolonged general coactivation can alter knee joint loads and contribute to the onset and progression of knee osteoarthritis (Griffin & Guilak, 2005; Hodges et al., 2016).

### *4.2. Preparatory Phase Coactivation Differences*

Females with and without ACL injury exhibited the greatest amount of stabilization strategy differences in all four CIs in the preparatory phase of the DVJ, whereas males exhibited no statistical difference between groups. Typically, a non-contact ACL injury occurs within approximately the first 50ms of initial ground contact (Krosshaug et al., 2007). The ability of the body to respond to an external stimulus within this time frame is unlikely since the latency of muscular response can be 60-100ms after the stimulus due to electromechanical delay (Burke et al., 1991; Lephart et al., 2002). Past studies have indicated that preparatory muscle activation has the ability to influence reactive muscle activation strategies. Swanik and colleagues (1999) indicated that muscle pre-activity increases the sensitivity of muscle spindles, which allows unanticipated joint perturbations to be detected more quickly (Swanik et al., 1999). Other research has identified that increased medial coactivation such as, VM (Palmieri-Smith, Wojtys, et al., 2007) with ST and MG (Zhang & Wang, 2001), in the preparatory phase can reduce peak knee abduction angles during deceleration periods, while an increase in lateral coactivations, specifically in VL and BF, can be related to greater instances of knee abduction angles during the deceleration period of a jump landing (Palmieri-Smith, Wojtys, et al., 2007; Zhang & Wang, 2001). This indicates that appropriate preparatory activation strategies can serve as a protective mechanism against known ACL biomechanical risks during periods of deceleration, as further indicated in the work done by Romanchuk et al. (2020) which revealed that failing a jump landing is initiated in the flight phase (Romanchuk, Smale, et al., 2020).

Uninjured female controls indicated a different strategy in preparatory activation as they showed significantly higher lateral Q:H coactivation levels compared to medial Q:H, with similar trends showing in overall Q:G coactivations. This, in part, can be due to the performance goal of movement efficiency, where other studies have indicated lower coactivation levels during the preparatory phase (prior to heel strike) of a jump landing to avoid increased work needed to compress the knee joint and limit degrees of freedom (da Fonseca et al., 2006; Hamstra-Wright et al., 2006; Sigward & Powers, 2006). Females with an ACL injury, however, indicated higher medial CI involvement than lateral.

### *4.3. Deceleration Phase Coactivation Differences*

In the deceleration phase of the DVJ, females with an ACL injury displayed significantly higher medial Q:G coactivation levels compared to the uninjured female controls. Such differences were present during the initial stages of the deceleration phase when participants are making initial ground contact, and thus, might require a greater integration of support moments such as plantarflexion of the gastrocnemii during landing (Winter, 1980). Previous research assessing sex specific landing biomechanics and energetics during an unanticipated DVJ in adolescent athletes found that females utilized their ankle to absorb a large portion of the landing forces whereas males utilized their hips and reached smaller peak knee joint power (Romanchuk, Del Bel, & Benoit, 2020).

Males with an ACL injury produced higher medial Q:H coactivation during the deceleration phase, however not significantly, possibly due to the increased variability and smaller samples size of the CI . Throughout the deceleration phase, the quadriceps act agonistically, while the hamstrings act antagonistically. High agonist activity in conjunction with low levels of antagonist activity can reduce knee joint stability by causing anterior displacement of the tibia (Colby et al., 2000; Hewett et al., 2006; Keith L. Markolf et al., 1995). However, such implications of anterior tibial translation were only tested in vitro (Keith L. Markolf et al., 1995). Greater instances of generalized coactivation of the medial-lateral and anterior-posterior has been shown to decrease frontal-plane motion (Keith L. Markolf et al., 1995) and as such, might be the preferred dynamic knee stabilization strategy. However, studies have indicated that those who are highly skilled and active show decreased and asymmetrical anterior-posterior and medial-lateral coactivation levels while still maintaining neuromuscular control (da Fonseca et al., 2006; Hamstra-Wright et al., 2006; Sigward & Powers, 2006).

