EVALUATION OF LOWER EXTREMITY ENERGY ABSORPTION STRATEGIES IN ADOLESCENT MALES AND FEMALES WITH AND WITHOUT AN ACL INJURY

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List of Acronyms

ACL	Anterior Cruciate Ligament
ACLi	Anterior Cruciate Ligament injury
ACL-R	Anterior Cruciate Ligament Reconstruction
ANOVA	Analysis of Variance
BMI	Body Mass Index
CBRU	Clinical Biomechanics Research Unit
CHEO	Children’s Hospital of Eastern Ontario
CI	Confidence Interval
DVJ	Drop Vertical Jump
FDR	False Discovery Rate
GRF	Ground Reaction Force
HSS Pedi-FABS	Hospital for Special Surgery Pediatric Functional Activity Brief Scale
IC	Initial Contact
IR	Internal Rotation
MVIC	Maximum Voluntary Isometric Contraction
Pedi-IKDC	Pediatric International Knee Documentation Committee
ROM	Range of Motion
SnPM	Statistical Non-Parametric Mapping
TO	Take-Off

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General Abstract

Introduction: Anterior cruciate ligament (ACL) injuries are the most common ligamentous injury in the adolescent knee, resulting in long-term health consequences including early onset knee osteoarthritis and a high predominance of re-injury. The current ACL rehabilitation measures need improvement, in particular for adolescents. Information surrounding energy absorption strategies during demanding tasks may provide important insight into functional capacity and movement quality and could be a variable that is considered in ACL rehabilitation programs. The purpose of this thesis was therefore to evaluate energy absorption strategies in adolescent males and females with and without ACL injuries. Specifically, to first identify sex and injury status differences in lower extremity kinematics and kinetics in adolescent males and females with and without an ACL injury, and then second, determine if there is a generalizable relationship between strength and energy absorption strategies within these populations during drop-vertical jumps.

Methods: Fifty-two ACL injured (17 males) and 68 control adolescent (34 males) males and females between the ages of 10 and 18 performed five trials of a lunge and drop vertical jump (DVJ) task. Ankle plantarflexion, and knee extension and flexion maximum voluntary isometric contractions (MVIC) were collected, along with 3D kinematics and kinetics including joint angles, joint moments, and energy absorption at the hip, knee, and ankle joint. Two-way analyses of variance (ANOVA), statistical non-parametric mapping (SnPM), and multiple linear regressions were used to determine statistically significant differences and relationships in joint kinematics, kinetics, and MVIC's between the male and female ACL injured and control individuals.

Results: Males displayed greater knee extension torque compared to females, while controls displayed greater knee extension and ankle plantarflexion torque compared to ACL injured. There were no energy absorption differences found during the DVJ, however, during the lunge male controls display greater energy absorption compared to females. Furthermore, small effect sizes were found in the hip, knee, and ankle joint energy absorption for knee strength (knee extension or knee flexion), sex, and injury status. However, sex, injury status, and knee strength did not significantly add to the prediction of energy absorption.

Conclusion: These findings indicate that isometric strength might be an important variable to be considered in ACL injury rehabilitation and injury prevention programs with injured individuals displaying weaker knee extension and ankle plantarflexion torques. However, energy absorption may not be as important of a variable to consider as there were limited statistically significant differences between injury status and sex at the hip, knee, and ankle joints. Additionally, there does not appear to be a generalizable relationship between hip, knee, and ankle energy absorption and knee flexion and extension isometric strength in male and female control and ACL injured individuals. Injured individuals absorb similar energy levels at each joint compared to controls, with isometric strength showing a weak relationship with energy absorption. Therefore, it is possible that there is not a specific energy absorption or muscular strength strategy that can be used to improve adolescent ACL rehabilitation measures.

CHAPTER 1: INTRODUCTION

Over the last two decades, adolescent and female participation in sport has been steadily increasing, concurrently leading to an increase in anterior cruciate ligament (ACL) injuries (Agel et al., 2016; Report Card Development Team, 2018). Specifically, the adolescent population (ages 6-18) has seen a 2.3% increase in injury rate (Beck et al., 2017); furthermore, adolescent females are three to nine times more likely to tear their ACL compared to male counterparts (Agel et al., 2016; Griffin et al., 2000; Hewett et al., 1999; Ireland, 2002). In the United States, 50-70% of ACL injuries require reconstruction, with similar rates expected in Canada; however, unfortunately, even after reconstruction, 23-25% of adolescents who return to sport will experience a re-injury (Dodwell et al., 2014; Failla et al., 2015; Wiggins et al., 2016). Despite the current increase in injury rate, there is limited biomechanics research in the adolescent population, as well as a lack of sex- and age-specific guidelines for ACL rehabilitation measures within this adolescent population.

Energetic analysis can be used to quantify the energy responsible for producing certain movement strategies (Norcross et al., 2010). The ACL injury mechanism can be broken down into kinematic (joint angles) and kinetic (joint moments) components (Haddas et al., 2015; C. Montgomery et al., 2018; Waldén et al., 2015) and energy absorption is a function and combination of these components (Decker et al., 2003; Romanchuk, del Bel, et al., 2020). Seeing as new methodologies ought to be developed to improve the current ACL rehabilitation measures, and since information surrounding energy absorption strategies provides important insight into functional capacity and movement quality, it could be an important variable to consider in ACL rehabilitation programs. Furthermore, if we can understand how energy absorption is altered following an ACL injury in adolescent populations, we can begin to modify and train the variables appropriately to decrease the probability of injury and/or re-injury (Pollard et al., 2017). The primary objective of this thesis was therefore to evaluate energy absorption strategies in males and females with and without ACL injuries.

CHAPTER 2: LITERATURE REVIEW

2.1 ACL Injury Incidence

The ACL is one of the four major ligaments in the knee, located in the intercondylar fossa of the knee joint (Scheffler, 2012). The ACL originates anteriorly on the tibia and extends posteriorly and superiorly to attach onto the posterior aspect of the femur (Markatos et al., 2013). The ACL primarily resists anterior translation of the tibia in relation to the femur, and when the knee nears full extension, it secondarily resists internal rotation (Butler, 1980; Duthon et al., 2006). These types of movements, full extension and internal rotation of the knee, have the mechanical potential to apply a high tensile force on the ligament, increasing the risk of excessive loading, potentially leading to an ACL tear (Yu & Garrett, 2007).

The ACL is one of the most commonly injured ligaments in the knee (Sepúlveda et al., 2017), with an estimated 0.17-0.23 ACL injuries per 1000 collegiate soccer and basketball adult athlete exposures (Agel et al., 2016), and adult females are three to nine times more likely to tear their ACL compared to their male counterparts (Agel et al., 2005; Griffin et al., 2000; Hewett et al., 1999; Ireland, 2002). Interestingly, this trend translates to an adolescent population with injury rates two to four times higher in females compared to males in soccer and basketball athletes (Powell & Barber-Foss, 2000a; Renstrom et al., 2008a), with female incidences peaking between 14-18 years compared to males at 19-25 years (Beck et al., 2017; Sanders et al., 2016). This disparity is compounded by the fact that the rate of ACL injuries is increasing by 2.3% per year for individuals aged 6 to 18 (Beck et al., 2017), with females aged 13-17 having the highest ACL injury (ACLi) incidence of any other sex-age strata (M. M. Herzog et al., 2017).

Along with an increase in ACL injuries, there has been a 29-fold increase in ACL reconstructions (ACL-R) for individuals under the age of 20 since 1997-1998 (Nogaro et al., 2020). Unfortunately, 15-23% of ACL-R patients will suffer a re-injury, translating to approximately one in four individuals from the reconstructed population experiencing a re-injury (Wiggins et al., 2016). Speculations behind this increase include a higher percentage of people competing in sport, re-ruptures due to incomplete rehabilitation, and improved injury recognition (Beck et al., 2017; Wiggins et al., 2016). As such, there appears to be a need for better rehabilitation and injury prevention programs in the ACL-injured adolescent population.

2.2 ACL Injury Mechanisms

Understanding the mechanisms of injury is a key component in understanding how to prevent and rehabilitate the injury. There are typically two different classifications of ACLi mechanism: contact and non-contact (Boden et al., 2000) with the majority of ACL injuries being non-contact (72-82%) (Boden et al., 2000; Myklebust et al., 2007). A non-contact injury mechanism generally consists of a landing motion or a sudden deceleration prior to a change-of-direction, most commonly during pivoting, cutting, stopping and landing sporting maneuvers (Boden et al., 2000; Gianotti et al., 2009; Takahashi et al., 2019). These movements result in a combination of forces that puts the ACL at risk of rupturing. Kinematics in the sagittal plane that have been associated with a higher risk for ACLi include lower hip and knee flexion, and higher ankle dorsiflexion angles; all of which are more commonly seen in females compared to males and possibly contributing to this injuries sex bias (Alentorn-Geli et al., 2009; Landry et al., 2007b, 2007a; C. Montgomery et al., 2018; Waldén et al., 2015).

2.3 Adolescent ACL Injury Sex Bias

The injury rates above show a sex difference within ACL injuries, with females being more likely to tear their ACL (Agel et al., 2005; Griffin et al., 2000; M. M. Herzog et al., 2017; Hewett et al., 1999; Ireland, 2002; Powell & Barber-Foss, 2000a; Renstrom et al., 2008b). In fact, this sex disparity is only present in females over the age of 12, making adolescent and adult females at-risk groups for ACL injuries (Shea et al., 2004; Slauterbeck et al., 2006; Werner et al., 2016). When evaluating ACL injuries, the sex-based biomechanics and muscular characteristics from each individual are therefore important to consider, but almost non-existent for adolescents.

2.3.1 Biomechanical

In terms of kinematics, adult females display higher peak knee valgus and knee internal rotation angles; and less hip and knee range of motion (ROM) in the sagittal plane than male counterparts during sporting maneuvers associated with ACLi (i.e., cutting, hopping, and landing) (Ford et al., 2010; Hewett et al., 2004; Schmitz et al., 2007; Sinclair et al., 2019). Lower knee flexion values affect how the joints in the lower extremity interact together to absorb the body's momentum, while higher peak knee valgus and internal rotation values are related to the potential ACLi mechanism (Schmitz et al., 2007; Sinclair et al., 2019).

The segments of the lower extremity go through rapid increases in length during adolescent growth which may contribute to increases in moments at the knee joint due to longer lever arms (Hewett et al., 2015). Peak knee valgus moments during sidestepping have been strongly associated with hip internal rotation and therefore ACLi (McLean et al., 2005). Furthermore, adult females display higher average peak knee valgus internal moments; higher peak knee flexion and peak knee abduction external moments; lower maximum ankle inversion internal moments; and lower ground reaction forces (GRF) compared to male counterparts during drop vertical jump (DVJ), drop landing, and sidestepping movements (Haddas et al., 2015; Liederbach et al., 2014; McLean et al., 2005). Taken together, there are clear kinematic and kinetic differences observed between adult males and females, many of which are associated with ACL injury mechanisms, and it therefore stands to reason that these differences must be considered if we are to develop interventions to reduce knee injuries and improve care. Additionally, consider that these above studies relate to the adult population, and there is little evidence to inform interventions in the youth population on this topic.

2.3.2 Muscular Contribution to ACL Loading

The quadriceps, hamstrings, and gastrocnemii are muscle groups associated with knee flexion and extension and they all have a different role in supporting the knee joint. The quadriceps and hamstrings are, respectively, the major extensors and flexors of the knee joint. The quadriceps stiffen the knee joint and absorb energy during landing, while the hamstrings enhance the compression force and lower the ACL loading shear force at the tibiofemoral joint upon contraction (Biscarini et al., 2013). The gastrocnemii are knee-spanning muscles in the shank that are responsible for assisting with knee flexion and stabilising against rotational loads (Flaxman et al., 2017).

The relationship between each of these muscles and ACL injury is currently controversial in the literature. A study performed on contractions of an isolated muscle state that increased quadriceps contraction is antagonistic to the ACL and an injury risk (Hirokawa et al., 1992; Li et al., 1999). When a compressive force (i.e., weight-bearing load) is applied to the quadriceps, the force applied to the ACL increased significantly at less than 50° of knee flexion (Fleming, Renstrom, Beynnon, et al., 2001). Interestingly, when tibial torque was added in either direction, the force on the ACL was increased nearing full extension of the knee. This position may be causing the quadriceps to actually protect the ACL by contracting to line up the tibial plateau surface with the femoral condyle surfaces in a phenomenon known as the neutral position shift (Markolf et al., 2004; Torzilli et al., 1994). In terms of the hamstrings, as they are located posteriorly and their line of action is directed posteriorly, they develop a posterior tibial translation, opposing the anterior tibial translation from a quadriceps contraction and unloading the ACL (Biscarini et al., 2013; W. Herzog & Read, 1993). Li and colleagues (1999) suggest that at specific knee flexion angles of 15º, 30º, and 60º a contraction of the hamstrings is effective in reducing in-situ forces at the ACL. The additional extensor torque coming from the quadriceps changes the levels of shear and axial forces at the tibiofemoral joint and it is necessary to maintain a net knee extensor torque at the knee joint which will, in turn, protect the ACL (Biscarini et al., 2013; Li et al., 1999). Finally, the gastrocnemii are traditionally viewed as an antagonist to the ACL because contractions of the gastrocnemius, whether isolated or co-contracting with the quadriceps or hamstrings, increased ACL strain as measured in vivo during isolated movements (Fleming, Renstrom, Ohlen, et al., 2001). When the gastrocnemii and quadriceps work together, they have been shown to produce too large of an anterior tibial translation for the hamstrings to oppose (Mokhtarzadeh et al., 2013). However, more recent evidence suggests that the gastrocnemii help to stabilise the knee and minimise ACL loads (Mokhtarzadeh et al., 2013; Morgan, Donnelly, & Reinbolt, 2014). It is important to note, however, that these studies (Mokhtarzadeh et al., 2013; Morgan et al., 2014) are simulation studies that used a musculoskeletal model that did not use participant-specific anatomy nor kinematics free of soft tissue artifact.

Studies show that lower extremity strength can counterbalance poor knee joint stability and support the knee joint (Lloyd et al., 2005; Steffen et al., 2016). This becomes important when you consider that due to higher testosterone influxes during puberty, males will experience an increase in muscles mass, power, strength and coordination, specifically, in the quadriceps and hamstring muscles, which has not been observed to the same extent in female counterparts (Barber-Westin et al., 2006; Myer et al., 2004; Parker et al., 1990; Quatman et al., 2006; Round et al., 1999). This possible strength discrepancy between males and females may alter the way muscular demands and forces are tolerated at the lower extremity joints throughout puberty (Shultz, 2008). For example, females tend to have a muscular strength imbalance between the quadriceps and hamstrings, displaying relatively higher isokinetic quadriceps strength compared to isokinetic hamstrings strength during puberty compared to male counterparts (Hewett et al., 2004; Huston & Wojtys, 1996; Wild et al., 2013). In adults, this leads to reduced co-activation levels and a higher likelihood of anterior knee translation which could increase the potential for injury since co-activation of the quadriceps and hamstrings has been shown to help oppose and/or reduce anterior tibial translation (MacWilliams et al., 1999; Yanagawa et al., 2002; Yasuda & Sasaki, 1987). Huston & Wojtys (1996) state that a “balance of power” between the quadriceps and hamstring muscle groups is crucial for normal knee function as dynamic muscle stabilisation protects the joint. Since females tend to have muscular imbalance and reduced co-activation levels, their “balance of power” is compromised, leading to altered knee function and potential for injury (Hewett et al., 2004; Huston & Wojtys, 1996). Furthermore, females are shown to have greater valgus motion at the knee compared to male counterparts throughout puberty, which may result in altered muscular control of the lower extremity muscles during dynamic movements and should be avoided to minimize risk of injury (Hewett et al., 1996, 2004). Muscular contraction has been shown to decrease the varus and valgus laxity of the knee and a more equal distribution of forces transmitted across the medial and lateral compartments of the knee joint would lead to a decreased landing force, protecting the knee joint and thus, the ACL (Lloyd & Buchanan, 2001; Markolf et al., 1978). Taken together, the relative lack of muscular development in females during puberty may result in insufficient muscular torque available to protect the ACL during dynamic movements, resulting in a greater potential for injury (Wild et al., 2013).

2.4 Functional Task Assessments

The vertical jump landing is an athletic maneuver commonly found in sport (ex. landing from a jump in volleyball, landing after a header in soccer, or landing from a lay-up in basketball). The DVJ is the comparable injury screening tool used in clinics and it has been validated as an accurate movement screening tool to identify individuals with an elevated ACL injury risk (Hewett et al., 2005; Padua et al., 2009). The DVJ is associated with non-contact ACL injuries because it elicits a dynamic knee valgus motion which has been shown to be associated with the mechanism of ACL injury (Cesar et al., 2016).

Along with the DVJ, the lunge is commonly used in ACLi prevention neuromuscular training programs, and it also replicates movements found in sports (Ekstrom et al., 2007; Petushek et al., 2019; Wingfield, 2013). The lunge relates to ACL injuries as this movement helps understand loading at the knee joint, which relates to overall dynamic knee joint stabilisation and therefore ACLi. In fact, Alkjær and colleagues (2002) state that copers (individuals able to return to pre-injury sport without ACL reconstruction) and non-copers (individuals unable to return to pre-injury sport) display significantly different movement patterns during a lunge (Alkjar et al., 2002). They found that copers, non-copers, and controls can perform the lunge properly but have different movement patterns that can be quantified according to which group they are in. Therefore, since the lunge task has the potential to differentiate between groups according to kinematics, it should be considered in ACLi assessments. Additionally, Petushek and colleagues (2019) found that exercises that target the hip muscles and ACL agonist muscles (i.e., hamstrings), along with stabilisation exercises are the best for ACLi prevention programs. Considering that a DVJ is considered a landing stabilisation exercise (Petushek et al., 2019) and the hamstrings are activated in a lunge (Jönhagen et al., 2009), they are both clinically relevant and appropriate tasks for ACLi risk assessments.

2.5 Lower Extremity Energy Absorption

Potential energy stored before a movement is transformed into kinetic energy upon a landing, such as when landing from a jump. To prevent the body from collapsing and slow the accelerated joint flexions, the lower extremity absorbs the kinetic energy through hip flexion, knee flexion, and ankle dorsiflexion (Decker et al., 2003; DeVita & Skelly, 1992; Romanchuk, del Bel, et al., 2020). Additionally, it has been suggested that with more joint flexion during landing, more energy is absorbed throughout the lower extremity and less energy is transferred to the ACL, therefore, protecting the ligament (Alentorn-Geli et al., 2009). The lower extremity resists collapsing by applying an extensor moment to counteract the collapse and reduce the body's negative velocity to zero via eccentric muscle contractions to absorb the kinetic energy, characterised as work being performed on the lower extremity muscles (DeVita & Skelly, 1992). Typically, negative joint work values represent energy absorption performed by extensor muscles and total energy absorption is calculated by integrating the negative portion of the joint power curves (DeVita & Skelly, 1992).

There are multiple ways to calculate and quantify energy absorption, with the common method being by way of energetic analysis, combining kinematic (joint angular velocity) and kinetic (net joint moment) data to quantify the energy at each joint (Winter, 2009). Generally, bi-articulate leg muscles are considered important in the power transfer from proximal to distal joints during explosive leg extensions (i.e., a jump) (Jacobs et al., 1996). While mono-articular muscles are primarily involved in the delivery of power, bi-articulate muscles are involved with transfer of energy within the muscles (Gregoire et al., 1984). The proximal to distal power transfer is thought to be the most efficient conversion of successive rotation movements into translation of the body's centre of gravity (Jacobs et al., 1996). In fact, upon landing, the energy from all sequential moments at the hip, knee, and ankle flow in a proximal to distal direction (Gregoire et al., 1984).

Energy absorption has been introduced as a way to evaluate performance, and researchers claim that an energetic analysis is important and highly informative as it quantifies the energy responsible for producing the movement strategies (Norcross et al., 2010). It has also been suggested that energy absorption is related to loading of passive tissues (DeVita & Skelly, 1992). In fact, Boo and colleagues (2018) state that altered energy absorption strategies may lead to abnormal loading of the ACL, leading to an ACLi. Also, ACL injured individuals post reconstruction may have a large contribution of energy from the hip to eccentrically decelerate the body during the initial 50 milliseconds of the landing phase (Boo et al., 2018). They also point to a decreased capacity of the knee joint to absorb the loads compared to a healthy knee. Pollard and colleagues (2017) conducted a study with 30 healthy female soccer players on an ACLi training prevention program (Pollard et al., 2017). After 12 weeks of a program that evaluated the knee/hip energy absorption ratio by way of DVJ, the researchers found that the participants increased their hip extensor energy absorption and their hip-to-knee energy absorption ratio, leading to an ACL-protective lower extremity energy absorption strategy (Pollard et al., 2017). In summary, lower extremity energy absorption strategies are associated with ACL loading, can be modified (DeVita & Skelly, 1992; Norcross et al., 2010; Zhang et al., 2000) and are trainable (Pollard et al, 2017) in adults. Therefore, if the sex and injury status energy absorption strategy differences can be determined in adolescents, ACLi prevention and rehabilitation programs can target and modify this variable.