In high-risk movements that require maximum performance, this inhibition of the antagonist muscle might be considered an effective adaptation for performance output, as indicated by Ford and colleagues (2008) (Ford et al., 2008). Such decreases in antagonist coactivation involvement have been shown in situations of high-skilled performers (Basmajian, 1977; Frost et al., 2002; Sigward & Powers, 2006). This indicates that in situations where movement experience is high, inappropriate coactivation patterns that limit the degrees of freedom of a movement but elicit greater joint compression, may not be necessary and perhaps, could be detrimental to performance outcomes (Bernstein, 1967; Davids, Lees, & Burwitz, 2000; Ford et al., 2008). From a mechanical standpoint, if antagonist muscle forces are increased, more work is required to generate force which can decrease the efficiency of the movement (Winter, 2009). Therefore, if we are to ignore the requirements for joint stability by decreasing the antagonist contraction (which results in lower coactivation) this will translate into increased power output during the acceleration phase (Ford et al., 2008). This could also help explain the increased knee excursion values in the frontal plane that were present in the uninjured females compared to females with an ACL injury in this study. Previous research found similar results in uninjured adult participants revealing greater knee excursion values during a hop task compared to those with an ACL injury (Smale, Alkjaer, et al., 2019).

A study done by Shultz et al. (2009) revealed that during periods of decelerating from a landing, greater peak anterior shear forces were experienced with greater knee flexion excursion (Shultz, Nguyen, Leonard, & Schmitz, 2009). This suggests that in an attempt to decrease anterior shear forces, those with an ACL injury coactivate to a greater extent to decrease knee excursion values. Such strategy, of increasing general coactivation, was evident during specific periods of significance during the DVJ in both male and female ACL injured groups, however, more so in females (Figure 3.1 & 3.2). Ithurburn and colleagues (2015) noted that participants with lower quadriceps femoris strength had decreased excursion values during a single-leg drop-landing task (Ithurburn, Paterno, Ford, Hewett, & Schmitt, 2015). Based on the identified asymmetries in knee flexion excursion and knee extension moments, they speculated that this decreased knee excursion was due to a compensatory mechanism of the participant relying more heavily on their uninjured limb (Ithurburn et al., 2015).

### *4.3. Acceleration Phase Coactivation Differences*

In the acceleration phase, females displayed significant differences in medial Q:H (80-88%) and in medial Q:G (66-76%). Significant differences between males with and without an ACL injury appeared in 44-75% of acceleration phase of the movement in the medial Q:H. Interestingly, isolating the medial Q:H, males with an ACL injury demonstrated higher VM and ST activations compared to the uninjured controls. If combined, the flexors and extensors of males with an ACL injury demonstrated significantly greater hamstrings involvement, while uninjured male controls had significantly greater quadriceps activations.

Both males and females demonstrated greater coactivation levels in those with an ACL injury. However, females with an ACL injury produced greater contributions of the MG during the push-off phase compared to uninjured female controls. A study done by Flaxman et al. (2012) looked at specific muscle classification based on its role in dictating knee joint stabilization strategies (Flaxman et al., 2012). It was determined that during a weight-bearing target matching protocol, the MG dictated specific activation patterns about an anterior-medial loading direction (Flaxman et al., 2012). The gastrocnemius muscles have also been identified as having the potential role of reducing anterior shear forces placed on the ACL by limiting anterior tibial translation (Lindström, Felländer-Tsai, Wredmark, & Henriksson, 2010). Klyne et al. (2012) in his research analyzing possible gastrocnemius compensatory mechanisms for knee joint stability in ACL injured participants suggested that increasing control of the gastrocnemius during high-risk movements could contribute to increasing knee joint stability without compromising the efficiency of the movement by avoiding prolonged periods of joint compression (Klyne et al., 2012). However, considering the results of Flaxman's et al. (2012) study that distinguished the LG as a general joint stabilizer and the MG as a specific stabilizer such inferences on their role in knee stabilization requires a more thorough examination of the gastrocnemii and soleus muscles in relation to knee joint stability (Flaxman et al., 2012).

### ***4.5. Medial-to-Lateral Coactivation Ratio***

Uninjured female controls presented with higher levels of asymmetrical coactivations, showing significantly more lateral than medial musculature activations compared to females with an ACL injury (Figures 3.4 and 3.5). This asymmetrical stabilization strategy, also referred to as a more generalized coactivation pattern, could lead to decreased dynamic stability, which was shown in our results as uninjured females had significantly more frontal plane motion compared to females with an ACL injury. Others have found similar results in stabilization strategies (less medial activation compared to lateral) in adult populations during a hop task, however, using peak external knee abduction moments (Palmieri-Smith et al., 2009). Previous research has identified that females preferentially activate their lateral quadriceps and hamstrings while displaying less medial activation during periods of deceleration during a squat and forward hop task (Myer et al., 2005; Palmieri-Smith, Wojtys, et al., 2007). Others have also indicated that greater VL and BF activation in combination with reduced preparatory VM activation are associated with larger knee abduction angles (Hewett, Myer, Ford, Robert S. Heidt, et al., 2005). These results might help explain the larger frontal-plane motion seen in the uninjured females who produced high lateral coactivations compared to medial.

### *4.6. Limitations*

Ford et al (2011) found an increase in knee abduction angles after periods of rapid adolescent growth, predominantly in females (Ford, Shapiro, Robert., Myer, Gregory, Van Den Bogert, Antonie, Hewett, 2011). We measured Tanner stages and, although not significantly different between groups, the change in puberty level may have influenced our results. That said, in our study the control group was slightly less mature, yet the knee abduction angles of the ACL injured group were reduced. Furthermore, since within each group we had a similar puberty level distribution, any influence from puberty level would have a similar within group effect. Nevertheless, future studies could separate adolescents into developmental stages to better understand how ACL injury and rapid maturation might impact the knee stabilization strategies. Lastly, this study only looked at the affected or dominant limb. Using this same control group, we found differences only in sagittal plane knee excursion in dominant vs non-dominant limb in knee joint kinematics during the DVJ (Geck et al., 2021, in preparation). This justified using the control groups dominant limb for comparative purposes with the ACL group. Nevertheless, previous research has found that participants with an ACL injury tend to favour their uninjured limb if they presented with lower quadriceps femoris strength and decreased knee excursion symmetry (Ithurburn et al., 2015), relying on their uninjured limb by increasing peak vertical ground-reaction and loading rate. However, when the uninjured limb was removed (single leg landing), the lower quadriceps femoris strength group demonstrated greater asymmetry in peak trunk flexion (Ithurburn et al., 2015; Oberländer, Brüggemann, Höher, & Karamanidis, 2013). Such research would suggest a need to look at both limbs as well as trunk involvement in order to understand compensatory mechanisms of those with an ACL injury.

## *5. Conclusion*

Our results indicate that females with an ACL injury produce coactivation strategies that differ from the uninjured female group which resulted in differing frontal-plane motion. It was found that females with an ACL injury increase dynamic knee joint stability through greater medial-to-lateral symmetry, greater generalised coactivation levels thus increasing joint compression, and greater preparatory medial quadriceps and hamstring activation. Uninjured females and both male groups used knee stabilization strategies that did not restrict their degrees of freedom through high generalised coactivations. Males, however, failed to show a difference between groups in dynamic knee joint stability, suggesting that those with an ACL injury compensated in a way to perform the DVJ efficiently and similarly to the uninjured group, while maintaining movement efficiency and dynamic knee joint stability.

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# Chapter 8. General Discussion

The aim of this Master's Thesis was to understand how an ACL injury might impact knee stabilization strategies while performing a highly-demanding task that can elicit biomechanical and neuromuscular outcomes associated with an ACL injury in adolescent males and females. To address this aim, two specific research questions were answered. The first (*Q1*) compared the lunge and DVJ, which are two functional tasks commonly used to assess RTA readiness, to determine which task is more demanding using uninjured male and female athletes. This was achieved by using a combination of discrete kinematic, kinetic and EMG data across the deceleration phase of each task. The task that was more demanding, thus more likely to produce similar biomechanical and neuromuscular demands that are found with ACL injuries, were then used to answer the second question (*Q2*). Question two was designed to examine how an ACL injury might impact the knee stabilization strategies of adolescent male and female athletes. To accomplish this, knee stabilization strategies and dynamic knee joint stability was assessed through muscular coactivations and frontal-plane knee excursion of adolescent male and female athletes with and without an ACL injury.