2.5.1 Sex Differences in Energy Absorption

Primary energy absorption strategies differ between adult males and females (DeVita & Skelly, 1992; M. M. Montgomery et al., 2014; Romanchuk, del Bel, et al., 2020; Schmitz et al., 2007; Zhang et al., 2000). During DVJs, males will absorb the greatest energy at the knee (41%) followed by the hip (38%) and then the ankle (22%) (Zhang et al. 2000). These ratios differ from those reported by DeVita and Skelly whereby female strategy shows the greatest absorption at the knee (41%), then the ankle (40%), and then hip (19%), also during a DVJ. In support, one study found that females absorb more energy at the ankle during single leg landings than male counterparts (Schmitz et al., 2007). Additionally, Romanchuck and colleagues (2020) observed that while the ankle absorbed the majority of the energy from a DVJ in both males and females, females absorbed a higher percentage of energy at the ankle compared to male counterparts (92.7% vs. 90.6%). In terms of absolutes, males have been reported to absorb greater amounts of total energy per unit of body weight compared to female counterparts (M. M. Montgomery et al., 2014; Schmitz et al., 2007).

Although studies highlight that sex-related differences exist in energy absorption strategies, they are inconsistent and the causes underlying these differences are unclear (Decker et al., 2003). Females tend to land in a more erect posture than male counterparts at initial ground contact during a vertical drop landing and display greater knee and ankle ROM and angular velocities compared to male counterparts (Decker et al., 2003). This suggests that females are not as effective at decelerating body mass and thus absorb the energy over a wider range of joint motion, which is speculated to compensate for their more erect posture (Decker et al., 2003).

When considering the muscular strategy involved, this energy absorption strategy requires increased effort from the knee extensor (quadriceps) and ankle plantarflexor (gastrocnemii) muscles to decelerate the body and absorb that energy (Decker et al., 2003). Since females have a higher risk of ACLi (Agel et al., 2005; Griffin et al., 2000; M. M. Herzog et al., 2017; Hewett et al., 1999; Ireland, 2002; Powell & Barber-Foss, 2000a; Renstrom et al., 2008a), and abnormal energy absorption strategies are thought to increase risk of ACLi (Boo et al., 2018), evaluating the link between sex and injury in energy absorption is clearly warranted.

2.5.2 Effect of ACL Injury on Energy Absorption

There is limited literature on the differences in energy absorption between ACL injured participants and matched controls. Garrison and colleagues (2018) found that the energy absorbed at the hip was significantly greater in the injured limb of the ACL reconstructed (ACL-R) participants compared to the matched limb of the healthy control participants (46.4 ± 16.0% vs. 31.7 ± 11.0%), while the energy absorbed at the knee was significantly smaller in the injured limb (42.7 ± 14.65% vs. 60.6 ± 8.9%, injured vs. control, respectively) during a double-legged squat task. However, for a lateral vertical jump, there was a significant increase in the energy absorbed at the hip for the injured limb compared to a control (16.34 ± 8.88% vs. 8.27 ± 4.70% injured vs. control, respectively) and a significant decrease in the energy absorbed at the ankle (79.41 ± 8.09% vs. 87.14 ± 10.59% injured vs. control, respectively) (Boo et al., 2018). Interestingly, they found that there was no significant difference in energy absorbed at the knee (4.25 ± 4.80% vs. 4.59 ± 6.46%, injured vs. control, respectively) (Boo et al., 2018). Therefore, we can postulate that after reconstruction, ACL injured individuals will have greater contributions from the hip to absorb the energy during a landing maneuver (Boo et al., 2018; Garrison et al., 2018). Furthermore, while there is very limited literature investigating energy absorption strategies in the adolescent ACL injured population (Boo et al., 2018; Garrison et al., 2018; Romanchuk, del Bel, et al., 2020); none of these studies considers sex as a variable. Thus, further investigation into the differences between energy absorption strategies in an ACL injured population, is necessary, especially in an adolescent female population.

CHAPTER 3: PURPOSE AND HYPOTHESES

Objective 1 of this thesis was to examine the differences in strength and energy absorption strategies in adolescent males and females, with and without ACL injuries in two functional tasks typically used to assess functional capacity during rehabilitation (i.e., DVJ and lunges). Given that strength is a modifiable variable that is affected by ACL injury and a cornerstone of all rehabilitation programs, we first hypothesized that females and ACL injured would display lower peak torque values during knee extension and ankle plantarflexion compared to males and control individuals (Huston & Wojtys, 1996; Kain et al., 1988; Mokhtarzadeh et al., 2013). Secondly, we hypothesized that females would absorb a higher percentage of energy at the ankle compared to male counterparts; while the knee would absorb the highest percentage of energy, regardless of sex (DeVita & Skelly, 1992; Zhang et al., 2000). Finally, we hypothesized that injured individuals, regardless of sex, would absorb more energy at the hip and ankle compared to matched controls while the knee would not be affected (Boo et al., 2018; Garrison et al., 2018). This objective was carried out in Manuscript 1 (Chapter 5).

Objective 2 was to determine if there is a relationship between strength and energy absorption strategies in male and female control and ACL injured individuals. The goal of this objective was to expand on the findings of objective 1 and determine if the findings are related to a generalizable relationship between energy absorption strategies and strength, as opposed to population-based characteristics associated with sex and injury status. We investigated the association between knee flexion and extension isometric strength at the ankle, knee and hip and their respective energy absorption during the DVJ task. We first hypothesized that sex will not be a relevant variable to predict energy absorption at the hip, knee, and ankle based off knee extension and flexion isometric strength, however, it was secondarily hypothesized that injury status will be relevant in the prediction of energy absorption at the hip, knee, and ankle based off knee extension and flexion isometric strength (Decker et al., 2003; DeVita & Skelly, 1992; Pollard et al., 2017; Schmitz et al., 2007). This objective was carried out in Manuscript 2 (Chapter 6).

CHAPTER 4: GENERAL METHODLOGY

4.1 Study Design

This Master's thesis used data collected in the Clinical Biomechanics Research Unit (CBRU) at the University of Ottawa under the supervision of Dr. Daniel Benoit in collaboration with Dr. Sasha Carsen at the Children's Hospital of Eastern Ontario (CHEO). The data for this project is only a portion of the data collected for a larger on-going project looking at the neuromuscular patterns and biomechanical loading of healthy and injured knee joints pre- and post-ACL reconstruction in an adolescent population. Participants performed a series of hop, functional, and endurance tasks as part of the protocol, however, this thesis evaluated only the data from the lunge and DVJ (Appendix A, table A.1 for full protocol). The data in this thesis included healthy controls and ACL-deficient female and male participants, all between the ages of 10 and 18 years. Ethics approval has been granted by the Research Ethics Boards at the University of Ottawa (H09-17-10) and CHEO (17/74X). A cross sectional study design was used to evaluate energy absorption strategies during two movements (DVJ and lunge) in control and ACL injured male and female adolescent participants. Lower extremity 3D kinematic and kinetic data were recorded during DVJs and lunges, along with isometric strength from maximal voluntary isometric contractions collected usig an isokinetic dynamometer.

4.2 Participants

An *a priori* power analysis in G*Power software (3.1.0, Dusseldorf, Germany) based on ankle energy absorption values during a DVJ (Romanchuk, Bel, et al., 2020) indicated a sample size of 52 was required to achieve a power of 0.80, with an input effect size of 0.85 at $\alpha = 0.05$. The sample size for the hip, knee, and ankle energy absorption was calculated and the most conservative estimate was taken. Study one included both injured (n=35; 18 females; 17 males) and control participants (n=36; 18 females; 18 males), while study 2 included both injured (n=54; 37 females; 17 males) and control participants (n=68; 39 females; 29 males) for a total of 122 participants.

Control participants were recruited from the Ottawa/Gatineau area through word of mouth, while injured participants who have a confirmed ACL rupture via clinical observation, arthroscopy, and/or MRI were recruited through CHEO. Inclusion criteria required them to be actively participating in an organized sport. Exclusion criteria included a history of previous traumatic lower extremity injury (i.e., meniscal tear, ligament rupture), any recent injury to the lower extremity in the past six months other than their ACL injury for the ACLi group, and any other musculoskeletal impairment that may bias the results of the study. Leg dominance was determined by which leg they would use to kick a soccer ball for maximum distance (van Melick et al., 2017).

4.3 Protocol

4.3.1 Consent and Questionnaires

Prior to collecting data, the participants or legal guardian if under 18 read and signed a consent form explaining the purpose of the study, the procedure, and any potential risks. The participants then completed a series of questionnaires including: i) an assessment of sport exposure (HSS Pedi-FABS) (Del Bel et al., 2020; Fabricant et al., 2013); ii) a subjective assessment of knee joint function (Pedi-IKDC) (Kocher et al., 2011); iii) an assessment of their level of activity participation currently and before injury (Tegner Activity Scale) (Tegner & Lysholm, 1985); iv) a subjective assessment of psychological Impact on returning to sport (ACL-RSI) (Webster et al., 2008) and v) a pubescent-stage self-assessment form (Tanner Stage) (Taylor et al., 2001). Participants had the option of completing the forms with a guardian present, and in English or French.

4.3.2 Participant Preparation and Equipment

After completion of the consent and questionnaires, participants were asked to change into provided tight-fitting spandex shirt and shorts. Then, the participant's height (cm), weight (kg), and anthropometric measurements (cm) including anterior superior iliac spine, posterior superior iliac spine, knee, and ankle width; leg and tibial length; and thigh and shank circumference were recorded. After measurements, the participants were provided with a pair of standardized running shoes (KBS7FW3343; MS7F505027, Joe Fresh, ON, Canada) to be used for the rest of the collection. Once fitted with shoes, they completed a warm-up consisting of five minutes of cycling on a stationary cycle ergometer (Monark 828E, Vansbro, Sweden) and were provided an opportunity to stretch.

To track the 3D kinematics of the body during the movement tasks, 84 retroreflective markers (14mm diameter) were placed on specific anatomical landmarks according to a hybrid cluster-marker set (Appendix A: figure A.1.) (modified from Mantovani & Lamontagne, 2017). The marker trajectories were recorded at 200Hz using a 10-camera infrared motion analysis system (8 Vero, 2 Vantage cameras; Vicon, Nexus, Oxford, UK). Along with 3D kinematics, ground reaction force (GRF) data were collected for the movement tasks using a combination of two force plates (2 FP4060-08, Bertec Corp., Columbus, USA). The GRF data were sampled at 1000Hz and amplified with an internal gain of 1000 to ensure optimal detection of impact forces.

4.3.3 Maximum Voluntary Isometric Contractions

The participants completed a series of maximum voluntary isometric contractions (MVIC) performed on an isokinetic dynamometer (System 4 Pro, Biodex Medical Systems, Shirley, USA) to collect, measure, and evaluate maximum torque generation. They included the following: i) knee flexion and extension recorded with the participant in a seated position with the knee joint held at 60° of flexion and hip at 90º ii) ankle plantarflexion recorded with the participant in a seated position with the ankle joint held at 10° of plantarflexion and knee joint held at 0° flexion (Sale et al., 1982) and iii) hip abduction recorded with the participant standing with the hip joint at 10° abduction and 0° extension (Romanchuk, del Bel, et al., 2020; Worrell et al., 2001). Participants performed three trials per exercise, receiving verbal encouragement and on-screen biofeedback of the torque signal assisting them to maintain their maximal force for 5 seconds. There was approximately 1 minute of rest between all trials. This effort level was then recorded using a visual analog scale.

4.3.5 Functional Movement Tasks

After placement of the retroreflective markers, the participants performed a series of static and dynamic tasks. First, participants performed a static trial with one foot on each of the force plates while standing with their arms abducted to shoulder height and elbows flexed to 90°, for 10 seconds. The dynamic tasks protocol was divided in two, with the first half requiring participants to complete a series of hops and the second half requiring participants to complete tasks typically used in rehabilitation and injury prevention programs (Bizzini et al., 2013; Impellizzeri et al., 2013; Wright et al., 2015). For both tasks, the participant was allowed two practice trials prior the start of the collection

Participants performed a series of DVJ's and lunges. For the DVJ task, participants: i) stepped off a raised platform set at the height of their tibial plateau ii) landed with two feet, including one foot on each force plate iii) performed a maximal vertical jump as soon as possible and finally, iv) landed back onto the respective force plates with two feet. During these trials, their arms were free to move as the participant felt comfortable. Participants completed as many trials as necessary to gather five successful trials. Trials were considered successful if they were able to maintain their balance for approximately three seconds without shifting their foot position; their entire foot landed on the respective force plate each landing; and they stepped off the platform, as opposed to jumping.

For the lunge trials, participants had their hands placed on their head with their feet shoulder-width apart standing on two separate force places. They began their lunge by stepping forward with one leg from this position on to a force plate in front of them and lunged down without touching the force plate with their back knee. The trial was complete when they returned to the starting position. Participants performed as many trials as necessary to collect five successful lunge trials per leg all at a self-selected pace, lowering their body as far as they felt comfortable as long as their entire foot is on the force plate. The trial was considered successful if they kept their hands on their head, their entire foot landed on the respective force plate, and they completed the trial without losing balance. Researchers regularly checked in with the participants throughout to make sure there is no pain or discomfort, or feelings of fatigue.

4.4 Data Processing

4.4.1 Isometric Strength

Torque data were filtered with a 4th order zero-lag low-pass Butterworth filter with a cut-off frequency of 15Hz. To identify the maximum torque reached during the isometric contraction, a 50ms moving average was used. The maximum torque values for knee extension and ankle plantarflexion were normalized to the participant's body weight multiplied by their leg length (Hof, 1996).

4.4.2 Kinematics and Kinetics

Marker trajectories and GRFs were filtered with a 4th order zero-lag low-pass Butterworth filter with matching cut-off frequencies of 15Hz (Bisseling & Hof, 2006;

Kristianslund et al., 2012) using custom pipelines in Vicon Nexus (v2.9, Vicon, UK). Inverse dynamics for the hip, knee, and ankle moment and angles in the sagittal plane were computed in Matlab (2018a, Mathworks, Natick, USA), using a modified Vicon Nexus model made for scaling and computing purposes relative to a standing reference trial. Lower limb inverse dynamics in the sagittal plane for the hip, knee, and ankle moments and angles were also calculated.

Waveform data for the DVJ and lunge were time normalized prior to statistical analyses. The DVJ and lunge were normalized to 100% of the time spent on the force plate. Only the initial landing phase of the DVJ was analyzed (Bencke et al., 2000; Myer et al., 2006). The DVJ landing was split into two phases: 1) the deceleration phase: the first 1-50%, defined as initial contact (IC) (GRF > 10N) until maximum knee flexion; 2) the acceleration phase: 51-100%, defined as maximum knee flexion until TO (GRF < 10N) with only the deceleration phase analyzed in this thesis (Bencke et al., 2000; Myer et al., 2006). The lunge was split into two phases: 1) the eccentric phase was the first 1-50% of the cycle defined as (IC) (GRF > 10N) until maximum knee flexion; 2) the concentric phase, 51-100% of the cycle defined as maximum knee flexion until the foot leaves the force place at take-off (TO) (GRF < 10N). Again, only the eccentric phase was analyzed (Flaxman et al., 2017; Myer et al., 2006).

4.4.3 Energy Absorption

Negative joint work values represent energy absorption performed by the extensor muscles during the landing (DeVita & Skelly, 1992). Energy absorption for the hip, knee, and ankle was calculated using joint power curves, determined by multiplying joint angular velocities (rad/s) and the internal joint moments (Nm) for each trial (Equation 1; (Winter, 2009)).

$$Pm= Mj\omega j \qquad W \ (1)$$

The internal joint moments were normalized to body weight. Total energy absorption was calculated by integrating the negative portion of the joint power curves over the eccentric phase of the lunge and the deceleration phase of the DVJ (DeVita & Skelly, 1992). Relative energy absorption at each joint was expressed as a percentage of the summed energy absorption over all three joints.

4.5 Statistical Analysis

The outcome variables are the peak isometric torque and total energy absorption with secondary variables including peak sagittal hip, knee, and ankle joint angles and moments. All statistical analyses were performed using a combination of three softwares: Matlab (2018a, Mathworks, Natick, USA), SPSS Statistics 26.0 (IBM Corp., Armonk, NY, USA), and R (v4.1.2, The R Foundation, Vienna, Austria) with a significance level set at $p = 0.05$ for statistical tests. Boxplots were created to determine outliers; data points more than 1.5 box-lengths from the edge of their box were deemed an outlier. After further inspection, outliers that are a result of irreducible errors in the data collection process were excluded; all others were included in subsequent analyses. All variables were assessed for normality to determine whether a parametric or a non-parametric statistical test would be more appropriate for the data. The homogeneity of variances was evaluated using a Levene's test. Cohen's d effect sizes were calculated for each significant finding using these guidelines; small effect size, $d < 0.5$, medium effect size, $0.5 < d < 0.8$, and large effect size, $d > 0.8$ (Field, 2013). 95% confidence intervals (CI) were reported with the mean group differences.

To satisfy **<u>Objective 1</u>**, a two-way between subject factorial analyses of variance (ANOVA) was used to evaluate differences between groups to determine if sex (male and female) and injury status (injured and control) differences exist for the discrete variables of isometric strength and energy absorption. Independent t-test's, including interactions, using statistical non-parametric mapping (SnPM) were used to determine difference in the variables with continuous waveforms (i.e., joint angles and moments), using its factorial ANOVA analog test. The non-parametric version was chosen as the data did not pass the assumption of normality. SnPM is a technique that considers the entire time-dependent waveform between data sets, and it was applied to all of the data within the DVJ and lunge waveforms according to the previously identified phases (Pataky et al., 2013).

If a significant effect of sex or injury status or an interaction effect 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 difference existed. 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:

$$Critical\ Value = \left(\frac{i}{m}\right) Q \ (2)$$

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).

To satisfy **Objective 2**, correlations between knee strength and energy absorption were determined for the hip, knee, and ankle joint. The torque variable that had the strongest correlation with each joint was chosen for further analysis. Multiple linear regression analyses were then used to determine if knee strength, sex, and injury status can predict energy absorption at the hip, knee, and ankle. Independence of observations was tested using the Durbin-Watson test. Linearity, homoscedasticity, and normality were assessed by visual inspection of data while multicollinearity was assessed using Tolerance values. homoscedastic, and normality were assessed by visual inspection of data using partial regression plots while multicollinearity was assessed using Tolerance values.

Unusual points included outliers, leverage, and influential points, these were identified as those exceeding ±3 standard deviations, greater than 0.2 leverage value, and Cook's Distance greater than 1, respectively and were inspected to determine the appropriate action. All statistical analysis were completed using a combination of MATLAB (2018b, MathWorks, Natick, USA), SPSS Statistics 26.0 (IBM Corp., Armonk, NY, USA), R (v4.1.2, The R Foundation, Vienna, Austria), and Excel (2021, Microsoft, Washington, USA) with the level of significance of α=0.05.

CHAPTER 5: MANUSCRIPT 1

EXAMINATION OF ENERGY ABSORPTION STRATEGIES IN CONTROL AND ACL INJURED ADOLESCENT MALES AND FEMALES

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Abstract

Purpose: Research in adult populations indicates that energy absorption and muscular strength can have important implications for ACL injury prevention and rehabilitation, while sex (male vs. female) and injury status (ACL injured vs. control) can greatly affect these variables. To our knowledge, there is no literature exploring these variables in the adolescent healthy and ACL injured populations. Therefore, the purpose of this study was to identify sex and injury status differences in lower extremity strength and energy absorption in adolescent males and females.

Methods: Thirty-five adolescents (18 females and 17 males) with an ACL injury and 36 controls (18 males and 18 females) performed drop-vertical jump and lunge tasks, with 3D kinematics recorded using a motion analysis system. Knee extension and ankle plantarflexion maximum voluntary isometric contractions were collected using an isokinetic dynamometer. A two-way analysis of variance (ANOVA) was used to determine differences in isometric strength, while non-parametric Kruskal-Wallis H tests were used to determine differences in energy absorption. Between-group differences in lower extremity kinematics and kinetics were evaluated with statistical non-parametric mapping (SnPM) .

Results: Males produced greater knee extension torque compared to females (p=0.007), while control participants produced greater values compared to ACL injured (p <0.001). No significant interaction effects were found. There was a significant difference found in ankle plantarflexion torque by injury status (p = 0.006) with control participants displaying greater values compared to ACL injured. During drop-vertical jumps, no significant differences were found at the hip or ankle for energy absorption, however, a significant difference in knee energy absorption was found (p = 0.005) with male controls displaying greater values compared to their female counterparts.

Conclusion: These findings indicate that isometric strength may be an important variable to be considered in ACL injury rehabilitation and injury prevention programs with injured individuals displaying weaker knee extension and ankle plantarflexion torques. However, energy absorption may not be as important of a variable to consider as there were few statistically significant differences between injury status and sex at the hip, knee, and ankle joints.

Introduction

The anterior cruciate ligament (ACL) is the most commonly torn ligament in the knee, with an estimated 0.17-0.23 ACL injuries per 1000 athlete exposures (Agel et al., 2016; Sepúlveda et al., 2017). This injury is detrimental to adolescents as the injury rate has been rising by 2.3% per year for individuals aged 6-18 (Beck et al., 2017), while also presenting a sex-bias with adult females being three to nine times more likely to experience an ACL injury compared to male counterparts (Agel et al., 2005; Griffin et al., 2000; Hewett et al., 1999; Ireland, 2002). Specifically, adolescent females are two to four times more likely to tear their ACL compared to male counterparts, with females aged 13-17 having the highest ACL injury incidences of any other age-sex strata (M. M. Herzog et al., 2017; Powell & Barber-Foss, 2000b; Renstrom et al., 2008b). Interestingly, this sex disparity is only present in females over the age of 12, making adolescent and adult females at-risk groups for ACL injuries (Shea et al., 2004; Slauterbeck et al., 2006; Werner et al., 2016). Despite this, there is currently limited literature on ACL injuries within the adolescent population. Additionally, approximately one in four ACL injured individuals will experience a re-injury (Wiggins et al., 2016), on top of a 29-fold increase in ACL reconstructions (ACL-R) for individuals under the age of 20 since 1997-1998 (Nogaro et al., 2020). Therefore, there is clearly a need for improved ACL rehabilitation and injury prevention programs in the adolescent population. First, understanding the mechanism of injury is crucial in designing such appropriate rehabilitation and prevention programs.

This injury most commonly occurs in a non-contact manner, meaning the kinematics and kinetics that lead to excessive loading on the ACL are self imporsed (Boden et al., 2000; Myklebust et al., 2007). Joint angles in the sagittal plane that have been associated with a higher risk for ACL injury include lower hip and knee flexion, and higher ankle dorsiflexion angles; all of which are more commonly seen in females compared to males (Alentorn-Geli et al., 2009; Landry et al., 2007b, 2007a; C. Montgomery et al., 2018; Waldén et al., 2015). Additionally, females display higher peak knee valgus and knee internal rotation angles; and less hip and knee range of motion (ROM) in the sagittal plane than male counterparts during sporting maneuvers associated with ACL injury (i.e., cutting, hopping, and landing) (Ford et al., 2010; Hewett et al., 2004; Schmitz et al., 2007; Sinclair et al., 2019). It has been speculated that knee injuries will occur while the knee is in a low value of flexion (Griffin et al., 2000), while higher peak knee valgus and internal rotation values are related to the potential ACL injury mechanism (Schmitz et al., 2007; Sinclair et al., 2019). Kinetically, peak knee valgus moments during sidestepping have been strongly associated with hip internal rotation (IR), and therefore ACL injury since high hip IR angles have been associated with ACL injury mechanisms (McLean et al., 2005). Furthermore, females have higher average peak knee valgus internal moments; higher peak knee flexion and peak knee abduction external moments; and lower maximum ankle inversion internal moments compared to male counterparts (Haddas et al., 2015; Liederbach et al., 2014; McLean et al., 2005).

Energy absorption and muscular contribution are related to kinematics and kinetics and can have important considerations when it comes to ACL injury prevention and rehabilitation (Boo et al., 2018). However, there are sex and injury status differences among these variables that should also be considered when designing rehabilitation programs. First, ACL injured individuals post reconstruction may have a large contribution of energy from the hip to eccentrically decelerate the body during the initial 50 milliseconds of the landing phase (Boo et al., 2018; Garrison et al., 2018). They also point to a decreased capacity of the knee joint to absorb the loads compared to a healthy knee (Boo et al., 2018; Garrison et al., 2018).

Interestingly, during drop vertical jumps (DVJs), it was found that healthy males absorb the greatest amount of energy at the knee (41%) followed by the hip (38%) and then the ankle (22%) (Zhang et al. 2000). However, females have the greatest absorption at the knee (41%), then the ankle (40%), and then hip (19%) (DeVita & Skelly, 1992). In support, one study found that females absorb more energy at the ankle during single leg landings than male counterparts (Schmitz et al., 2007). When considering the muscular strategy involved, this energy absorption strategy increases the work involved from the knee extensor (quadriceps) and ankle plantarflexor (gastrocnemii) muscles to decelerate the body and absorb that energy (Decker et al., 2003). Since females have a higher risk of ACL injury (Agel et al., 2005; Griffin et al., 2000; M. M. Herzog et al., 2017; Hewett et al., 1999; Ireland, 2002; Powell & Barber-Foss, 2000a; Renstrom et al., 2008a), and certain energy absorption strategies are thought to increase risk of ACL injury (Boo et al., 2018), evaluating the link between sex and injury in energy absorption is clearly warranted.

What is critical to note is that the above literature is almost exclusively on adult populations. To evaluate the link between sex and ACL injury status in the adolescent population, we first need to determine where the differences lie in terms of strength related muscular contributions and energy absorption upon landing. Therefore, the purpose of this study was to compare the lower limb strength and energy absorption strategies in adolescent females and males with and without an ACL injury. Specifically, this study evaluated isometric ankle plantar flexion and knee extension torque and hip, knee, and ankle energy absorption in the sagittal plane. It was hypothesized that females and patients with ACL injuries would display lower peak torque values during knee extension and ankle plantarflexion compared to males and control individuals respectively (Huston & Wojtys, 1996; Kain et al., 1988; Mokhtarzadeh et al., 2013). Secondly, it was hypothesized that both control and injured females would absorb a higher percentage of energy at the ankle compared to male counterparts, and that the knee would absorb the highest percentage of energy, regardless of sex (DeVita & Skelly, 1992; Zhang et al., 2000). Finally, it was hypothesized that injured individuals, regardless of sex, would absorb more energy at the hip and ankle compared to matched controls, while the knee would not be affected (Boo et al., 2018; Garrison et al., 2018).

Methods

Participants

A total of 71 participants including both injured (n=35; 18 females; 17 males) and control participants (n=36; 18 females; 18 males) were included in this study (Table 1.1, Table 1.2). Control participants were recruited from the Ottawa/Gatineau area while injured participants, who have a confirmed ACL rupture via clinical observation, arthroscopy, and/or MRI, were recruited through the Children's Hospital of Eastern Ontario (CHEO). Inclusion criteria required them to be actively participating in an organized sport. Exclusion criteria included a history of previous traumatic lower extremity injury (i.e., meniscal tear, ligament rupture), any recent injury to the lower extremity in the previous six months, and any other musculoskeletal impairment that may bias the results of the study.

Procedures

All participants read and signed a consent form approved by each institution's respective research ethics board, (uOttawa – H09-17-10; CHEO – 17/74X) and completed the following questionnaires; i) the Hospital for Special Surgery Pediatric Functional Activity Brief Scale (HSS Pedi-FABS) (Del Bel et al., 2020; Fabricant et al., 2013) to assess sport exposure, ii) the

Pediatric International Knee Documentation Committee (Pedi-IKDC) to subjectively assess knee joint function (Kocher et al., 2011), iii) the Tegner Activity Scale to assess level of activity participation currently and before injury (Tegner & Lysholm, 1985), iv) the ACL Return to Sport Index (ACL-RSI) to subjectively assess psychological impact on returning to sport (Webster et al., 2008), and v) the Tanner Stage to self-assess current pubescent-stage (Taylor et al., 2001). Following the questionnaires, anthropometric measurements including height, weight, and leg and tibial length were recorded. The participants then completed a 5-minute warm-up on a cycle ergometer (Monark 828E, Vansbro, Sweden) with minimum resistance.

Next, maximum voluntary isometric contractions (MVIC) for knee extension, with the participant in a seated position with the knee joint held at 60° and hip at 90º of flexion, and for ankle plantar flexion, with the participant in a seated position with the ankle joint held at 10° of plantarflexion and knee joint held approximately 10-20° of flexion, were recorded using an isokinetic dynamometer (Systems 4 Pro, Biodex Medical Systems, New York. USA) (Figure 5.1). Participants performed three trials per exercise, receiving verbal encouragement and on-screen biofeedback of the torque signal to encourage them to maintain their maximal force for 5 seconds.

Figure 5.1: Participants position during knee extension (A) and ankle plantarflexion (B) isometric test

After the MVIC trials, 84 retroreflective markers were placed on anatomical landmarks, according to a hybrid cluster market set (Appendix A, figure A.1). These trajectories were sampled at 200 Hz using a 10-camera infrared motion analysis system (8 Vero, 2 Vantage; Vicon, Oxford, UK). The supporting software (Nexus v2.7, Vicon, Oxford, UK) simultaneously recorded marker trajectories and ground reaction forces (GRFs) from two force plates sampled at 1000 Hz (FP4060-08, Bertec Corporation, Columbus, OH, USA).

Finally, the participant performed a series of functional movement tasks including the lunge and DVJ trials (Figure 5.2; Appendix A, table A.1 for full protocol). Participants were given practice trials to familiarise themselves with each task. For the lunge trials, participants had their hands placed on their head with their feet shoulder-width apart. They began their lunge by stepping forward with one leg from this position on to a force plate in front of them and lunged down without touching the force plate with their back knee. The trial was complete when they returned to the starting position (Figure 5.2A). Participants performed as many trials as necessary to collect five successful trials per leg at a self-selected pace, lowering their body as far as they felt comfortable as long as their entire foot remained on the force plate. The trial was considered successful if they kept their hands on their head, their entire foot landed on the respective force plate, and they completed the trial without losing balance.

For the DVJ task, participants were instructed to: i) step off a raised platform set at the height of their tibial plateau, ii) land with two feet, including one foot on each force plate, iii) perform a maximal vertical jump as soon as possible, and finally, iv) land back onto the respective force plates with two feet (Figure 5.2B). Participants completed as many trials as necessary to gather five successful trials. Trials were considered successful if they were able to maintain their balance for approximately three seconds without shifting their foot position; their entire foot landed on the respective force plate each landing; and they stepped off the platform, as opposed to jumping.

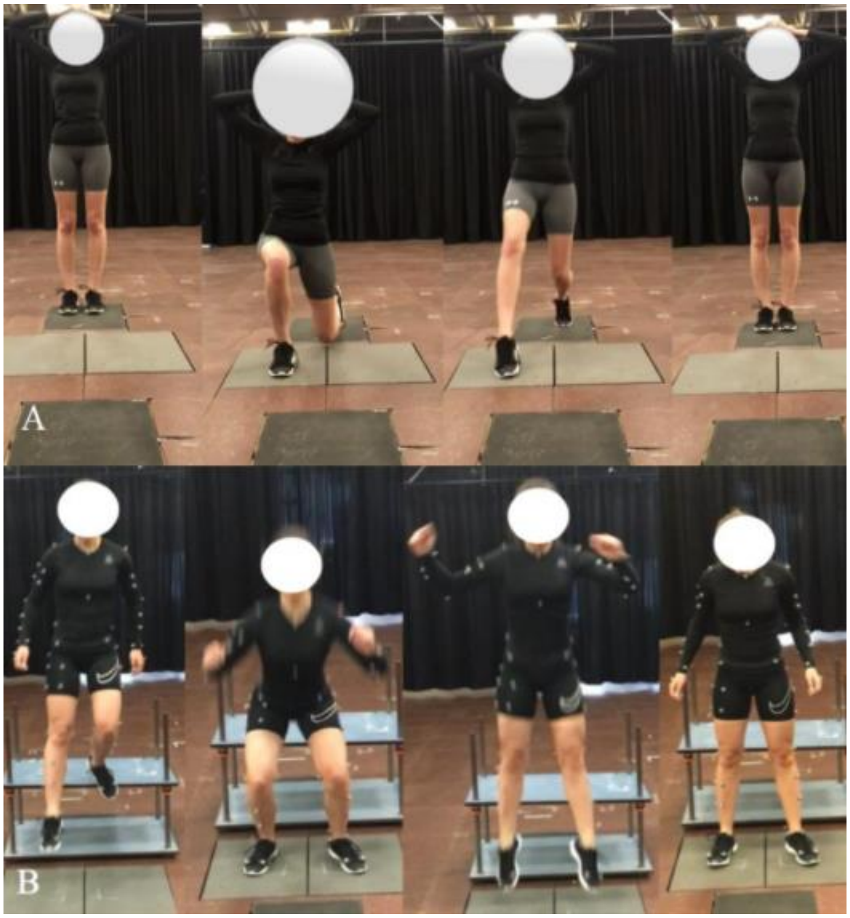

Figure 5.2: Lunge (A) and drop vertical jump (B) trial example

Data Processing and Analysis

Isometric Strength

Torque data were filtered using a 4th-order zero-lag low pass Butterworth filter with a cut-off frequency of 15 Hz. The maximum torque reached during the isometric contraction was identified using a 50ms moving average. The maximum torque values for knee extension and ankle plantarflexion were normalized to the participant's leg length multiplied by their body weight (Hof, 1996).

Kinematics

Marker trajectories and GRF data were filtered using a 4th-order zero-lag low pass Butterworth filter with matching cut-off frequencies of 15 Hz (Bisseling & Hof, 2006; Kristianslund et al., 2012) using custom pipelines in Vicon Nexus (v2.9, Vicon, UK). Filter order and cut-off frequency were chosen based on residual analysis (Winter, 2009). Hip, knee, and ankle angles and moments in the sagittal plane were calculated using a modified University of Ottawa Motion Analysis Vicon Nexus model (Mantovani & Lamontagne, 2017) made for scaling and computing purposes relative to a standing reference trial.

Energy absorption for the hip, knee, and ankle was calculated using joint power curves, which were determined by multiplying joint angular velocities and internal joint moments normalized to body weight. Total energy absorption was calculated by integrating the negative portion of the joint power curves (DeVita & Skelly, 1992).

Time Normalization

All discrete data for the lunge and DVJ were trimmed using unfiltered data to establish the eccentric phase, identified as the initial contact (IC (GRF < -10 N)) (Navacchia et al. 2019; Romanchuk, del Del Bel, and Benoit 2020) until peak knee flexion. Once trimmed, each variable of each participant was then averaged over the trials and time normalized to fit a 1-100% scale.

Statistical Analysis

A two-way between subject factorial analysis of variance (ANOVA) was used to evaluate differences between groups to determine if sex (male and female) and injury status (ACL-injured and control) differences exist for the discrete variable of isometric strength and energy absorption. All variables were assessed for normality through Shapiro-Wilk tests. If data rejected the assumption of normality, a Kruskal Wallis H test was performed with post-hoc Dunn's test performed for any significant results. Equality of variance was tested through Levene's tests. If an interaction effect was observed, a Bonferroni correction was performed to correct for multiple comparisons.

Independent t-test's using statistical non-parametric mapping (SnPM) was used to determine difference in the variables with continuous waveforms (i.e., joint angles and moments), using its factorial ANOVA analog test. SnPM is a technique that considers the entire time-dependent waveform between data sets, and it will be applied to all of the data within the DVJ and lunge waveforms according to the previously identified phases (Pataky et al., 2013). If a significant effect of sex, injury status or an interaction effect was observed, a Benjamini-Hochberg correction for multiple comparisons was performed with a set false discovery rate (FDR) of 0.05.

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 (e.g., marker coming loose on skin). Those that reflected accurate data were included in the subsequent analysis. 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 (2018b, 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 5.1

Descriptive data of female ACL injured and control participants

Variable	**Female Injured** (mean ± SD)	**Female Control** (mean ± SD)	***p*-value**
Age (years)	14.6 ± 1.2	14.5 ±1.3	0.798
Height (cm)	164.7 ± 6.3	166.3 ± 5.5	0.439
Weight (kg)	59.4 ± 9.2	57.7 ±7.9	0.565
BMI (kg/m^2)	21.8 ± 2.9	20.8 ± 1.8	0.206
Tanner Stage	4.1 ± 0.8	4.1 ± 0.6	1.000

Note: *p*-values corrected using the Bonferroni correction, *indicates statistical significance of $p < 0.05$

Table 5.2

Descriptive data of male ACL injured and control participants

Variable	**Male** Injured (mean ± SD)	**Male Control** (mean ± SD)	***p*-value**
Age (years)	15.5 ± 1.1	14.2 ± 1.2	0.003*
Height (cm)	174.7 ± 9.0	173.3 ± 13.5	0.634
Weight (kg)	76.4 ± 31.7	59.4 ± 12.7	0.043*
BMI (kg/m^2)	24.8 ± 9.7	19.8 ± 2.8	0.049*
Tanner Stage	4.0 ± 0.9	3.7 ± 1.1	0.191

Note: *p*-values corrected using the Bonferroni correction, *indicates statistical significance of $p < 0.05$

Results

All 71 participants were able to complete the lunge and drop-vertical jump tasks and were included in the analysis. No differences were found in age (p = 0.798), height (p = 0.439), weight (p = 0.565), BMI (p = 0.206), and Tanner stage (p = 0.874) for the female injured and control participants (Table 5.1). For the male injured and control participants, statistically significant difference were found for age (p = 0.003), weight (p = 0.043), and BMI (p = 0.049), however, there were no differences found for height (p = 0.634) and Tanner stage (p = 0.191) (Table 5.2). Group means for all kinematic and kinetic variables can be found in Table 5.3. Results from the two-way ANOVA can be found in Table 5.4 and the results from the Kruskal Wallis H test for the non-normally distributed data can be found in Table 5.5 with the post-hoc Dunn’s test in Table 5.6. The SnPM results for the kinematic and kinetic variables can be found in Table 5.7, with the Benjamini-Hochberg correction in Table 5.8.

Table 5.3

Kinematic and kinetic variable group means (SD) for control and ACL injured male and females during the isometric strength, DVJ, and lunge tasks.

Task	Variable	Male Control Mean ± SD	Female Control Mean ± SD	Male Injured Mean ± SD	Female Injured Mean ± SD
Isometric Strength	*Knee Extension*	0.364 ± 0.06	0.340 ± 0.06	0.309 ± 0.12	0.226 ± 0.07
	Ankle Plantarflexion	0.275 ± 0.08	0.263 ± 0.06	0.228 ± 0.07	0.212 ± 0.06
DVJ	*Hip Energy Absorption (Nm/kg)*	-523.1 ± 228.9	-353.6 ± 155.3	-506.8 ± 212.7	-465.0 ± 185.8
	Knee Energy Absorption (Nm/kg)	-201.8 ± 76.4	-128.1 ± 52.8	-228.0 ± 103.6	-169.2 ± 72.2
	Ankle Energy Absorption (Nm/kg)	-111.8 ± 155.7	-34.4 ± 31.8	-116.1 ± 253.7	-61.5 ± 53.7
Lunge	*Hip Energy Absorption (Nm/kg)*	-308.8 ± 122.9	-249.1 ± 74.1	-356.3 ± 103.8	-346.9 ± 134.8
	Knee Energy Absorption (Nm/kg)	-89.2 ± 35.1	-61.1 ± 27.7	-95.6 ± 29.1	-66.3 ± 26.1
	Ankle Energy Absorption (Nm/kg)	-101.9 ± 66.6	-66.3 ± 29.7	-110.6 ± 65.7	-69.0 ± 43.8

Isometric Strength

Table 5.4

P-values from a two-way ANOVA testing for sex (male vs. female), injury status (ACL injured vs. control), and interaction effect for isometric strength

Variable	*p*-value			Effect Size
	Sex	*Injury Status*	*Interaction Effect*	
Knee Extension	0.007*	<0.001*	0.128	S: 0.601 IS: 1.013
Ankle Plantarflexion	0.417	0.006*	0.927	IS: 0.687

Note: Cohen's *d* effect sizes presented for significant main effects of sex (S) and injury status (IS). *p*-values corrected using the Bonferroni correction for multiple comparisons. *Indicated statistical significance of $p < 0.05$.

The interaction effect between sex and injury status on isometric knee extension torque was not statistically significant, $F(3,67) = 2.371$, $p = 0.128$, partial $\eta^2 = 0.034$. Therefore, an analysis of the main effect for sex and injury status was performed, which indicated that the main effect was statistically significant for sex, $F(3,67) = 7.799$, $p = 0.007$, partial $\eta^2 = 0.104$ and injury status, $F(3,67) = 19.364$, $p = <.001$, partial $\eta^2 = 0.224$. Control participants were associated with a higher mean knee extension value compared to ACL injured participants, ($p < 0.001$). In terms of sex, male participants were associated with a higher mean knee extension value compared to the female participants, (p = 0.007). Cohen's d revealed a medium effect size for sex (0.061) and a large effect size for injury status (Table 5.4).

For the plantarflexion torque, the interaction effect between sex and injury status on ankle plantarflexion was not statistically significant, $F(3,67) = 0.008$, $p = 0.927$, partial $\eta^2 = 0.000$. Therefore, an analysis of the main effect for sex and injury status was performed which indicated that the main effect was not statistically significant for sex $F(3,67) = 0.666$, $p = 0.417$, partial $\eta^2 = 0.010$, however, the main effect for injury status was statistically significant $F(3,67) = 8.185$, $p = 0.006$, partial $\eta^2 = 0.109$. Control participants had mean ankle plantarflexion value higher than ACL injured participants (p = 0.017). Cohen's d revealed a medium effect size for injury status (Table 5.4).