## 8.1 Effect of Task

The consideration of limb dominance during the lunge and DVJ was first looked at prior to analyzing for within task and between sex differences. Unlike other studies (Kemp et al., 2020; Pollard 2010) results based on the kinetic and kinematic variables failed to identify an effect of limb dominance during the lunge and DVJ, therefore, only the dominant / injured limb was used to answer *Q1* and *Q2*. We hypothesized that the lunge would produce greater PKF and sagittal plane iKEXC values and the DVJ would elicit greater iEMG, frontal plane iKEXC, and iJP values.

The lunge and DVJ are both multi-joint functional tasks that require different neuromuscular activations in attempts to maintain dynamic knee joint stability. Previous research has identified the lunge task's ability to differentiate copers (return to same level of activity post ACL-reconstruction) from non-copers (unable to return to activity post ACL-reconstruction) based on their functional performance (Alkjaer et al. 2002, Alkjaer et al. 2009; Alkjaer et al. 2020). Based on this information and the lunge being a bilateral movement commonly performed during sport, its use as an assessment tool seems rather appropriate (Alkjaer et al., 2002). The DVJ is categorized as a 'high-risk' maneuver that is associated with an ACL injury. Previous research has established the importance of analyzing the DVJ as it elicits greater external work production through increased biomechanical and neuromuscular involvement in order to maintain dynamic knee joint stability (Nagano et al., 2007). Therefore, understanding the performance outcomes of the lunge and DVJ and how they differ from each other will help characterize the use of each task for RTA assessment. It is presumed that as the degree of loading demands increases so will the level of difficulty due to the increase in muscle recruitment, joint loads, and required joint stability (da Fonesca et al., 2006; Hakkinen and Komi, 1983). Previous research has identified that individuals who perform the deceleration phase of a movement with greater joint loads, high knee abduction and extension angles, and greater lateral musculature involvement, especially at initial contact, are at an increased risk of sustaining an ACL injury (Hewett, Myer, Ford, Heidt et al., 2005; Mizner, 2008; Markolf 1995; Zhang 2001; Sell 2006).

Our findings revealed greater differences between the DVJ and lunge in the iEMG and iJP variables with high sensitivity to sex differences. In most variables, female athletes required greater iEMG values in both the lunge and DVJ compared to the male athletes. By comparison, male athletes typically produced greater kinematic and kinetic values in both the lunge and DVJ.

Large differences were found in the lunge task in PKF, KEXC, iVL, and iVM compared to the DVJ. This decrease in kinematic variables in the DVJ could be caused by a reduction in movement time (Alkjaer et al., 2002) and an increased need for joint compression via muscular contraction (Rozzi et al., 1999; Sell et al., 2006). The iBF variable presented with the greatest between sex differences in both the lunge and DVJ, with female athletes producing significantly greater iEMG values compares to male athletes. Previous research has highlighted the necessity for greater hamstring involvement during the load acceptance (deceleration) phase of a task in order to counteract the external loads placed on the body and maintain dynamic knee joint stability (Baratta et al., 1988; Ambegaonkar et al., 2011). However, increased lateral musculature in comparison to medial musculature has been associated with increased knee abduction angles (Zhang & Wang, 2001), and thus, increased risk for sustaining an ACL injury. Duration of movement time has the ability to increase the demand of a task, however, the biomechanical and neuromuscular loads produced by the DVJ in this study is more closely associated with instances of ACL injury.