Energy Absorption

Table 5.5

Results from the Kruskal Wallis H test testing for differences in energy absorption at the hip, knee, and ankle between the four groups of female injured, female control, male injured, and male control

Task	**Variable**	***p*-value**
DVJ	*Hip EA (Nm/kg)*	0.051
	Knee EA (Nm/kg)	0.005*
	Ankle EA (Nm/kg)	0.238
Lunge	*Hip EA (Nm/kg)*	0.050*
	Knee EA (Nm/kg)	0.005*
	Ankle EA (Nm/kg)	0.078

Note: Energy absorption (EA) for the hip, knee, and ankle values are presented in this table. *P*-values are corrected using the Bonferroni method. *Indicated a statistically significant difference of $p < 0.05$.

Table 5.6

Results from Dunn's post-hoc test to determine location of statistically significant differences in female injured, female control, male injured, and male control during DVJ and lunge tasks for hip, knee, and ankle energy absorption.

Task	**Variable**	***p* – value**			
		FACL/MACL	*FCON/MCON*	*FACL/FCON*	*MCON/MACL*
DVJ	*Hip EA (Nm/kg)*	1.000	0.110	0.213	1.000
	Knee EA (Nm/kg)	0.614	0.022*	0.556	1.000
	Ankle EA (Nm/kg)	1.000	0.428	0.759	1.000
Lunge	*Hip EA (Nm/kg)*	1.000	1.000	0.143	1.000
	Knee EA (Nm/kg)	0.074	0.099	1.000	1.000
	Ankle EA (Nm/kg)	0.249	0.659	1.000	1.000

Note: Energy absorption (EA) values for the hip, knee, and ankle post-hoc analyses are presented in this table. *P*-values are corrected using the Bonferroni method. *Indicates a statistically significant difference of $p < 0.05$. FACL: female ACL injured, MACL: male ACL injured, FCON: female control, MCON: male control.

For the DVJ, distributions of hip, knee, and ankle energy were not similar for all groups, as assessed by visual inspection of boxplots. Hip and ankle energy absorption values were not statistically significantly different between groups, $X^2(3) = 7.790$, p = 0.051, $X^2(3) = 4.225$, p = 0.238, respectively. However, for the knee energy absorption, the results showed that the distribution scores were significantly different between groups, $X^2(3) = 12.986$, p = 0.005. The post-hoc analysis revealed statistically significant differences only in knee energy absorption values between the female control and male control ($p = 0.022$) (Table 5.6).

Next for the lunge, distributions of hip, knee, and ankle energy absorption were not similar for all groups, as assessed by visual inspection of boxplots. Hip and ankle energy absorption values were not significantly different between groups, $X^2(3) = 7.819$, p = 0.050, $X^2(3) = 6.815$, p = 0.078, respectively. The ankle energy absorption values were statistically significant, $X^2(3) = 12.788$, p = 0.005, however, there were no statistically significant differences revealed in the post-hoc analysis in any of the group combinations.

Kinematics and Kinetics

Table 5.7

Results for SnPM independent t-tests on kinematic and kinetic continuous variables prior to the Benjamini-Hochberg procedure

Task	**Comparison**	**Variable**	***p*-value**
DVJ	FACL/MACL	HFA	$p > 0.05$
		KFA	$p > 0.05$
		AFA	0.018*
		HFM	$p > 0.05$
		KFM	$p > 0.05$
		AFM	$p > 0.05$
	FCON/MCON	HFA	$p > 0.05$
		KFA	$p > 0.05$
		AFA	$p > 0.05$
		HFM	0.016*
		KFM	$p > 0.05$
		AFM	$p > 0.05$
	FACL/FCON	HFA	$p > 0.05$
		KFA	$p > 0.05$
		AFA	$p > 0.05$
		HFM	$p > 0.05$
		KFM	$p > 0.05$
		AFM	$p > 0.05$
	MACL/MCON	HFA	$p > 0.05$
		KFA	$p > 0.05$
		AFA	$p > 0.05$
		HFM	$p > 0.05$
		KFM	$p > 0.05$
		AFM	$p > 0.05$
Lunge	FACL/MACL	HFA	$p > 0.05$
		KFA	0.011*
		AFA	$p > 0.05$
		HFM	$p > 0.05$
		KFM	0.002*
		AFM	0.023*
	FCON/MCON	HFA	$p > 0.05$
		KFA	0.001*
		AFA	$p > 0.05$
		HFM	0.012*
		KFM	$p > 0.05$
		AFM	0.003*
	FACL/FCON	HFA	$p > 0.05$
		KFA	$p > 0.05$

	AFA	$p > 0.05$
	HFM	$p > 0.05$
	KFM	$p > 0.05$
	AFM	$p > 0.05$
MACL/MCON	HFA	$p > 0.05$
	KFA	$p > 0.05$
	AFA	$p > 0.05$
	HFM	$p > 0.05$
	KFM	0.010*
	AFM	$p > 0.05$

Note: SnPM assessment may reveal multiple time-varying *p*-values, only the smallest *p*-value is shown. *Indicated statistical significance. FACL: female ACL injured, MACL: male ACL injured, FCON: female control, MCON: male control, HFA: hip flexion angle, KFA: knee flexion angle, AFA: ankle flexion angle, HFM: hip flexion moment, KFM: knee flexion moment, AFM: ankle flexion moment

Table 5.8

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

Task	**Comparison**	**Variable**	***p*-value**	**Rank**	**Benjamini-Hochberg Critical Value**	**Significance**
DVJ	FCON/MCON	HFM	0.0161	1	0.0500	*
	FACL/MACL	AFA	0.0181	2	0.0250	*
Lunge	FCON/MCON	KFA	0.0006	1	0.0071	*
	FACL/MACL	KFM	0.0016	2	0.0143	*
	FCON/MCON	AFM	0.0025	3	0.0214	*
	MACL/MCON	KFM	0.0101	4	0.0286	*
	FACL/MACL	KFA	0.0112	5	0.0357	*
	FCON/MCON	HFM	0.0121	6	0.0429	*
	FACL/MACL	AFM	0.0231	7	0.0500	*

Note: FACL: female ACL injured, MACL: male ACL injured, FCON: female control, MCON: male control, KFA: knee flexion angle, AFA: ankle flexion angle, HFM: hip flexion moment, KFM: knee flexion moment, AFM: ankle flexion moment.

Kinematics and Kinetics (Male vs. Female)

For the DVJ task, SnPM identified significantly greater hip flexion moments in the male control compared to the female control (*p* = 0.016) and significantly greater ankle flexion angle in the male ACL injured compared to the female ACL injured (*p* = 0.018) (Figure 5.3). There were no other statistically significant differences found in the kinematics and kinetics when comparing the sexes (male vs. female) for the DVJ.

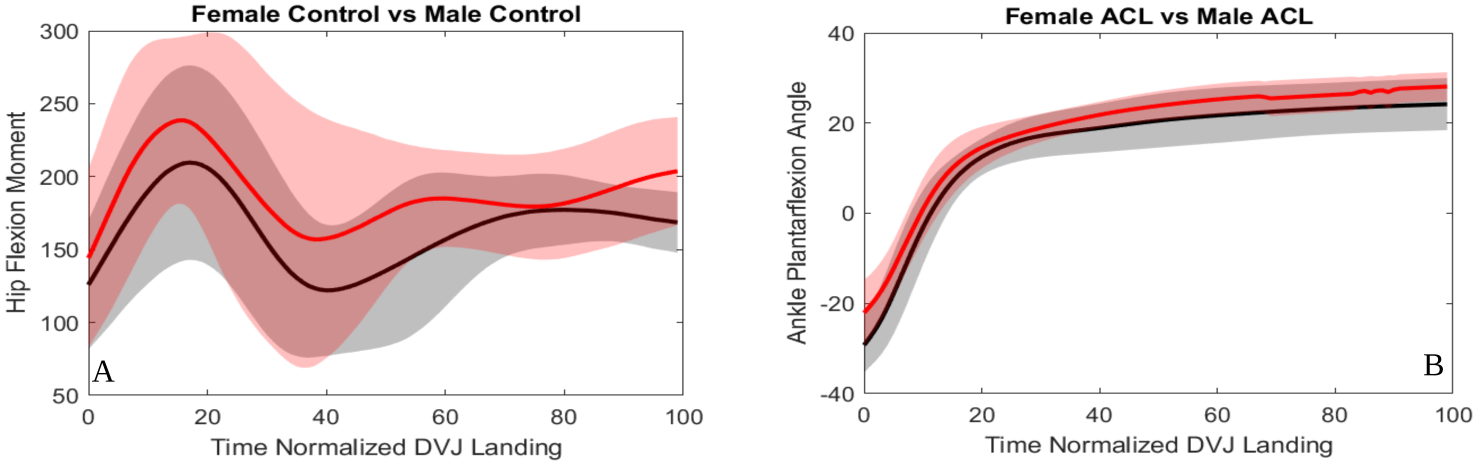

Figure 5.3. Time normalized hip flexion moment for female and male controls (A) and ankle plantarflexion angle for female and male ACL injured (B) during the eccentric phase of the drop-vertical jump task. Black line represents females while the red line represents males.

For the lunge task, SnPM identified statistically significant differences in the knee flexion angle, ankle flexion moment, and hip flexion moment between the female and male control participants (Figure 5.3). For the knee flexion angle, males displayed greater values compared to females (*p* = 0.001), the ankle flexion moment showed females displaying greater values compared to males (*p* = 0.003), and finally, males had greater values in the hip flexion moment compared to females (*p* = 0.012). For the ACL injured participants, males displayed higher knee flexion moments (*p* = 0.002) and knee flexion angle (*p* = 0.011) compared to females (Figure 5.4). Finally, the female ACL injured displayed greater ankle plantar flexion moments compared to the male ACL injured (*p* = 0.0231) (Figure 5.5).

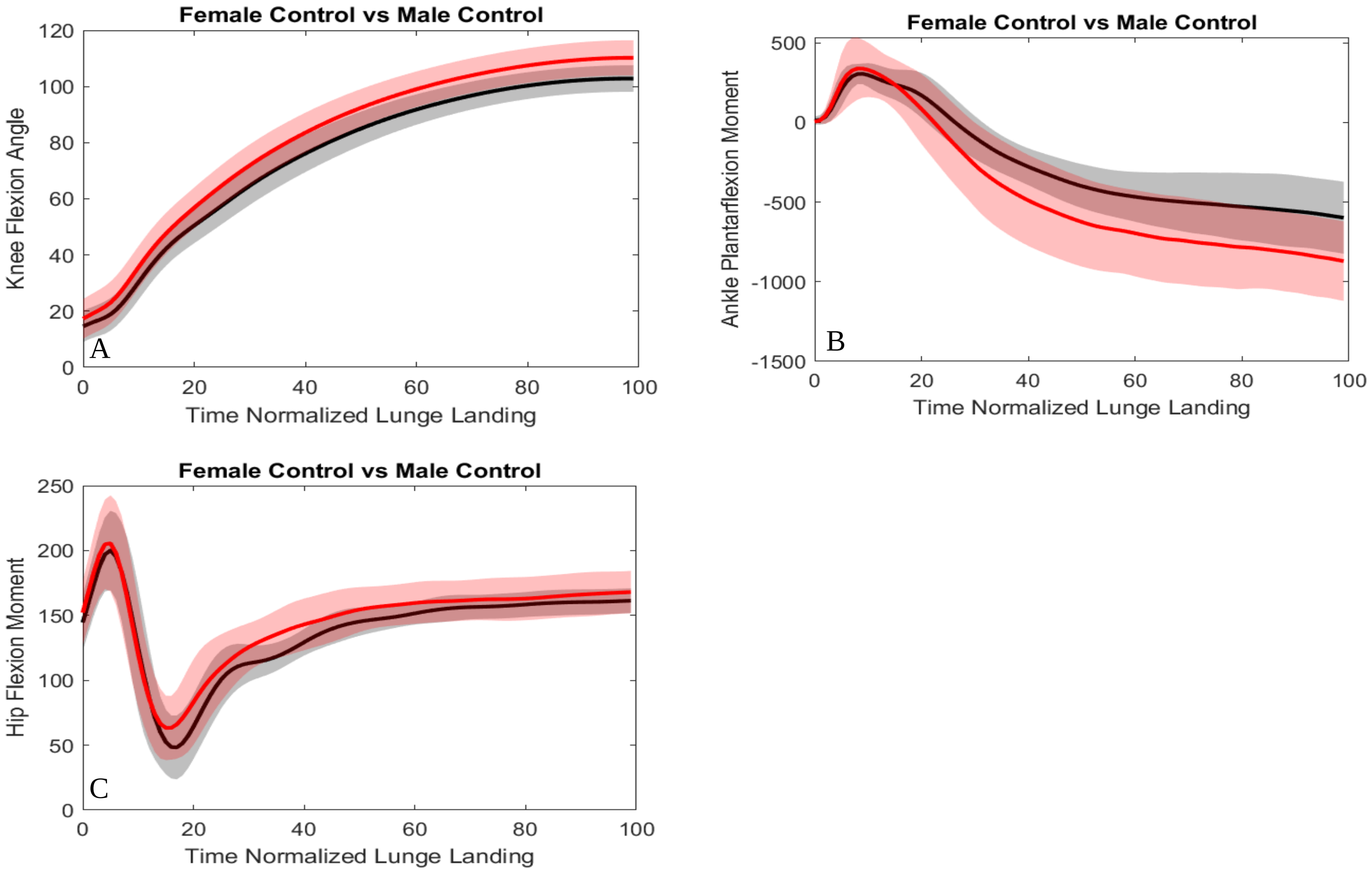

Figure 5.4. Time normalized knee flexion angle (A), ankle plantarflexion moment (B), and hip flexion moment (C) for female and male control participants during the eccentric phase of the lunge task. Black line represents females while the red line represents males.

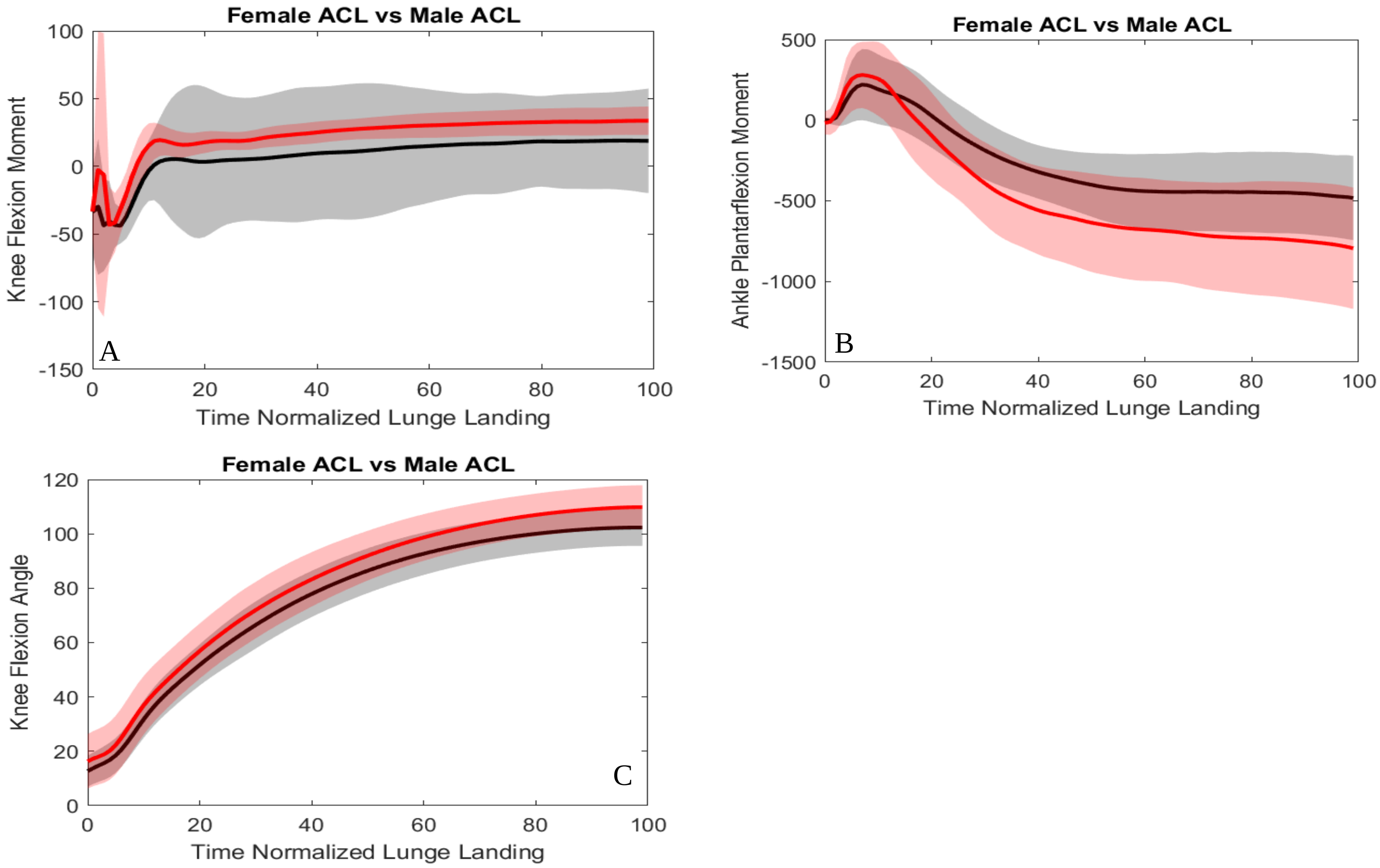

Figure 5.5. Time normalized knee flexion moment (A), ankle plantarflexion moment (B), and knee flexion angle (C) for female and male ACL injured participants during the eccentric phase of the lunge task. Black line represents females while the red line represents males.

Kinematics and Kinetics (ACL Injured vs. Control)

The DVJ task showed no statistically significant differences between the ACL injured and control participants in any of the kinematics nor joint moment comparisons.

The lunge task has one significant difference between the male injured and male control for knee flexion moment with male ACL displaying greater values compared to controls at the beginning of the eccentric phase of movement (p = 0.010) (Figure 5.6).

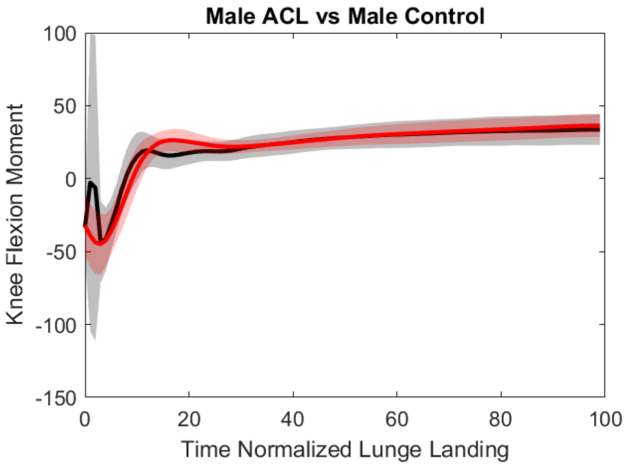

Figure 5.6. Time normalized knee flexion moment for male ACL injured and controls during the eccentric phase of the lunge task. Black line represents ACL injured while the red line represents control participants.

Discussion

The purpose of this study was to compare the torque and energy absorption strategies in adolescent females and males with and without an ACL injury during lunges and DVJs. The results show that ACL injured and female participants display lower knee extension torque values compared to control and male counterparts respectively. For the ankle plantarflexion torque, the control participants displayed higher values compared to ACL injured, as expected, however, there was no statistically significant differences between male and female participants. Therefore, the hypothesis stating that females and ACL injured will display lower peak torques compared to male and control participants in both the knee extension and ankle plantarflexion task was partially supported. Next, the hypothesis stating that females will absorb a higher percentage of energy at the ankle was not supported as there were no statistically significant differences at the ankle for either task. Additionally, the knee did not absorb the greatest percentage of energy. Instead, the hip absorbed the greatest percentage of energy. Finally, the hypothesis that injured individuals will display greater percentages of energy at the hip and ankle was not supported as there were no statistically significant differences at the hip and ankle between any groups. As well, the hypothesis that there will be no difference at the knee joint was partially supported as there was only a significant difference in the energy absorbed at the knee joint between the female control and male control for the DVJ task.

Starting with the isometric strength values, control and male participants displayed increased knee extension values compared to ACL injured and females respectively. These results are to be expected as an ACL injury will compromise muscle strength due to lack of use and females have been shown to lack the pubertal muscular development that has been observed in males (Barber-Westin et al., 2006; Myer et al., 2004; Parker et al., 1990; Quatman et al., 2006; Round et al., 1999). The literature agrees with the results that knee extension strength in the injured limb is weaker after injury compared to the contralateral limb (Kline et al. n.d.; Tengman et al. 2014). As well, Tengman and colleagues (2014) compared the injured limb to control limbs on uninjured participants and found that the injured limb produced lower peak knee extension torque. In terms of sex, the results from Tengman and colleagues (2014) agree with the results from this study stating that females display lower peak knee extension torques compared to male counterparts. Considering that knee extension torque has been associated with lower extremity loading and sagittal plane biomechanics it is important to consider in rehabilitation and injury prevention programs (Lisee et al., 2019). Displaying low knee extension torque may mean that the quadricep muscles are not able to contract as efficiently to protect the ACL (Markolf et al., 2004; Torzilli et al., 1994) and it may, therefore, be dangerous as it could lead to reduced limb symmetry in injured individuals, leading to risk of ACL re-injury (Tengman et al., 2014).

For the ankle plantarflexion torque, it is interesting how there is no statistically significant difference between sexes, however, it could be because recent evidence suggest that the gastrocnemii help to stabilize the knee and minimize ACL loads (Mokhtarzadeh et al., 2013; Morgan et al., 2014). Therefore, this muscle group may not be developing as differently between sexes throughout puberty compared to the major muscle groups (i.e., quadriceps and hamstrings). There is surprisingly little literature on ankle plantarflexion torque in the ACL injured population, however, the literature that does exist disagrees with the results from this study finding no differences in ankle plantarflexion strength between injured and control individuals (Hoch et al., 2019; Thomas et al., 2013). These studies on adults suggest that the plantarflexor muscles heal quickly after injury and are not as affected, explaining the lack of significance (Hoch et al., 2019; Karanikas et al., 2009; Thomas et al., 2013). However, because the gastrocnemii are related to knee flexion, they are relevant to the ACL and since an ACL injury may contribute to weakness in the gastrocnemii due to disuse (Thomas et al., 2013), this potentially explains the significant ankle plantarflexion weakness found in ACL injured individuals compared to controls.

Having muscular strength about the knee joint is important as these muscles will contribute to the knee stabilization during dynamic weight bearing movements and potentially protect the ACL from injury (Snyder-Mackler et al., 1994). Overall, determining which muscles are affected by sex and injury status are crucial to determining appropriate rehabilitation strategies, especially considering how influential lower extremity musculature weakness may be affecting lower extremity control and stability (Thomas et al., 2013).The results from this study suggest that knee extension and ankle plantarflexion torque are important and should continue to be considered in ACL rehabilitation and injury prevention programs as there are clear differences between injured and uninjured individuals. (Agel, Arendt, and Bershadsky 2005; Griffin et al. 2000; Hewett et al. 1999; Ireland 2002; Wiggins et al. 2016).

It was hypothesized that females would absorb a higher percentage of energy at the ankle joint, however, we did not find this. Our results differ from literature which states that adult females will absorb a higher percentage of energy at the ankle compared to adult males (DeVita and Skelly 1992; Schmitz et al. 2007; Zhang, Bates, and Dufek 2000). It was expected that females would absorb more energy at the ankle compared to males because they tend to display greater knee and ankle ROM values (Decker et al., 2003), however, the results from this study suggest that males have greater ankle plantarflexion angles in the DVJ along with greater knee flexion angles in the lunge task compared to females (Norcross et al., 2010). Females did display significantly greater ankle plantarflexion moments compared to males in the lunge task, so it is interesting how they did not absorb a significantly greater amount of energy at the ankle compared to males as well. It is possible that the increased moment allows for greater dissipation of the energy to larger muscles in the lower extremity, allowing the gastrocnemii muscles to stabilize the joint instead of straining the joint by attempting to absorb a larger portion of the energy.

Next, it was hypothesized that the knee would absorb the greatest amount of energy overall. Instead, the results show that the hip absorbed the most energy in all groups. The results disagree with literature, which suggest that, in adults, the knee would absorb the most energy (DeVita & Skelly, 1992; Zhang et al., 2000). However, it has been suggested that because the hip joint is associated with larger muscle groups (i.e., the quadriceps and hamstrings, gluteal muscles), it has a greater ability to absorb a greater amount of energy, specifically during demanding tasks such as a DVJ (Zhang et al., 2000). Relying on the distal joints has been suggested to be a less effective strategy to protect the ACL, therefore the ability to transfer and absorb energy at the proximal joints (i.e., the hip joint) is beneficial to the ACL (Romanchuk, Del Bel, and Benoit 2020).

Finally, there were no statistically significant differences in the energy absorbed at the hip and ankle joints between the control and injured individuals. Contrastingly, literature states that the hip joint of an injured individual will absorb a greater amount of energy compared to an uninjured individual (Boo et al., 2018; Garrison et al., 2018). The utilization of the hip joint to dissipate energy has been inadvertently associated with increasing the strain on the ACL by increasing the utilization of the hip joint to eccentrically decelerate the lower extremity during a landing potentially explaining why injured individual would display greater amount of energy absorbed at the hip joint (Boo et al., 2018) so it is interesting how there were no statistically significant differences. The results about the ankle also contrast with the literature, which states that there is less energy absorbed at the ankle in the injured population compared to controls (Boo et al., 2018). Interestingly, the results from Boo and colleagues (2018) disagrees with the results from Romanchuk and colleagues (2020) which states that the ankle absorbs the greatest amount of energy overall. It is likely that having an increased amount of energy at the ankle in the injured population is due to an increase reliance on distal joints because of insufficient strength and ability to appropriately transfer the energy absorption to the proximal joints (Decker et al. 2003; Romanchuk, del Del Bel, and Benoit 2020; Zhang, Bates, and Dufek 2000). Again, it is interesting how there were no significant differences in the energy absorbed at the ankle. Additionally, there were no relevant statistically significant differences in kinematics or joint moments between the injured and uninjured groups. Additionally, it was hypothesized that there would be no difference in the energy absorbed at the knee joint between the injured and control groups and the only significant difference found was between the female control and male control groups during the DVJ task with males displaying an increased amount of energy at this joint compared to females. There were no kinematic differences between these groups, however, the male controls displayed significantly greater hip flexion moments compared to female controls. This could potentially be related to the increase knee extension torque in the males compared to the females. The lack of difference in the other groups could be because of a decreased ability overall to absorb loads across the knee joint due to limited muscular strength in said joint (Boo et al., 2018) or simply too much variability in the data. Contrastingly, it may be beneficial to absorb less energy at the knee and more at the hip, allowing the energy to be transferred more proximally and dissipated across the joints, therefore protecting the ACL (Romanchuk, del Del Bel, and Benoit 2020).

Methodological Considerations

This study used a small selection of participants from a larger study performed in the Clinical Biomechanics Research Unit to allow for equal sample sizes when performing the statistical analysis. It is important to note that within the male population there is a significant difference in age, weight, and BMI which could have affected the isometric strength and energy absorption results. Future studies could gather more participants to eliminate those statistically significant differences. It is also possible that increasing the sample size will increase the power in the post-hoc testing, which could lead to more significant results. Furthermore, there is limited research on adolescent when it comes to ACL injuries (Boo et al., 2018; Garrison et al., 2018; Romanchuk, del Bel, et al., 2020), the majority of the research is focused on the adult population. Finally, this study matched the percentage of ACL injured individuals who injured their dominant limb to percentage of dominant test limbs in the control population, therefore, this study does not consider any contralateral limb differences within the ACL injured population, which could have some interesting results in regards to ACL rehabilitation. Particularly if you were to consider any between-limb difference pre-injury and post-rehabilitation to evaluate the effectiveness of the rehabilitation.

Conclusion

The overall goal of this study was to evaluate the link between sex and injury status in the adolescent population by first locating where the differences lie within this population for the variables of isometric strength and lower limb energy absorption. There are clear injury status differences in the knee extension and ankle plantarflexion torque and a sex difference for the knee extension torque, therefore, they are important variables to consider in ACL rehabilitation and injury prevention programs. Additionally, while there was not a significant difference between the males and females for the ankle plantarflexion, it may be because the gastrocnemii are recognized as more of a stabilization muscle and are not always used to their full capacity (Hoch et al., 2019; Thomas et al., 2013). Regarding energy absorption, there were limited differences associated with either the sex or injury status, which may be suggesting that energy absorption is not as much of an important variable to consider in adolescent ACL injury rehabilitation and prevention programs. Finally, for the DVJ, the hip absorbed the greatest amount of energy, followed by the knee, and then the ankle for both the injured and control groups; while for the lunge similarly the hip absorbed the greatest amount of energy, however, it was followed by the ankle, and lastly the knee, again, for both the injured and control groups.

References

Agel, J., Arendt, E. A., & Bershadsky, B. (2005). Anterior cruciate ligament injury in National Collegiate Athletic Association basketball and soccer: A 13-year review. In *American Journal of Sports Medicine* (Vol. 33, Issue 4, pp. 524–530). SAGE PublicationsSage CA: Los Angeles, CA. https://doi.org/10.1177/0363546504269937

Agel, J., Rockwood, T., & Klossner, D. (2016). Collegiate ACL Injury Rates Across 15 Sports: National Collegiate Athletic Association Injury Surveillance System Data Update (2004-2005 Through 2012-2013). *Clinical Journal of Sport Medicine*. https://doi.org/10.1097/JSM.0000000000000290

Alentorn-Geli, E., Myer, G. D., Silvers, H. J., Samitier, G., Romero, D., Lázaro-Haro, C., & Cugat, R. (2009). Prevention of non-contact anterior cruciate ligament injuries in soccer players. Part 1: Mechanisms of injury and underlying risk factors. *Knee Surgery, Sports Traumatology, Arthroscopy*, *17*(7), 705–729. https://doi.org/10.1007/s00167-009-0813-1

Alkjar, T., Simonsen, E. B., Peter Magnusson, S., Aagaard, H., & Dyhre-Poulsen, P. (2002). Differences in the movement pattern of a forward lunge in two types of anterior cruciate ligament deficient patients: Copers and non-copers. *Clinical Biomechanics*, *17*(8), 586–593. https://doi.org/10.1016/S0268-0033(02)00098-0

Ardern, C. L., Taylor, N. F., Feller, J. A., & Webster, K. E. (2014). Fifty-five per cent return to competitive sport following anterior cruciate ligament reconstruction surgery: an updated systematic review and meta-analysis including aspects of physical functioning and contextual factors. *British Journal of Sports Medicine*, *48*(21), 1453–1552. https://doi.org/10.1136/bjsports-2013-093398

Barber-Westin, S. D., Noyes, F. R., & Galloway, M. (2006). Jump-land characteristics and muscle strength development in young athletes: A gender comparison of 1140 athletes 9 to 17 years of age. *American Journal of Sports Medicine*. https://doi.org/10.1177/0363546505281242

Beck, N. A., Todd, J., Lawrence, R., Nordin, J. D., Defor, T. A., & Tompkins, M. (2017). ACL Tears in School-Aged Children and Adolescents Over 20 Years. *PEDIATRICS*, *139*(3). https://doi.org/10.1542/peds.2016-1877

Bencke, J., Næsborg, H., Simonsen, E. B., & Klausen, K. (2000). Motor pattern of the knee joint muscles during side-step cutting in European team handball: Influence on muscular co-ordination after an intervention study. *Scandinavian Journal of Medicine and Science in Sports*. https://doi.org/10.1034/j.1600-0838.2000.010002068.x

Benjamini, Y., & Hochberg, Y. (1995). Controlling the False Discovery Rate: A Practical and Powerful Approach to Multiple Testing. *Journal of the Royal Statistical Society: Series B (Methodological)*, *57*(1), 289–300. https://doi.org/10.1111/J.2517-6161.1995.TB02031.X

Biscarini, A., Botti, F. M., & Pettorossi, V. E. (2013). Selective contribution of each hamstring muscle to anterior cruciate ligament protection and tibiofemoral joint stability in leg-extension exercise: A simulation study. *European Journal of Applied Physiology*, *113*(9), 2263–2273. https://doi.org/10.1007/s00421-013-2656-1

Bisseling, R. W., & Hof, A. L. (2006). Handling of impact forces in inverse dynamics. *Journal of Biomechanics*. https://doi.org/10.1016/j.jbiomech.2005.07.021

Bizzini, M., Impellizzeri, F. M., Dvorak, J., Bortolan, L., Schena, F., Modena, R., & Junge, A. (2013). Physiological and performance responses to the "FIFA 11+" (part 1): is it an appropriate warm-up? *Journal of Sports Sciences*, *31*(13), 1481–1490. https://doi.org/10.1080/02640414.2013.802922

Boden, B. P., Dean, C. S., Feagin, J. A., & Garrett, W. E. (2000). Mechanisms of anterior cruciate ligament injury. *Orthopedics*, *23*(6), 573–578. https://doi.org/10.3928/0147-7447-20000601-15

Boo, M. E., Garrison, J. C., Hannon, J. P., Creed, K. M., Goto, S., Grondin, A. N., & Bothwell, J. M. (2018). Energy Absorption Contribution and Strength in Female Athletes at Return to Sport After Anterior Cruciate Ligament Reconstruction: Comparison With Healthy Controls. *Orthopaedic Journal of Sports Medicine*, *6*(3). https://doi.org/10.1177/2325967118759522

Buckthorpe, M. (2019). Optimising the Late-Stage Rehabilitation and Return-to-Sport Training and Testing Process After ACL Reconstruction. *Sports Medicine*, *49*, 1043–1058. https://doi.org/10.1007/s40279-019-01102-z

Butler, D. (1980). Ligamentous restraints to anterior drawer in the human knee : a biomechanical study . J Bone Joint Surg. *The Journal of Bone and Joint Surgery*, *62*(November 2015), 259–270.

Cesar, G. M., Tomasevicz, C. L., & Burnfield, J. M. (2016). Frontal plane comparison between drop jump and vertical jump: implications for the assessment of ACL risk of injury. *Sports Biomechanics*, *15*(4), 440–449. https://doi.org/10.1080/14763141.2016.1174286

Decker, M. J., Torry, M. R., Wyland, D. J., Sterett, W. I., & Steadman, J. R. (2003). Gender differences in lower extremity kinematics, kinetics and energy absorption during landing. *Clinical Biomechanics*. https://doi.org/10.1016/S0268-0033(03)00090-1

Del Bel, M. J., Kemp, L. G., Girard, C. I., Rossignol, J., Goulet, S. F., Bourgon, J.-F., Carsen, S., & Benoit, D. L. (2020). Translation and Validation of the Hospital for Special Surgery Pediatric Functional Activity Brief Scale for French Paediatric Populations. *Physiotherapy Canada*. https://doi.org/10.3138/ptc-2019-0033

DeVita, P., & Skelly, W. A. (1992). Effect of landing stiffness on joint kinetics and energetics in the lower extremity. *Medicine and Science in Sports and Exercise*, *24*(1), 108–115. https://doi.org/10.1249/00005768-199201000-00018

Dodwell, E. R., Lamont, L. E., Green, D. W., Pan, T. J., Marx, R. G., & Lyman, S. (2014). 20 years of pediatric anterior cruciate ligament reconstruction in New York state. *American Journal of Sports Medicine*, *42*(3), 675–680. https://doi.org/10.1177/0363546513518412

Duthon, V. B., Barea, C., Abrassart, S., Fasel, J. H., Fritschy, D., & Ménétrey, J. (2006). Anatomy of the anterior cruciate ligament. In *Knee Surgery, Sports Traumatology, Arthroscopy* (Vol. 14, Issue 3, pp. 204–213). https://doi.org/10.1007/s00167-005-0679-9

Ekstrom, R. A., Donatelli, R. A., & Carp, K. C. (2007). Electromyographic analysis of core trunk, hip, and thigh muscles during 9 rehabilitation exercises. *Journal of Orthopaedic and Sports Physical Therapy*. https://doi.org/10.2519/jospt.2007.2471

Fabricant, P. D., Robles, A., Downey-Zayas, T., Do, H. T., Marx, R. G., Widmann, R. F., & Green, D. W. (2013). Development and validation of a pediatric sports activity rating scale: The hospital for special surgery pediatric functional activity brief scale (HSS Pedi-FABS). *American Journal of Sports Medicine*, *41*(10), 2421–2429. https://doi.org/10.1177/0363546513496548

Failla, M. J., Arundale, A. J. H., Logerstedt, D. S., & Snyder-Mackler, L. (2015). Controversies in knee rehabilitation. Anterior cruciate ligament injury. In *Clinics in Sports Medicine* (Vol. 34, Issue 2, pp. 301–312). W.B. Saunders. https://doi.org/10.1016/j.csm.2014.12.008

Field, A. (2013). Discovering statistics using IBM SPSS statistics. In *Statistics*.

Flaxman, T. E., AlkjÆr, T., Simonsen, E. B., Krogsgaard, M. R., & Benoit, D. L. (2017). Predicting the Functional Roles of Knee Joint Muscles from Internal Joint Moments. *Medicine and Science in Sports and Exercise*. https://doi.org/10.1249/MSS.0000000000001125

Fleming, B. C., Beynnon, B. D., Nichols, C. E., Johnson, R. J., & Pope, M. H. (1993). An in vivo comparison of anterior tibial translation and strain in the anteromedial band of the anterior cruciate ligament. *Journal of Biomechanics*, *26*(1), 51–58. https://doi.org/10.1016/0021-9290(93)90612-I

Fleming, B. C., Renstrom, P. A., Beynnon, B. D., Engstrom, B., Peura, G. D., Badger, G. J., & Johnson, R. J. (2001). The effect of weightbearing and external loading on anterior cruciate ligament strain. *Journal of Biomechanics*, *34*(2), 163–170. https://doi.org/10.1016/S0021-9290(00)00154-8

Fleming, B. C., Renstrom, P. A., Ohlen, G., Johnson, R. J., Peura, G. D., Beynnon, B. D., & Badger, G. J. (2001). The gastrocnemius muscle is an antagonist of the anterior cruciate ligament. *Journal of Orthopaedic Research*, *19*(6), 1178–1184. https://doi.org/10.1016/S0736-0266(01)00057-2

Ford, K. R., Shapiro, R., Myer, G. D., Van Den Bogert, A. J., & Hewett, T. E. (2010). Longitudinal Sex Differences during Landing in Knee Abduction in Young Athletes. *Med Sci Sports Exerc*, *42*(10), 1923–1931. https://doi.org/10.1249/MSS.0b013e3181dc99b1

Garrison, J. C., Hannon, J., Goto, S., Giesler, L., Bush, C., & Bothwell, J. M. (2018). Participants at three months post-operative anterior cruciate ligament reconstruction (ACL-R) demonstrate differences in lower extremity energy absorption contribution and quadriceps strength compared to healthy controls. *Knee*, *25*(5), 782–789. https://doi.org/10.1016/j.knee.2018.06.014

Gianotti, S. M., Marshall, S. W., Hume, P. A., & Bunt, L. (2009). Incidence of anterior cruciate ligament injury and other knee ligament injuries: A national population-based study. *Journal of Science and Medicine in Sport*. https://doi.org/10.1016/j.jsams.2008.07.005

Gregoire, L., Veeger, H., Huijing, P., & van Ingen Schenau, G. (1984). Role of Mono-and Biarticular Muscles in Explosive Movements. In *Int J Sports Med* (Vol. 5, Issue 6).

Griffin, L. Y., Agel, J., Albohm, M. J., Arendt, E. A., Dick, R. W., Garrett, W. E., Garrick, J. G., Hewett, T. E., Huston, L., Ireland, M. L., Johnson, R. J., Kibler, W. B., Lephart, S., Lewis, J. L., Lindenfeld, T. N., Mandelbaum, B. R., Marchak, P., Teitz, C. C., & Wojtys, E. M. (2000). Noncontact anterior cruciate ligament injuries: risk factors and prevention strategies. In *The Journal of the American Academy of Orthopaedic Surgeons*. https://doi.org/10.5435/00124635-200005000-00001

Haddas, R., James, C. R., & Hooper, T. L. (2015). Lower extremity fatigue, sex, and landing performance in a population with recurrent low back pain. *Journal of Athletic Training*. https://doi.org/10.4085/1062-6050-49.3.61

Herzog, M. M., Marshall, S. W., Lund, J. L., Pate, V., Mack, C. D., & Spang, J. T. (2017). Incidence of anterior cruciate ligament reconstruction among adolescent females in the United States, 2002 through 2014. *JAMA Pediatrics*. https://doi.org/10.1001/jamapediatrics.2017.0740

Herzog, W., & Read, L. J. (1993). Lines of action and moment arms of the major force-carrying structures crossing the human knee joint. *Journal of Anatomy*, *182 (Pt 2)*(Pt 2), 213–230.