### 8.2. Effect of ACL Injury

The second study, using the DVJ identified in *Q1*, assessed the knee stabilization strategies of male and female athletes with and without an ACL injury. Using muscular coactivations split medial-laterally and anterior-posteriorly in combination with frontal-plane knee excursion, this study examined the impact of an ACL injury on dynamic joint stability. It was found that the preparatory phase elicited greater significant differences than any other phase in the female groups, while males produced many of their differences during the acceleration phase of the DVJ. These preparatory phase activation differences in those with an ACL injury may serve as a protective mechanism against known ACL biomechanical risks during periods of deceleration. Previous research has identified that pre-activity of the VM, ST, and MG can reduce peak knee abduction angles, while increased VL, BF, and LG have been related to greater knee abduction angles (Palmieri-Smith et al., 2007; Zhang & Wang, 2001). This increase in medial coactivations were not indicated in the uninjured females but were found in females with an ACL injury. Interestingly, males indicated significant differences in acceleration phase coactivations, highlighting higher VM and ST activations in males with an ACL injury compared to the uninjured controls when isolating the medial Q:H. Similarly, males with an ACL injury demonstrated significantly greater hamstring activations, while uninjured male controls had significantly greater quadriceps activations.

This study’s findings suggest that females with an ACL injury produce coactivation strategies that differ to the uninjured females and that reduce the amount of frontal-plane motion about the knee through greater generalized coactivations. Females with an ACL injury increased dynamic joint stability through greater medial quadriceps and hamstring activation during the preparatory phase of the DVJ. Females without an ACL injury produced coactivations that have been attributed to an increased risk of an ACL injury including greater overall quadriceps levels with lateral musculature dominance, and lower hamstrings coactivation.

### 8.3 Limitations

Participants with an ACL injury were matched based on Tegner Activity Level (Females: p = 0.122; Males: p = 0.761), however, not based on Tanner Stage (Females: p = 0.001; Males: p = 0.005). Previous research has indicated the impact at which maturation level can have on neuromuscular and biomechanical control, revealing significantly noticeable differences in muscular development in females compared to males and increases in knee abduction angles (Ford, Shapiro, Robert., Myer, Gregory, Van Den Bogert, Antonie, Hewett, 2011). Thus, the change in puberty level may have influenced our results. That said, in our study the control group with a

Tanner Stage of 3.2 was slightly less mature, and yet the frontal-plane motion of the ACL injured group, with a Tanner Stage of 3.8, was reduced.

This study did not control for type of training in either the uninjured or ACL injured groups. Previous research has demonstrated the importance of neuromuscular training in order to increase performance levels and reduce risk of injury (Mandelbaum et al., 2005; Noyes & Barber-Westin, 2018). Research has also indicated the importance of strengthening prior to ACL reconstruction, suggesting better outcomes for RTA post-surgery and at a quicker time frame (Failla et al., 2016; Hartigan, Axe, & Snyder-Mackler, 2009; Kyung Kim, Hye Hwang, & HaH ParK, 2015). Additionally, adding performance metrics to measure movement efficiency and effectiveness, such as jump height or rate of force development, may also assist in interpreting compensatory mechanisms of those with an ACL injury or possible differences between male groups that were hidden in this study.

### 8.4 General Conclusion

This thesis demonstrates that the DVJ is more likely to elicit neuromuscular and biomechanical loads that have been associated with an ACL injury compared to the lunge. Integrated EMG and iJP variables revealed the most statistically significant differences in both task and sex comparisons, indicating its overall higher demand. Differences were found in the lunge task, however, research has indicated that duration of movement has a large impact on results (Alkjaer et al., 2002). Since majority of non-contact ACL injuries occur within approximately 50ms from initial contact (Krosshaug et al., 2007; Mattacola, Jacobs, Rund, & Johnson, 2004; Yoon & Hwang, 2000), duration of movement is less likely to increase risk of injury and therefore, is less suitable to evaluate RTA.

Using the DVJ, this thesis demonstrated that uninjured females produce coactivations that contribute to greater frontal-plane motion about the knee compared to females with an ACL injury. Uninjured females, however, presented with greater lateral coactivations than medial, indicating a significant medial-lateral imbalance. Such imbalance is related to greater knee abduction angles (Palmieri-Smith, Wojtys, et al., 2007; Zhang & Wang, 2001), contributing to a decrease generalized dynamic knee joint stability (Hewett et al., 2006; Keith L. Markolf et al., 1995). Females with an ACL injury presented with opposing strategies to the uninjured controls. Such strategies were: increased medial CI during the preparatory phase, overall higher coactivation levels (increased muscular activation and greater symmetry between agonist and antagonist), and increased gastrocnemius coactivation. These strategies reduced frontal-plane motion suggesting an increase in dynamic knee stability during the DVJ. Based on these results, uninjured females use knee stabilization strategies that decrease dynamic knee stability. While females with an ACL injury utilize differing knee stabilization strategies that increase dynamic knee joint stability in order to perform a DVJ. Males demonstrated similar coactivations between uninjured and ACL injured, with differences in medial Q:H coactivations primarily through greater musculature amplitudes. Males, however, failed to show a difference between groups in dynamic knee stability, suggesting that those with an ACL injury compensated in a way to perform the DVJ efficiently and similarly to the uninjured group, while maintaining dynamic knee joint stability.

We are optimistic that the outcomes of this thesis will assist in the continued progression of adolescent RTA guidelines. The observed sex and knee status differences in knee stabilization strategies and dynamic knee stability may be useful in distinguishing the appropriate rehabilitation and specific requirements for a successful RTA. Furthermore, in a clinical setting, results of this thesis may help in understanding what to monitor in landing performance during rehabilitation and prevention efforts.

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# Appendix A

## 9.1 Table 1

*Summary of all tasks performed by participants during each data collection*

**Clinical / Functional Tasks**

The purpose of these tests is to evaluate the relative difference in functional capacity of the patient's limbs. The tests selected have been clinically validated in a rehabilitation setting (Adams et al., 2012), however given that the testing is being performed in a laboratory setting; they may not be a true representation of the functional capacity of the individual.

| Task | | Description |
|---|---|---|
| Max Anterior Hops | Distance | Participants will be instructed to hop as far as they can on one foot facing forward. |
| Max Lateral Hops | Distance | Participants will be instructed to hop as far as they can on one foot to the side (facing perpendicular to the direction of the marked line on the laboratory floor). |
| Timed 6m Hop | Time | Participants will be instructed to hop on one foot as fast as they can to cover a distance of six meters. |
| Cross Hops | Distance | Participants will be instructed to hop on one foot back and forth across a marked line on the floor, while attempting to cover maximum distance during four hops side to side across the line. |
| Triple Hops | Distance | Participants will be instructed to hop on one foot three times in a row for maximum distance. |
| Muscular Endurance | Quadriceps Deficit<br>Hamstrings Deficit | Participants will be on the Biodex Dynamometer and will be instructed to maximally generate knee extension and knee flexion torques sequentially. This will be repeated for a total of 40 repetitions at a set speed of 90 degrees/second to evaluate the muscular endurance of the patient over the 40 repetitions of maximal concentric dynamic contractions on a Biodex Dynamometer. This task will provide an indication of how the patient may perform following repeated exercise as may be the case during practice or game situations. Knee flexion and extension torques will be averaged over the first 5 repetitions (#1) and the last 5 repetitions (#2). The deficit will be determined as a ratio of the (#2) / (#1). A lower deficit score indicates a higher level of fatigue after 40 repetitions. |
| Isometric Strength | Knee Extension<br>Knee Flexion<br>Plantarflexion<br>Hip Abduction | Participants performed maximal isometric contractions with knee held at 60 degrees of knee flexion. |

**Dynamic Tasks**

The purpose of these tests is, similar to the previous set, to evaluate the relative difference in functional capacity of the patient’s limbs during a variety of sport-related movements that are also often used in injury prevention programs (Barengo et al., 2014)

| Task | Description |
|---|---|
| Two-Legged Squats | Participants will be instructed to stand on two force plates that are side-by-side, with one foot on each plate and shoulder-width apart. They will then be instructed to hold their hands on their head while squatting down at a self-selected pace as low as they can comfortably, before returning to the starting position. |
| Counter-Movement Jumps | Participants will be instructed to stand on two force plates that are side-by-side, with one foot on each plate and shoulder-width apart. They will then be instructed to hold their hands on their head while performing a maximum vertical jump |
| Lunges | Participants will be instructed to stand facing a force plate so that when they step forward, their foot of interest is in the center of the force plate while their knee and hip joints are both flexed to 90 degrees. They will be instructed to hold their hands on their head while stepping forward, lunging, and returning to the starting position at a self-selected pace. |
| Side-Cuts | Participants will be instructed to run at an approach velocity that is 75% of their maximum sprint velocity, before performing a 45-degree side-cut. They will step and plant the leg of interest on the force plate and accelerate towards a set of cones that are marked at an angle of 45 degrees from the force plate. |
| Drop-Vertical Jump | Participants will begin on a platform (adjusted to the height of their tibia) and will drop down onto two force plates, with each foot landing on a separate plate. Immediately after landing, they will be instructed to perform a maximum vertical jump. |