Hewett, T. E., Lindenfeld, T. N., Riccobene, J. v., & Noyes, F. R. (1999). The effect of neuromuscular training on the incidence of knee injury in female athletes. A prospective study. *American Journal of Sports Medicine*, *27*(6), 699–706. https://doi.org/10.1177/03635465990270060301

Hewett, T. E., Myer, G. D., & Ford, K. R. (2004). Decrease in Neuromuscular Control About the Knee with Maturation in female athletes. *J Bone Joint Surg Am*, *86-A*(8), 1601–1608. https://journals.lww.com/jbjsjournal/Abstract/2004/08000/Decrease_in_Neuromuscular_Control_About_the_Knee.1.aspx

Hewett, T. E., Myer, G. D., Ford, K. R., Heidt, R. S., Colosimo, A. J., McLean, S. G., Van Den Bogert, A. J., Paterno, M. V, & Succop, P. (2005). Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes: A prospective study. *American Journal of Sports Medicine*, *33*(4), 492–501. https://doi.org/10.1177/0363546504269591

Hewett, T. E., Myer, G. D., Kiefer, A. W., Ford, K. R., Myer, G. D., Kiefer, A. W., & Ford, K. R. (2015). Longitudinal Increases in Knee Abduction Moments in Females during Adolescent Growth. *Med. Sci. Sports Exerc*, *47*(12), 2579–2585. https://doi.org/10.1249/MSS.0000000000000700

Hewett, T. E., Stroupe, A. L., Nance, T. A., & Noyes, F. R. (1996). Plyometric training in female athletes: Decreased impact forces and increased hamstring torques. *American Journal of Sports Medicine*, *24*(6), 765–773. https://doi.org/10.1177/036354659602400611

Hirokawa, S., Solomonow, M., Yun lu, Lou, Z. P., & D'Ambrosia, R. (1992). Anterior-posterior and rotational displacement of the tibia elicited by quadriceps contraction. *The American Journal of Sports Medicine*. https://doi.org/10.1177/036354659202000311

Hoch, J. M., Baez, S. E., & Hoch, M. C. (2019). Examination of ankle function in individuals with a history of ACL reconstruction. *Physical Therapy in Sport : Official Journal of the Association of Chartered Physiotherapists in Sports Medicine*, *36*, 55–61. https://doi.org/10.1016/J.PTSP.2019.01.002

Hof, A. L. (1996). Scaling gait data to body size. *Gait and Posture*, *4*(3), 222–223. https://doi.org/10.1016/0966-6362(95)01057-2

Huston, L. J., & Wojtys, E. M. (1996). Neuromuscular Performance Characteristics in Elite Female Athletes. *The American Journal of Sports Medicine*, *24*(4), 427–436. https://doi.org/10.1177/036354659602400405

Impellizzeri, F. M., Bizzini, M., Dvorak, J., Pellegrini, B., Schena, F., & Junge, A. (2013). Physiological and performance responses to the FIFA 11+ (part 2): a randomised controlled trial on the training effects. *Journal of Sports Sciences*, *31*(13), 1491–1502. https://doi.org/10.1080/02640414.2013.802926

Ireland, M. L. (2002). The female ACL: Why is it more prone to injury? *Journal of Orthopaedics*, *33*(4), 637–651. https://doi.org/10.1016/S0972-978X(16)00023-4

Jacobs, R., Bobbert, M. F., & van Ingen Schenau, G. J. (1996). Mechanical output from individual muscles during explosive leg extensions: The role of biarticular muscles. *Journal of Biomechanics*, *29*(4), 513–523. https://doi.org/10.1016/0021-9290(95)00067-4

Jönhagen, S., Halvorsen, K., & Benoit, D. L. (2009). Muscle activation and length changes during two lunge exercises: implications for rehabilitation. *Scandinavian Journal of Medicine & Science in Sports*, *19*(4), 561–568. https://doi.org/10.1111/J.1600-0838.2007.00692.X

Kain, C. C., McCarthy, J. A., Arms, S., Pope, M. H., Steadman, J. R., Manske, P. R., & Shively, R. A. (1988). An in vivo analysis of the effect of transcutaneous electrical stimulation of the quadriceps and hamstrings on anterior cruciate ligament deformation. *The American Journal of Sports Medicine*, *16*(2), 147–152. https://doi.org/10.1177/036354658801600210

Karanikas, K., Arampatzis, A., & Brüggemann, G. P. (2009). Motor task and muscle strength followed different adaptation patterns after anterior cruciate ligament reconstruction. *European Journal of Physical and Rehabilitation Medicine*, *45*(1).

Kline, P. W., Morgan, K., Johnson, D. L., Ireland, M. L., & Noehren, B. (n.d.). *Impaired quadriceps rate of torque development and knee mechanics after anterior cruciate ligament reconstruction with patellar tendon autograft*. https://doi.org/10.1177/0363546515595834

Kocher, M. S., Smith, J. T., Iversen, M. D., Brustowicz, K., Ogunwole, O., Andersen, J., Yoo, W. J., McFeely, E. D., Anderson, A. F., & Zurakowski, D. (2011). Reliability, validity, and responsiveness of a modified International Knee Documentation Committee Subjective Knee Form (Pedi-IKDC) in children with knee disorders. *The American Journal of Sports Medicine*, *39*(5), 933–939. https://doi.org/10.1177/0363546510383002

Kristianslund, E., Krosshaug, T., & Van den Bogert, A. J. (2012). Effect of low pass filtering on joint moments from inverse dynamics: Implications for injury prevention. *Journal of Biomechanics*. https://doi.org/10.1016/j.jbiomech.2011.12.011

Landry, S. C., McKean, K. A., Hubley-Kozey, C. L., Stanish, W. D., & Deluzio, K. J. (2007a). Neuromuscular and lower limb biomechanical differences exist between male and female elite adolescent soccer players during an unanticipated run and crosscut maneuver. *American Journal of Sports Medicine*, *35*(11). https://doi.org/10.1177/0363546507307400

Landry, S. C., McKean, K. A., Hubley-Kozey, C. L., Stanish, W. D., & Deluzio, K. J. (2007b). Neuromuscular and lower limb biomechanical differences exist between male and female elite adolescent soccer players during an unanticipated side-cut maneuver. *American Journal of Sports Medicine*, *35*(11). https://doi.org/10.1177/0363546507300823

Li, G., Rudy, T. W., Sakane, M., Kanamori, A., Ma, C. B., & Woo, S. L. Y. (1999). The importance of quadriceps and hamstring muscle loading on knee kinematics and in-situ forces in the ACL. *Journal of Biomechanics*, *32*(4), 395–400. https://doi.org/10.1016/S0021-9290(98)00181-X

Liederbach, M., Kremenic, I. J., Orishimo, K. F., Pappas, E., & Hagins, M. (2014). Comparison of landing biomechanics between male and female dancers and athletes, part 2: Influence of fatigue and implications for anterior cruciate ligament injury. *American Journal of Sports Medicine*, *42*(5), 1089–1095. https://doi.org/10.1177/0363546514524525

Lisee, C., Birchmeier, T., Yan, A., & Kuenze, C. (2019). Associations between isometric quadriceps strength characteristics, knee flexion angles, and knee extension moments during single leg step down and landing tasks after anterior cruciate ligament reconstruction. *Clinical Biomechanics*, *70*, 231–236. https://doi.org/10.1016/J.CLINBIOMECH.2019.10.012

Lloyd, D. G., & Buchanan, T. S. (2001). Strategies of muscular support of varus and valgus isometric loads at the human knee. *Journal of Biomechanics*. https://doi.org/10.1016/S0021-9290(01)00095-1

Lloyd, D. G., Buchanan, T. S., & Besier, T. F. (2005). Neuromuscular biomechanical modeling to understand knee ligament loading. *Medicine and Science in Sports and Exercise*, *37*(11), 1939–1947. https://doi.org/10.1249/01.MSS.0000176676.49584.BA

MacWilliams, B. A., Wilson, D. R., Desjardins, J. D., Romero, J., & Chao, E. Y. S. (1999). Hamstrings cocontraction reduces internal rotation, anterior translation, and anterior cruciate ligament load in weight-bearing flexion. *Journal of Orthopaedic Research*, *17*(6), 817–822. https://doi.org/10.1002/jor.1100170605

Mantovani, G., & Lamontagne, M. (2017). How Different Marker Sets Affect Joint Angles in Inverse Kinematics Framework. *Journal of Biomechanical Engineering*. https://doi.org/10.1115/1.4034708

Markatos, K., Kaseta, M. K., Lallos, S. N., Korres, D. S., & Efstathopoulos, N. (2013). The anatomy of the ACL and its importance in ACL reconstruction. In *European Journal of Orthopaedic Surgery and Traumatology* (Vol. 23, Issue 7, pp. 747–752). Eur J Orthop Surg Traumatol. https://doi.org/10.1007/s00590-012-1079-8

Markolf, K. L., Graff-Radford, A., & Amstutz, H. C. (1978). In vivo knee stability. A quantitative assessment using an instrumented clinical testing apparatus. *Journal of Bone and Joint Surgery - Series A*. https://doi.org/10.2106/00004623-197860050-00014

Markolf, K. L., O’Neill, G., Jackson, S. R., & McAllister, D. R. (2004). Effects of applied quadriceps and hamstrings muscle loads on forces in the anterior and posterior cruciate ligaments. *American Journal of Sports Medicine*. https://doi.org/10.1177/0363546503262198

McLean, S. G., Huang, X., & Van Den Bogert, A. J. (2005). Association between lower extremity posture at contact and peak knee valgus moment during sidestepping: Implications for ACL injury. *Clinical Biomechanics*. https://doi.org/10.1016/j.clinbiomech.2005.05.007

Mokhtarzadeh, H., Yeow, C. H., Hong Goh, J. C., Oetomo, D., Malekipour, F., & Lee, P. V. S. (2013). Contributions of the Soleus and Gastrocnemius muscles to the anterior cruciate ligament loading during single-leg landing. *Journal of Biomechanics*, *46*(11), 1913–1920. https://doi.org/10.1016/j.jbiomech.2013.04.010

Montgomery, C., Blackburn, J., Withers, D., Tierney, G., Moran, C., & Simms, C. (2018). Mechanisms of ACL injury in professional rugby union: A systematic video analysis of 36 cases. *British Journal of Sports Medicine*, *52*(15), 994–1001. https://doi.org/10.1136/bjsports-2016-096425

Montgomery, M. M., Shultz, S. J., & Schmitz, R. J. (2014). The effect of equalizing landing task demands on sex differences in lower extremity energy absorption. *Clinical Biomechanics*, *29*(7), 760–766. https://doi.org/10.1016/j.clinbiomech.2014.06.004

Morgan, K. D., Donnelly, C. J., & Reinbolt, J. A. (2014). Elevated gastrocnemius forces compensate for decreased hamstrings forces during the weight-acceptance phase of single-leg jump landing: Implications for anterior cruciate ligament injury risk. *Journal of Biomechanics*, *47*(13), 3295–3302. https://doi.org/10.1016/j.jbiomech.2014.08.016

Myer, G. D., Ford, K. R., & Hewett, T. E. (2004). Rationale and clinical techniques for anterior cruciate ligament injury prevention among female athletes. *Journal of Athletic Training*.

Myer, G. D., Ford, K. R., McLean, S. G., & Hewett, T. E. (2006). The effects of plyometric versus dynamic stabilization and balance training on lower extremity biomechanics. *American Journal of Sports Medicine*. https://doi.org/10.1177/0363546505281241

Myklebust, G., Maehlum, S., Holm, I., & Bahr, R. (2007). A prospective cohort study of anterior cruciate ligament injuries in elite Norwegian team handball. *Scandinavian Journal of Medicine & Science in Sports*, *8*(3), 149–153. https://doi.org/10.1111/j.1600-0838.1998.tb00185.x

Navacchia, A., Ueno, R., Ford, K. R., DiCesare, C. A., Myer, G. D., & Hewett, T. E. (2019). EMG-Informed Musculoskeletal Modeling to Estimate Realistic Knee Anterior Shear Force During Drop Vertical Jump in Female Athletes. *Annals of Biomedical Engineering*, *47*(12), 2416–2430. https://doi.org/10.1007/S10439-019-02318-W

Nogaro, M. C., Abram, S. G. F., Alvand, A., Bottomley, N., Jackson, W. F. M., & Price, A. (2020). Paediatric and adolescent anterior cruciate ligament reconstruction surgery. *The Bone & Joint Journal*, *102-B*(2), 239–245. https://doi.org/10.1302/0301-620X.102B2.BJJ-2019-0420.R2

Norcross, M. F., Blackburn, J. T., Goerger, B. M., & Padua, D. A. (2010). The association between lower extremity energy absorption and biomechanical factors related to anterior cruciate ligament injury. *Clinical Biomechanics*, *25*(10), 1031–1036. https://doi.org/10.1016/j.clinbiomech.2010.07.013

Padua, D. A., Marshall, S. W., Boling, M. C., Thigpen, C. A., William E. Garrett, J., & Beutler, A. I. (2009). The Landing Error Scoring System (LESS) Is a Valid and Reliable Clinical Assessment Tool of Jump-Landing Biomechanics: The JUMP-ACL Study. *Https://Doi.Org/10.1177/0363546509343200*, *37*(10), 1996–2002. https://doi.org/10.1177/0363546509343200

Parker, D. F., Round, J. M., Sacco, P., & Jones, D. A. (1990). A Cross-sectional survey of upper and lower limb strength in boys and girls during childhood and adolescence. *Annals of Human Biology*, *17*(3), 199–211. https://doi.org/10.1080/03014469000000962

Pataky, T. C., Robinson, M. A., & Vanrenterghem, J. (2013). Vector field statistical analysis of kinematic and force trajectories. *Journal of Biomechanics*, *46*(14), 2394–2401. https://doi.org/10.1016/j.jbiomech.2013.07.031

Petushek, E. J., Sugimoto, D., Stoolmiller, M., Smith, G., & Myer, G. D. (2019). Evidence-Based Best-Practice Guidelines for Preventing Anterior Cruciate Ligament Injuries in Young Female Athletes: A Systematic Review and Meta-analysis. *American Journal of Sports Medicine*, *47*(7), 1744–1753. https://doi.org/10.1177/0363546518782460

Pollard, C. D., Sigward, S. M., & Powers, C. M. (2017). ACL Injury Prevention Training Results in Modification of Hip and Knee Mechanics During a Drop-Landing Task. *Orthopaedic Journal of Sports Medicine*, *5*(9). https://doi.org/10.1177/2325967117726267

Powell, J. W., & Barber-Foss, K. D. (2000a). Sex-related injury patterns among selected high school sports. *American Journal of Sports Medicine*. https://doi.org/10.1177/03635465000280031801

Powell, J. W., & Barber-Foss, K. D. (2000b). Sex-related injury patterns among selected high school sports. *American Journal of Sports Medicine*. https://doi.org/10.1177/03635465000280031801

Quatman, C. E., Ford, K. R., Myer, G. D., & Hewett, T. E. (2006). Maturation leads to gender differences in landing force and vertical jump performance: A longitudinal study. *American Journal of Sports Medicine*. https://doi.org/10.1177/0363546505281916

Renstrom, P., Ljungqvist, A., Arendt, E., Beynnon, B., Fukubayashi, T., Garrett, W., Georgoulis, T., Hewett, T. E., Johnson, R., Krosshaug, T., Mandelbaum, B., Micheli, L., Myklebust, G., Roos, E., Roos, H., Schamasch, P., Shultz, S., Werner, S., Wojtys, E., & Engebretsen, L. (2008a). Non-contact ACL injuries in female athletes: An International Olympic Committee current concepts. *British Journal of Sports Medicine*. https://doi.org/10.1136/bjsm.2008.048934

Renstrom, P., Ljungqvist, A., Arendt, E., Beynnon, B., Fukubayashi, T., Garrett, W., Georgoulis, T., Hewett, T. E., Johnson, R., Krosshaug, T., Mandelbaum, B., Micheli, L., Myklebust, G., Roos, E., Roos, H., Schamasch, P., Shultz, S., Werner, S., Wojtys, E., & Engebretsen, L. (2008b). Non-contact ACL injuries in female athletes: An International Olympic Committee current concepts. *British Journal of Sports Medicine*. https://doi.org/10.1136/bjsm.2008.048934

Report Card Development Team. (2018). *The 2018 ParticipACTION Report Card on Physical Activity for Children and Youth*.

Romanchuk, N. J., Bel, M. J. Del, & Benoit, D. L. (2020). SEX-SPECIFIC ENERGY ABSORPTION STRATEGIES DURING UNANTICIPATED SINGLE-LEG LANDINGS IN ADOLESCENTS: IMPLICATIONS FOR KNEE INJURIES. *Orthopaedic Journal of Sports Medicine*, *8*(4_suppl3), 2325967120S0023. https://doi.org/10.1177/2325967120s00237

Romanchuk, N. J., del Bel, M. J., & Benoit, D. L. (2020). Sex-specific landing biomechanics and energy absorption during unanticipated single-leg drop-jumps in adolescents: implications for knee injury mechanics. *Journal of Biomechanics*, 110064. https://doi.org/10.1016/j.jbiomech.2020.110064

Round, J. M., Jones, D. A., Honour, J. W., & Nevill, A. M. (1999). Hormonal factors in the development of differences in strength between boys and girls during adolescence: A longitudinal study. *Annals of Human Biology*, *26*(1), 49–62. https://doi.org/10.1080/030144699282976

Sale, D., Quinlan, J., Marsh, E., McComas, A. J., & Belanger, A. Y. (1982). Influence of joint position on ankle plantarflexion in humans. *Journal of Applied Physiology Respiratory Environmental and Exercise Physiology*. https://doi.org/10.1152/jappl.1982.52.6.1636

Sanders, T. L., Maradit Kremers, H., Bryan, A. J., Larson, D. R., Dahm, D. L., Levy, B. A., Stuart, M. J., & Krych, A. J. (2016). Incidence of anterior cruciate ligament tears and reconstruction: A 21-year population-based study. *American Journal of Sports Medicine*, *44*(6), 1502–1507. https://doi.org/10.1177/0363546516629944

Scheffler, S. (2012). The cruciate ligaments: Anatomy, biology, and biomechanics. In *The Knee Joint: Surgical Techniques and Strategies* (Vol. 9782287993, pp. 11–21). https://doi.org/10.1007/978-2-287-99353-4_2

Schmitz, R. J., Kulas, A. S., Perrin, D. H., Riemann, B. L., & Shultz, S. J. (2007). Sex differences in lower extremity biomechanics during single leg landings. *Clinical Biomechanics*, *22*(6), 681–688. https://doi.org/10.1016/j.clinbiomech.2007.03.001

Sepúlveda, F., Sánchez, L., Amy, E., & Micheo, W. (2017). Anterior cruciate ligament injury: Return to play, function and long-term considerations. *Current Sports Medicine Reports*, *16*(3), 172–178. https://doi.org/10.1249/JSR.0000000000000356

Shea, K. G., Pfeiffer, R., Jo, H. W., Curtin, M., & Apel, P. J. (2004). Anterior cruciate ligament injury in pediatric and adolescent soccer players: An analysis of insurance data. *Journal of Pediatric Orthopaedics*. https://doi.org/10.1097/01241398-200411000-00005

Shultz, S. J. (2008). Differences in Lower Extremity Anatomical and Postural Characteristics in Males and Females Between Maturation Groups. *J Orthop Sports Phys Ther*, *38*(3), 137–149. https://doi.org/10.2519/jospt.2008.2645

Sinclair, J., Brooks, D., & Stainton, · Philip. (2019). Sex differences in ACL loading and strain during typical athletic movements: a musculoskeletal simulation analysis. *European Journal of Applied Physiology*, *119*(3), 713–721. https://doi.org/10.1007/s00421-018-04062-w

Slauterbeck, J. R., Hickox, J. R., Beynnon, B., & Hardy, D. M. (2006). Anterior Cruciate Ligament Biology and Its Relationship to Injury Forces. In *Orthopedic Clinics of North America* (Vol. 37, Issue 4, pp. 585–591). https://doi.org/10.1016/j.ocl.2006.09.001

Snyder-Mackler, L., Delitto, A., Stralka, S. W., & Bailey, S. L. (1994). Use of electrical stimulation to enhance recovery of quadriceps femoris muscle force production in patients following anterior cruciate ligament reconstruction. *Physical Therapy*, *74*(10), 901–907. https://doi.org/10.1093/ptj/74.10.901

Steffen, K., Nilstad, A., Kristianslund, E. K., Myklebust, G., Bahr, R., & Krosshaug, T. (2016). Association between lower extremity muscle strength and noncontact ACL injuries.