## 9.2 Figure 1

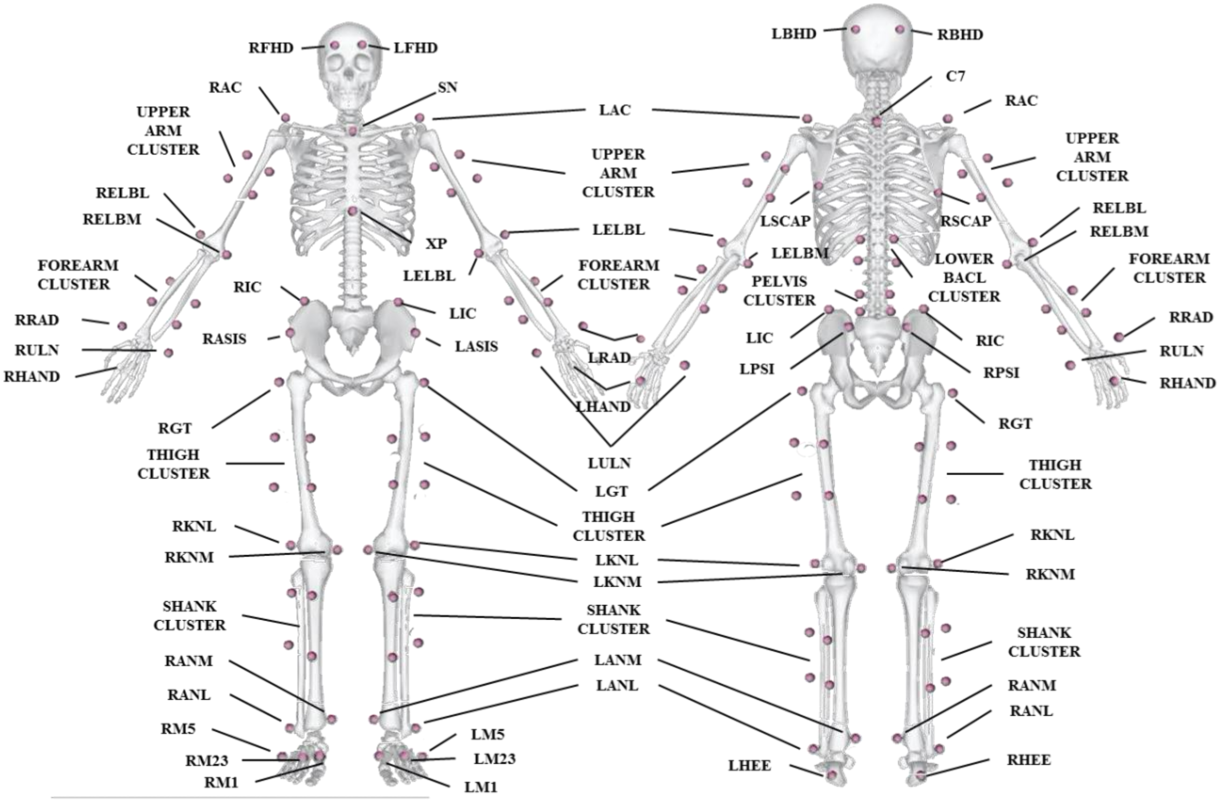

Figure 1. Clinical Biomechanics Research Unit (CBRU) cluster marker set, adapted from the Human Movement Biomechanics Laboratory cluster marker set. Plug-in-Gait marker set acted as the basis with the additions of medial knee, ankle and elbow markers (LMKN, RMKN, LMAN, RMAN, LELBM, RELBM), three thigh, 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 CLSUTER) and two metatarsal markers (RMT1, RMT5, LMT1, LMT5) (figure adapted from Mantovani and Lamontagne, 2016)