Medicine and Science in Sports and Exercise, 48(11), 2082–2089. https://doi.org/10.1249/MSS.0000000000001014

Takahashi, S., Nagano, Y., Ito, W., Kido, Y., & Okuwaki, T. (2019). A retrospective study of mechanisms of anterior cruciate ligament injuries in high school basketball, handball, judo, soccer, and volleyball. *Medicine, 98*(26), e16030. https://doi.org/10.1097/MD.0000000000016030

Taylor, S. J. C., Whincup, P. H., Hindmarsh, P. C., Lampe, F., Odoki, K., & Cook, D. G. (2001). Performance of a new pubertal self-assessment questionnaire: A preliminary study. *Paediatric and Perinatal Epidemiology, 15*(1), 88–94. https://doi.org/10.1046/j.1365-3016.2001.00317.x

Tegner, Y., & Lysholm, J. (1985). Rating systems in the evaluation of knee ligament injuries. *Clinical Orthopaedics and Related Research*. https://doi.org/10.1097/00003086-198509000-00007

Tengman, E., Brax Olofsson, L., Stensdotter, A. K., Nilsson, K. G., & Häger, C. K. (2014). Anterior cruciate ligament injury after more than 20 years. II. Concentric and eccentric knee muscle strength. *Scandinavian Journal of Medicine and Science in Sports, 24*(6), e501-509. https://doi.org/10.1111/SMS.12215

Thomas, A. C., Villwock, M., Wojtys, E. M., & Palmieri-Smith, R. M. (2013). Lower Extremity Muscle Strength After Anterior Cruciate Ligament Injury and Reconstruction. *Journal of Athletic Training, 48*(5), 610–620. https://doi.org/10.4085/1062-6050-48.3.23

Torzilli, P. A., Xianghua Deng, & Warren, R. F. (1994). The Effect of Joint-Compressive Load and Quadriceps Muscle Force on Knee Motion in the Intact and Anterior Cruciate Ligament-Sectioned Knee. *The American Journal of Sports Medicine*, *22*(1), 105–112. https://doi.org/10.1177/036354659402200117

van Melick, N., H van Cingel, R. E., Brooijmans, F., Neeter, C., van Tienen, T., Hullegie, W., & G Nijhuis-van der Sanden, M. W. (2016). Evidence-based clinical practice update: practice guidelines for anterior cruciate ligament rehabilitation based on a systematic review and multidisciplinary consensus. *British Journal of Sports Medicine*, *50*, 1506–1515. https://doi.org/10.1136/bjsports-2015-095898

van Melick, N., Meddeler, B. M., Hoogeboom, T. J., Nijhuis-van der Sanden, M. W. G., & van Cingel, R. E. H. (2017). How to determine leg dominance: The agreement between self-reported and observed performance in healthy adults. *PLoS ONE*. https://doi.org/10.1371/journal.pone.0189876

Waldén, M., Krosshaug, T., Bjørneboe, J., Andersen, T. E., Faul, O., & Hägglund, M. (2015). Three distinct mechanisms predominate in noncontact anterior cruciate ligament injuries in male professional football players: A systematic video analysis of 39 cases. *British Journal of Sports Medicine*, *49*(22), 1452–1460. https://doi.org/10.1136/bjsports-2014-094573

Webster, K. E., Feller, J. A., & Lambros, C. (2008). Development and preliminary validation of a scale to measure the psychological impact of returning to sport following anterior cruciate ligament reconstruction surgery. *Physical Therapy in Sport*, *9*, 9–15. https://doi.org/10.1016/j.ptsp.2007.09.003

Werner, B. C., Yang, S., Looney, A. M., & Gwathmey, F. W. (2016). Trends in pediatric and adolescent anterior cruciate ligament injury and reconstruction. *Journal of Pediatric Orthopaedics*. https://doi.org/10.1097/BPO.0000000000000482

Wiggins, A. J., Grandhi, R. K., Schneider, D. K., Stanfield, D., Webster, K. E., & Myer, G. D. (2016). Risk of Secondary Injury in Younger Athletes after Anterior Cruciate Ligament Reconstruction. In *American Journal of Sports Medicine* (Vol. 44, Issue 7, pp. 1861–1876). https://doi.org/10.1177/0363546515621554

Wild, C. Y., Steele, J. R., & Munro, B. J. (2013). Musculoskeletal and Estrogen Changes during the Adolescent Growth Spurt in Girls. *Medicine & Science in Sports & Exercise*, *45*(1), 138–145. https://doi.org/10.1249/MSS.0b013e31826a507e

Wingfield, K. (2013). Neuromuscular Training to prevent knee injuries in adolescent female soccer players. *Clinical Journal of Sport Medicine*. https://doi.org/10.1097/01.jsm.0000433153.51313.6b

Winter, D. A. (2009). Mechanical Work, Energy, and Power. In *Biomechanics and Motor Control of Human Movement*. https://doi.org/10.1002/9780470549148.ch6

Worrell, T. W., Karst, G., Adamczyk, D., Moore, R., Stanley, C., Steimel, B., & Steimel, S. (2001). Influence of joint position on electromyographic and torque generation during maximal voluntary isometric contractions of the hamstrings and gluteus maximus muscles. *Journal of Orthopaedic and Sports Physical Therapy*. https://doi.org/10.2519/jospt.2001.31.12.730

Wright, R. W., Haas, A. K., Anderson, J., Calabrese, G., Cavanaugh, J., Hewett, T. E., Lorring, D., McKenzie, C., Preston, E., Williams, G., & MOON Group. (2015). Anterior Cruciate Ligament Reconstruction Rehabilitation: MOON Guidelines. *Sports Health*, *7*(3), 239–243. https://doi.org/10.1177/1941738113517855

Yanagawa, T., Shelburne, K., Serpas, F., & Pandy, M. (2002). Effect of hamstrings muscle action on stability of the ACL-deficient knee in isokinetic extension exercise. *Clinical Biomechanics*, *17*(9–10), 705–712. https://doi.org/10.1016/S0268-0033(02)00104-3

Yasuda, K., & Sasaki, T. (1987). Exercise after anterior cruciate ligament reconstruction. The force exerted on the tibia by the separate isometric contractions of the quadriceps or the hamstrings. *Clinical Orthopaedics and Related Research*, *No. 220*, 275–283. https://doi.org/10.1097/00003086-198707000-00038

Yu, B., & Garrett, W. E. (2007). Mechanisms of non-contact ACL injuries. In *British Journal of Sports Medicine* (Vol. 41, Issue SUPPL. 1, pp. 47–51). https://doi.org/10.1136/bjsm.2007.037192

Zhang, S. N., Bates, B. T., & Dufek, J. S. (2000). Contributions of lower extremity joints to energy dissipation during landings. *Medicine and Science in Sports and Exercise*. https://doi.org/10.1097/00005768-200004000-00014

CHAPTER 6: MANUSCRIPT 2

THE RELATIONSHIP BETWEEN ISOMETRIC STRENGTH AND ENERGY ABSORPTION STRATEGIES IN ACL INJURED AND HEALTHY ADOLSECENTS

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Abstract

Purpose: This study investigated the association between knee isometric strength and lower extremity energy absorption during dynamic movements in ACL injured and control male and female participants. The purpose of this study was to determine if there is a generalizable relationship between strength and energy absorption strategies within this population during drop-vertical jumps, and if ACL injury altered this relationship.

Methods: Sixty-eight (39 females and 29 males) uninjured male and females and 52 ACL injured (35 females and 17 males) performed a drop-vertical jump and lunge task. Data were time-normalized to the eccentric phase of the movement. Maximal isometric knee extension and flexion voluntary contractions were also performed on an isokinetic dynamometer. Multiple linear regression models determined statistically significant relationships between energy absorption and isometric strength between the sex (male and female) and injury status (injured vs control) groups.

Results: Small effect sizes ($R^2 < 0.5$) were found for the hip, knee, and ankle joint energy absorption for knee strength, sex, and injury status ($R^2 = 0.043$, $R^2 = 0.039$, and $R^2 = 0.058$, respectively). None of the multiple regression models significantly predicted energy absorption for the hip ($p = 0.166$) , knee ($p = 0.202$), and ankle ($p = 0.081$) joints. Additionally, sex, injury status, and knee flexion or extension strength did not significantly add to the prediction of energy absorption for any of the three lower extremity joints.

Conclusion: The findings indicate that there is not a generalizable relationship between hip, knee, and ankle energy absorption and knee flexion and extension isometric strength in male and female control and ACL injured individuals. Injured individuals absorb similar energy levels at each joint compared to controls, with isometric strength showing a weak relationship with absorption. Therefore, it is possible that there is not a specific energy absorption or muscular strength strategy that can be used to improve adolescent ACL rehabilitation measures.

Introduction

The anterior cruciate ligament (ACL) is the most commonly torn ligament in the knee (Agel et al., 2016; Sepúlveda et al., 2017). This injury frequently occurs in adolescents; specifically, adolescent females who are two to four times more likely to tear their ACL compared to their male counterparts. In fact, females aged 13-17 yrs. have the highest ACL injury incidence of any age-sex strata (M. M. Herzog et al., 2017; Powell & Barber-Foss, 2000b; Renstrom et al., 2008b). Along with a current increase in ACL injuries, there has been a 29-fold increase in ACL reconstructions (ACL-R) for individuals under the age of 20 since 1997-1998 (Nogaro et al., 2020). Furthermore, there is still a high rate of re-injury with approximately 15-23% of adolescent ACL-R patients suffering a re-injury, translating to approximately one in four individuals from the reconstructed population experiencing a re-injury (Wiggins et al., 2016). Additionally, within this group of ACL-R individuals, only two in three returned to their pre-injury levels and only 55% returned to a competitive level of sport (Ardern et al., 2014). Despite the high rates of injury and re-injury in the adolescent population, there is very limited research on ACL injuries and rehabilitation within this population. Considering the high re-injury rate, there is a clear need for appropriate, age-specific rehabilitation guidelines.

Quantitative criteria, such as kinematics and kinetics, play an important role in the rehabilitation process (van Melick et al., 2016), and should be included as a fundamental aspect of rehabilitation programs. Studies show that lower extremity strength can counterbalance poor knee joint stability and support the knee joint by decreasing the varus and valgus laxity of the joint (Lloyd et al., 2005; Lloyd & Buchanan, 2001; Markolf et al., 1978; Steffen et al., 2016). Therefore, increased strength can result in a more equal distribution of forces transmitted across the knee (Lloyd et al., 2005; Lloyd & Buchanan, 2001; Markolf et al., 1978; Steffen et al., 2016).

A lack of appropriate muscular development may result in insufficient muscular torque available to protect the knee joint and the potential for ACL injury during dynamic movements (Wild et al., 2013). This is especially relevant when you consider that lower extremity strength develops differently during puberty between males and females, males will experience an increase in muscle mass, power, strength, and coordination that is not found in female counterparts (Barber-Westin et al., 2006; Myer et al., 2004; Parker et al., 1990; Quatman et al., 2006; Round et al., 1999; Shultz, 2008). This can lead to a discrepancy in how muscular demands and forces are tolerated at the lower extremity joints (Barber-Westin et al., 2006; Myer et al., 2004; Parker et al., 1990; Quatman et al., 2006; Round et al., 1999; Shultz, 2008). Thus, it is important to consider adolescent separately from adults. Additionally, it has been suggested that females have an imbalance between the strength of the quadricep and hamstring muscle groups, leading to the potential for reduced co-activation and an increased likelihood of anterior tibial translation (Hewett et al., 2004; Huston & Wojtys, 1996; MacWilliams et al., 1999; Wild et al., 2013; Yanagawa et al., 2002; Yasuda & Sasaki, 1987). Considering that the ACL is a primary restraint to anterior tibial translation, any increase in anterior tibial translation is risky in terms of ACL injury (Fleming et al., 1993).

Research surrounding energy absorption strategies may provide further insight into functional capacity and movement quality. Since energetic analysis quantifies the energy responsible for producing the movement strategies, it could be a variable that is considered more often in ACL rehabilitation programs (Norcross et al., 2010). It has also been suggested that energy absorption is related to the loading of passive tissues, such as the ACL (DeVita & Skelly, 1992). Pollard and colleagues (2017) conducted a study on an ACL injury training prevention program using energy absorption and concluded that their program led to adolescent female participants adjusting their movements to allow for more ACL protective energy absorption strategies. Specifically, this training prevention program addresses potential deficits in knee muscular strength coordination with an emphasis of reducing knee valgus during movement (Pollard et al., 2017). Additionally, studies show that adult females will absorb energy differently compared to males, with adult (DeVita & Skelly, 1992; Montgomery et al., 2014; Schmitz et al., 2007; Zhang et al., 2000) and adolescent (Romanchuk, del Bel, et al., 2020) females absorbing most of the energy at the knee, followed by the ankle, and finally the hip. In contrast, males will absorb most of the energy at the knee, followed by the hip, and finally the ankle. This discrepancy could be a symptom of greater knee and ankle range of motions, angular velocities, quadriceps strength in females compared to their male counterparts (Decker et al., 2003; Wild et al., 2013). Studies also suggest that absorbing energy at the knee first, at the ankle second, and at the hip third is representative of a strategy that will not protect the ACL (Decker et al., 2003; DeVita & Skelly, 1992; Pollard et al., 2017; Schmitz et al., 2007). A proximal to distal (hip-knee-ankle) strategy has been suggested to be the most efficient transfer of energy (Jacobs et al., 1996), which is quite different to what is suggested above. Specifically, absorbing most of the energy at the knee is considered risky to the ACL as it may not be able to withstand the resulting forces upon landing (Jacobs et al., 1996). Therefore, if we can understand how energy absorption is altered following an ACL injury in adolescent populations, we can begin to modify and train the variables appropriately to decrease the probability of injury and/or re-injury (Pollard et al., 2017).

Combining the information above, we conclude that lower extremity isometric strength and energy absorption are two of the key components of ACL reinjury prevention (Buckthorpe, 2019). A combination of adjusting neuromuscular deficits with clinical measures (i.e., isometric strength) and assessing movement quality with biomechanical measures (i.e., energy absorption) are key components for building appropriate rehabilitation programs (Buckthorpe, 2019). It is important to consider these variables regardless of sex to see if there is a relationship between isometric strength and energy absorption based off injury status. Furthermore, considering that females, a group more at risk to sustain ACL injuries, may have altered isometric strength and energy absorption strategies compared to males, it is important to consider the relationship between these variables. Additionally, if there is a relationship between isometric strength and specific energy absorption strategies, strength could be specifically targeted in rehabilitation programs to promote ACL protective energy absorption strategies. Therefore, the purpose of this study was to determine if there is a relationship between strength and energy absorption strategies during a drop-vertical jump (DVJ), with the goal of identifying if there is a generalizable relationship between these two variables and/or if they are based on population characteristics. With this goal in mind, it was first hypothesized that sex will not be a relevant variable to predict energy absorption at the hip, knee, and ankle based off knee extension and flexion isometric strength, however, it was secondarily hypothesized that injury status will be relevant in the prediction of energy absorption at the hip, knee, and ankle based off knee extension and flexion isometric strength (Decker et al., 2003; DeVita & Skelly, 1992; Pollard et al., 2017; Schmitz et al., 2007).

Methodology

Participants

A total of 120 participants including both injured (n=52; 35 females; 17 males) and control participants (n=68; 39 females; 29 males) were considered in this analysis (Table 6.1,

Table 6.2). Control participants were recruited from the Ottawa/Gatineau area while injured participants who have a confirmed ACL rupture via clinical observation, arthroscopy, and/or MRI were recruited through CHEO. Inclusion criteria included active participation in a competitive organized sport. Exclusion criteria included a history of previous traumatic lower extremity injury (i.e., meniscal tear, ligament rupture), any recent injury to the lower extremity in the past six months, and any other musculoskeletal impairment that may bias the results of the study.

Table 6.1

Patient demographic group means (SD) for male and female ACL injured

Variable	**Female** (mean ± SD)	**Male** (mean ± SD)	***p*-value**
Age (years)	15.3 ± 1.2	15.5 ± 1.1	0.721
Height (cm)	165.0 ± 5.4	174.8 ± 9.0	<0.001*
Weight (kg)	64.6 ± 8.8	76.4 ± 31.7	0.051
BMI (kg/m^2)	23.8 ± 3.4	24.8 ± 9.7	0.058
Tanner Stage	4.4 ± 0.7	4.0 ± 0.9	0.151

Note: *p*-values corrected using the Bonferroni correction, *indicates statistical significance of $p < 0.05$

Table 6.2

Patient demographic group means (SD) for male and female controls

Variable	**Female** (mean ± SD)	**Male** (mean ± SD)	***p*-value**
Age (years)	13.2 ± 1.6	13.2 ± 1.7	0.947
Height (cm)	161.7 ± 7.8	164.7 ± 13.5	0.261
Weight (kg)	50.6 ± 10.8	51.7 ± 12.7	0.694
BMI (kg/m^2)	19.1 ± 2.8	18.8 ± 2.8	0.636
Tanner Stage	3.1 ± 1.0	3.1 ± 1.1	0.852

Note: *p*-values corrected using the Bonferroni correction, *indicates statistical significance of $p < 0.05$

Procedure

All participants read and signed a consent form approved by each institution's respective research ethics board, (uOttawa - H09-17-10; CHEO – 17/74X) and completed the following questionnaires; i) the Hospital for Special Surgery Pediatric Functional Activity Brief Scale

(HSS Pedi-FABS) (Del Bel et al., 2020; Fabricant et al., 2013) to assess sport exposure, ii) the Pediatric International Knee Documentation Committee (Pedi-IKDC) to subjectively assess knee joint function (Kocher et al., 2011), iii) the Tegner Activity Scale to assess level of activity participation currently and before injury (Tegner & Lysholm, 1985), iv) the ACL Return to Sport Index (ACL-RSI) to subjectively assess psychological impact on returning to sport (Webster et al., 2008), and v) the Tanner Stage to self-assess current pubescent-stage (Taylor et al., 2001). Following the questionnaires, anthropometric measurements including height, weight, and leg and tibial length were recorded. The participants then completed a 5-minute warm-up on a cycle ergometer (Monark 828E, Vansbro, Sweden) with minimum resistance.

Next, knee flexion and extension with the participant in a seated position with the knee joint held at 60° of flexion and hip at 90º maximum voluntary isometric contractions (MVIC) were recorded using an isokinetic dynamometer (Systems 4 Pro, Biodex Medical Systems, New York. USA) (Figure 1). Participants performed three trials per exercise, receiving verbal encouragement and on-screen biofeedback of the torque signal to encourage them to maintain their maximal force for 5 seconds.

Figure 1: Maximum voluntary isometric contraction performed on a biodex isokintetic dynaometer. Participants were seated with their knee held at 60 degrees.

After the MVIC trials, 84 retroreflective markers were placed on anatomical landmarks, according to a hybrid cluster market set, to record marker trajectories. These trajectories were sampled at 200 Hz using a 10-camera infrared motion analysis system (8 Vero, 2 Vantage; Vicon, Oxford, UK). The supporting software (Nexus v2.7, Vicon, Oxford, UK) simultaneously recorded marker trajectories and ground reaction forces (GRF) from two force plates sampled at 2000 Hz (FP4060-08, Bertec Corporation, Columbus, OH, USA).

Finally, the participant performed DVJ trials (Figure 2). For the DVJ, participants were instructed to i) step off a raised platform set at the height of their tibial plateau (Figure 2A) ii) land with two feet, including one foot on each force plate (Figure 2B) iii) perform a maximal vertical jump and finally (Figure 2C), iv) land back onto the respective force plates (Figure 2D). Participants completed as many trials as necessary to gather five successful trials. Trials were considered successful if: they performed the movement as instructed, were able to maintain their balance for approximately three seconds without shifting their foot position, and their entire foot landed on the respective force plates.

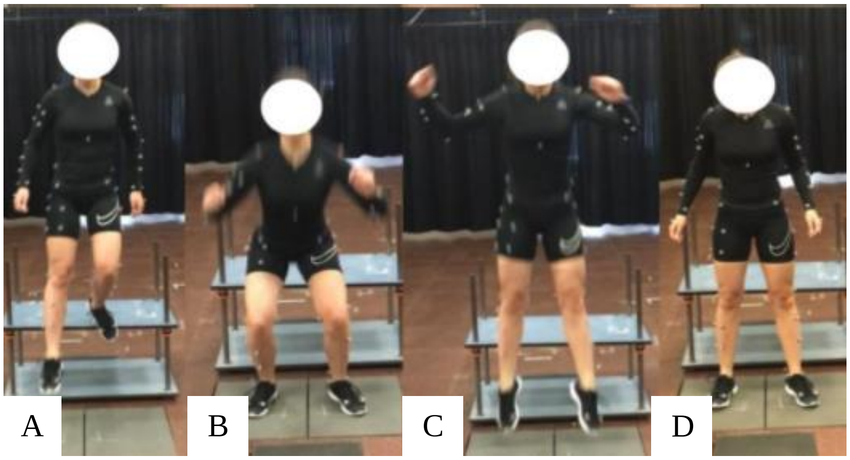

Figure 2: Visualization of a DVJ trial. **A**: stepping off platform. **B**: landing with two feet, with one foot on each force plate, **C**: performing a maximal vertical jump, **D**: landing on the force plates with one foot on each force plate.

Data Processing and Analysis

Isometric Strength

Torque data were filtered using a 4th-order zero-lag low pass Butterworth filter with a cut-off frequency of 15 Hz. The maximum torque reached during the isometric contraction was identified using a 50ms moving average.

Kinematics and Kinetics

Marker trajectories and GRF data were filtered using a 4th-order zero-lag low pass Butterworth filter with matching cut-off frequencies of 15 Hz (Bisseling & Hof, 2006; Kristianslund et al., 2012) using custom pipelines in Vicon Nexus (v2.9, Vicon, UK). Filter order and cut-off frequency were chosen based on residual analysis (Winter, 2009). Hip, knee, and ankle angles and moments in the sagittal plane were calculated relative to a standing reference trial using a modified University of Ottawa Motion Analysis Vicon Nexus model.

Energy absorption for the hip, knee, and ankle was calculated using joint power curves, which were determined by multiplying joint angular velocities and internal joint moments. Energy absorption was subsequently normalized to body weight. Total energy absorption was calculated by integrating the negative portion of the joint power curves (DeVita & Skelly, 1992). Relative energy absorption at each joint was expressed as a percentage of the summed energy absorption over all three joints.

Time Normalization

All discrete data for the DVJ were trimmed using unfiltered data to establish the eccentric phase, identified as the initial contact (IC [GRF < -10 N]) (Navacchia et al. 2019; Romanchuk, del Del Bel, and Benoit 2020) until peak knee flexion. Once trimmed, each variable of each participant was then averaged over the trials and time normalized to fit a 1-100% scale.