### 9.3 Table 2

*Transformed group means (SD) for uninjured males and females using kinematic, kinetics and EMG variables during the lunge and DVJ.*

| | **TASK** | | | | **SEX** | | | |
|---|---|---|---|---|---|---|---|---|
| | **Data** | | **Transformed Data** | | **Data** | | **Transformed Data** | |
| ***Variables*** | **Effect Size** | ***p*-value** | **Effect Size** | ***p*-value** | **Effect Size** | ***p*-value** | **Effect Size** | ***p*-value** |
| ***Kinematics*** | | | | | | | | |
| **PKF Mean** (°) | 0.422 | 0.001 | 0.536 | <0.001 | - | 0.227 | - | 0.181 |
| **iKEXC Sag** (°) | 3.174 | <0.001 | - | - | - | 0.076 | - | - |
| **iKEXC** | 0.639 | <0.001 | 1.811 | <0.001 | - | 0.680 | - | 0.389 |
| **iKJP** (Watt/kg) | 1.374 | <0.001 | 1.857 | <0.001 | 0.371 | 0.003 | 0.245 | 0.048 |
| ***Muscles*** **(%MVIC*s)** | | | | | | | | |
| **RF iEMG** | - | 0.952 | 0.843 | <0.001 | - | 0.344 | - | 0.164 |
| **VL iEMG** | 0.594 | <0.001 | 0.489 | <0.001 | - | 0.102 | 0.250 | 0.048 |
| **VM iEMG** | 0.403 | 0.002 | 0.790 | <0.001 | - | 0.529 | 0.268 | 0.038 |
| **BF iEMG** | - | 0.386 | 1.005 | <0.001 | 0.343 | 0.010 | 0.318 | 0.017 |
| **ST iEMG** | - | 0.589 | 0.448 | <0.001 | - | 0.444 | - | 0.345 |
| **LG iEMG** | 0.656 | 0.005 | 1.237 | <0.001 | - | 0.507 | - | 0.102 |
| **MG iEMG** | 1.028 | <0.001 | 1.439 | <0.001 | - | 0.923 | - | 0.905 |
| **GMed iEMG** | 0.257 | 0.039 | 0.541 | <0.001 | - | 0.115 | - | 0.290 |

*Note. Integrated electromyography (iEMG) for rectus femoris (RF), vastus lateralis (VL), vastus medialis (VM), biceps femoris (BF), semitendinosus (ST), lateral gastrocnemius (LG), medial gastrocnemius (MG), gluteus medius (GMed), peak knee flexion (PKF) mean, integrated knee excursion (iKEXC) in the sagittal and frontal planes, and integrated knee joint power (iKJP) are presented in this table for the lunge and drop-vertical jump (DVJ) tasks.* Cohen's *d* effect size presented for significant main effects of task (T) and sex (S). p-values corrected using the Bonferroni test and indicated by * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

## 9.4 Borg Rating of Perceived Exertion/Effort

Which number best describes your level of exertion/effort for this task?

| | |
|---|---|
| **6 – No exertion** | *20% of maximum effort* |
| **7 – Extremely light** | *30% of maximum effort* |
| **8 –** | *40% of maximum effort* |
| **9 – Very light** | *50% of maximum effort* |
| **10 –** | *55% of maximum effort* |
| **11 – Light** | *60% of maximum effort* |
| **12 –** | *65% of maximum effort* |
| **13 – Somewhat hard** | *70% of maximum effort* |
| **14 –** | *75% of maximum effort* |
| **15 – Hard** | *80% of maximum effort* |
| **16 –** | *85% of maximum effort* |
| **17 – Very hard** | *90% of maximum effort* |
| **18 –** | *95% of maximum effort* |
| **19 –Extremely hard** | *100% of maximum effort* |
| **20 – Maximal effort** | *Complete exhaustion* |

## Level of Difficulty

Which response best describes the level of difficulty performing this task?

**1 – Very easy**
**2 – Easy**
**3 – Moderate**
**4 – Difficult**
**5 – Very Difficult**