Statistical Analysis

First, correlations between knee strength and energy absorption were determined for the hip, knee, and ankle joint. The strength variable that had the strongest correlation with each joint was chosen for further analysis. Multiple linear regression analyses were then used to determine if knee strength, sex, and injury status can predict energy absorption at the hip, knee, and ankle. Independence of observations was testing using the Durbin-Watson test. Linearity, homoscedastic, and normality were assessed by visual inspection of data while multicollinearity was assessed using Tolerance values.

Unusual points included outliers, leverage, and influential points, these were identified as those exceeding ±3 standard deviations, greater than 0.2 leverage value, and Cook’s Distance greater than 1, respectively and were inspected to determine the appropriate action. If any outlier, leverage, or influential point was a result of an error in the data collection it was excluded (ex. Marker coming loose on skin). Those that reflected accurate data were included in the subsequent analysis. 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 were completed using a combination of MATLAB (2018b, MathWorks, Natick, USA), SPSS Statistics 26.0 (IBM Corp., Armonk, NY, USA), R (v4.1.2, The R Foundation, Vienna, Austria), 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 6.3).

Results

All 120 participants were able to complete the DVJ task and were included in the analysis. Initial dependent t-tests failed to identify an effect of limb dominance ($p > 0.05$ for 100% of analyses); therefore, the dominant limb was selected for further analyses. No differences were found in age ($p = 0.947$), height ($p = 0.261$), weight ($p = 0.694$), BMI ($p = 0.636$), and Tanner stage ($p = 0.852$) for the control males and females. Similarly, there were no differences found in age ($p = 0.721$), weight ($p = 0.051$), BMI ($p = 0.058$), and Tanner stage ($p = 0.151$) in the ACL injured male and females, however, there was a statistically significant difference found for height ($p = 1.5\text{x}10^{-5}$). Spearman's rank order correlation found that knee flexion torque was more strongly correlated with the energy absorption at the hip and knee joints compared to knee extension, while knee extension torque was more strongly correlated with the energy absorption at the ankle joint compared to knee flexion (Table 6.4). Therefore, knee flexion torque was considered as a variable in the multiple linear regressions for the hip and knee joint, while the ankle joint considered knee extension torque as the isometric strength variable.

Table 6.3

Group means (SD) for knee extension and flexion torque and hip, knee, and ankle energy absorption in the control and ACL injured male and females.

Variable	Male Control Mean ± SD	Female Control Mean ± SD	Male Injured Mean ± SD	Female Injured Mean ± SD
Knee Extension Torque (Nm)	167 ± 66.9	147 ± 31.7	206 ± 71.2	163 ± 36.7
Knee Flexion Torque (Nm)	77.8 ± 28.5	67.5 ± 18.0	90.0 ± 35.9	71.5 ± 12.0
Hip Energy Absorption (%)	62.4 ± 10.0	66.8 ± 8.96	63.0 ± 11.5	60.3 ± 22.5
Knee Energy Absorption (%)	27.9 ± 7.69	26.6 ± 6.82	28.5 ± 6.61	28.9 ± 20.2
Ankle Energy Absorption (%)	9.73 ± 9.79	6.51 ± 7.15	8.48 ±12.3	10.8 ± 13.3

Table 6.4

Spearman's rank order correlation results for hip, knee, and ankle joint comparing knee extension and knee flexion torque.

Joint	Knee Extension Torque	Knee Flexion Torque
Hip	0.639	0.915*
Knee	0.409	0.949*
Ankle	0.679*	0.484

Note: *represents larger correlation and the torque chosen for subsequent analysis.

Hip Joint

A multiple linear regression analysis was conducted to evaluate the prediction of hip energy absorption from knee flexion isometric strength, sex (male and female), and injury status (injured and control). There was linearity asessed by partial regression plots, there was independence of residuals, as assessed by a Durbin-Watson statistic of 1.960. There was homoscedasticity, as assessed by visual inspection of scatterplots. There was no evidence of multicollinearity, as assessed by tolerance values greater than 0.1, as well, the assumption of normality was met, as assessed by a Q-Q Plots.

The multiple regression model (sex, injury status and isometric strength) did not statistically significantly predicted energy absorption, F(3,116) = 1.724, $p = 0.166$, adjusted $R^2 = 0.018$; this is a small effect size according to Cohen (1988). None of the variables, sex, injury status, and isometric strength, added statistically significantly to the prediction, $p = 0.734$, $p = 0.081$, and 0.257 respectively. Regression coefficients and standard errors can be found in Table 6.5 and a scatterplot of the data with the regression lines found in Figure 6.1.

Table 6.5

Results from multiple linear regression for hip energy absorption from sex (male and female), injury status (injured and control) and knee flexion torque

Energy Absorption (J)	*B*	*95% CI for B*		*SE B*	β	R^2	$\triangle R^2$
		LL	*UL*				
Model						0.043	0.018
Constant	64.39	55.28	74.50	5.104			
Sex	1.029	-4.946	7.005	3.017	0.032		
Injury Status	5.063	-0.630	10.75	2.874	0.163		
Isometric Strength (Nm)	-0.071	-0.194	0.052	0.062	-0.109		

Note: B = unstandardized regression coefficient; *CI* = confidence interval; *LL* = lower limit; *UL* = upper limit; *SE B* = standard error of the coefficient; β = standardized coefficient; R^2 = coefficient of determination; $\triangle R^2$ = adjusted R^2, *$p < .05$.

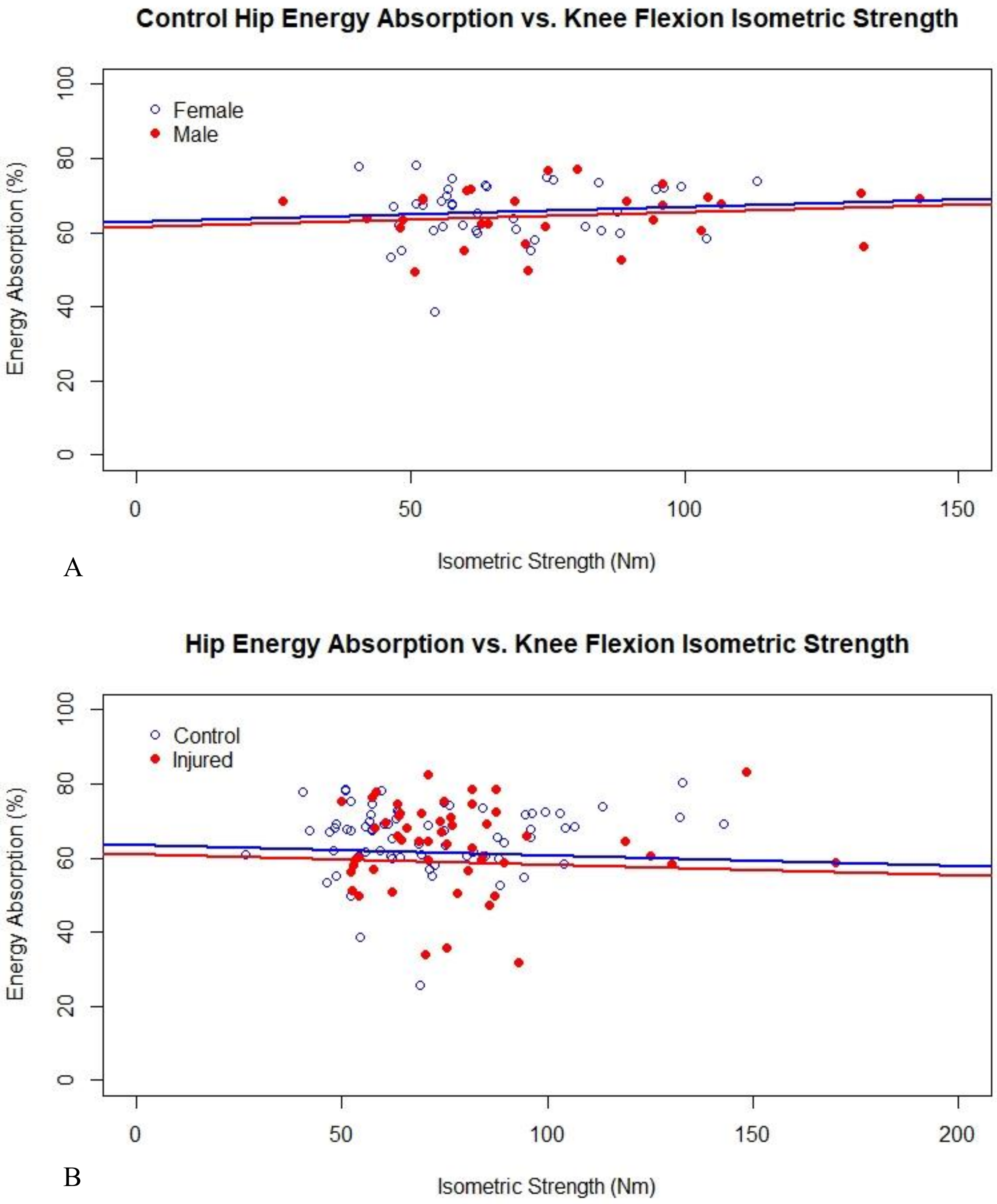

Figure 6.1. Scatterplots displaying relative hip energy absorption data vs. knee flexion isometric strength data for sex (A) and injury status (B).

Knee Joint

A multiple linear regression analysis was conducted to evaluate the prediction of knee energy absorption from knee flexion isometric strength, sex (male and female), and injury status (injured and control). There was linearity assessed by partial regression plots, there was independence of residuals, as assessed by a Durbin-Watson statistic of 1.588. There was homoscedasticity, as assessed by visual inspection of scatterplots. There was no evidence of multicollinearity, as assessed by tolerance values greater than 0.1, as well, the assumption of normality was met, as assessed by a Q-Q Plots.

The multiple regression model (sex, injury status and isometric strength) did not statistically significantly predicted energy absorption, F(3,116) = 1.565, p = 0.202, adjusted R^2 = 0.014, this is a small effect size according to Cohen (1988). None of the variables, sex, injury status, and isometric strength, added statistically significantly to the prediction, p = 0.344, p = 0.076, and 0.928 respectively. Regression coefficients and standard errors can be found in Table 6.6 and a scatterplot of the data with the regression lines found in Figure 6.2.

Table 6.6

Results from multiple linear regression for knee energy absorption from sex (male and female), injury status (injured and control) and knee flexion torque

Energy Absorption (J)	*B*	*95% CI for B*		*SE B*	β	R^2	$\triangle R^2$
		LL	*UL*				
Model						0.039	0.014
Constant	33.34	25.08	41.59	4.168			
Sex	-2.340	-7.219	2.540	2.464	-0.091		
Injury Status	-4.205	-8.852	0.444	2.347	-0.166		
Isometric Strength (Nm)	-0.005	-0.105	0.096	0.051	-0.009		

Note: B = unstandardized regression coefficient; *CI* = confidence interval; *LL* = lower limit; *UL* = upper limit; *SE B* = standard error of the coefficient; β = standardized coefficient; R^2 = coefficient of determination; $\triangle R^2$ = adjusted R^2, *$p < .05$.

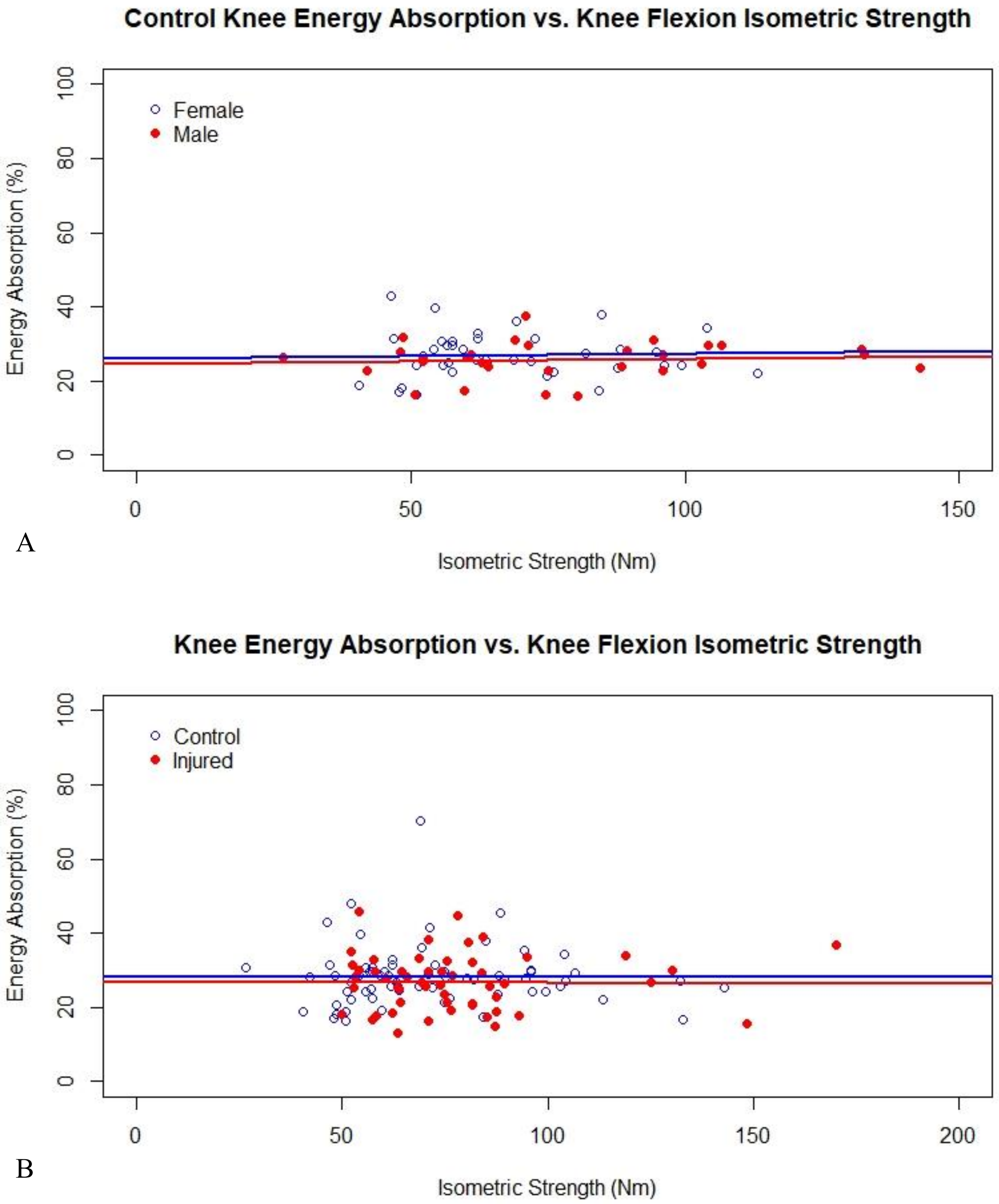

Figure 6.2. Scatterplots displaying relative knee energy absorption data vs. knee flexion isometric strength data for sex (A) and injury status (B).

Ankle Joint

A multiple linear regression analysis was conducted to evaluate the prediction of ankle energy absorption from knee extension isometric strength, sex (male and female), and injury status (injured and control). There was linearity assessed by partial regression plots, there was independence of residuals, as assessed by a Durbin-Watson statistic of 2.144. There was homoscedasticity, as assessed by visual inspection of scatterplots. There was no evidence of multicollinearity, as assessed by tolerance values greater than 0.1, as well, the assumption of normality was met, as assessed by a Q-Q Plots.

The multiple regression model (sex, injury status and isometric strength) did not statistically significantly predicted energy absorption, F(3,115) = 2.298, $p = 0.081$, adjusted $R^2 = 0.033$, this is a small effect size according to Cohen (1988). None of the variables, sex, injury status, and isometric strength, added statistically significantly to the prediction, $p = 0.177$, $p = 0.325$, and 0.090, respectively. Regression coefficients and standard errors can be found in Table 6.7 and a scatterplot of the data with the regression lines found in Figure 6.3.

Table 6.7

Results from multiple linear regression for ankle energy absorption from sex (male and female), injury status (injured and control) and knee extension torque

Energy Absorption (J)	*B*	*95% CI for B*		*SE B*	β	R^2	$\triangle R^2$
		LL	*UL*				
Model						0.058	0.033
Constant	2.571	-4.451	9.593	3.544			
Sex	2.779	-1.271	6.828	2.044	0.128		
Injury Status	-1.972	-5.922	1.979	1.994	-0.092		
Isometric Strength (Nm)	0.032	-0.005	0.068	0.019	0.161		

Note: *B* = unstandardized regression coefficient; *CI* = confidence interval; *LL* = lower limit; *UL* = upper limit; *SE B* = standard error of the coefficient; β = standardized coefficient; R^2 = coefficient of determination; $\triangle R^2$ = adjusted R^2, **p* < .05.

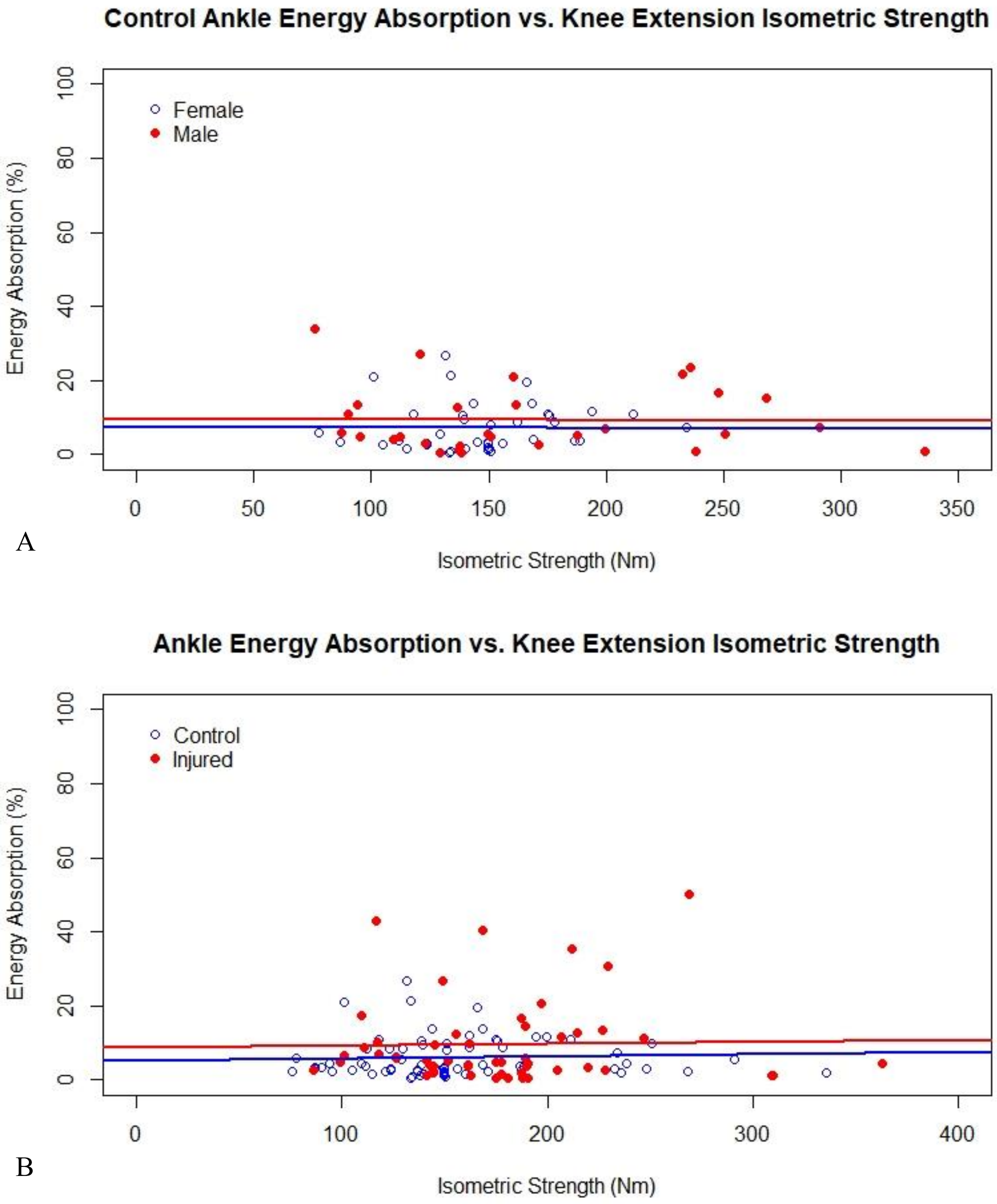

Figure 6.3. Scatterplots displaying relative ankle energy absorption data vs. knee flexion isometric strength data for sex (A) and injury status (B).

Discussion

The purpose of this study was to determine if there was a relationship between knee extension and flexion isometric strength and hip, knee, and ankle energy absorption during a DVJ for the adolescent male and female injured and control participants, as well as determine if sex or injury status is a factor in this relationship. The overall goal was to determine if there is a generalizable relationship between these variables or if they are simply based of off population characteristics such as sex (i.e., male vs. female). The multiple linear regression models did not predict energy absorption based off isometric strength for any of the joints for sex or injury status. Furthermore, sex did not predict energy absorption at the hip, knee, and ankle for either knee extension or flexion isometric strength. Therefore, the hypothesis that sex is not a relevant predictor of hip, knee, and ankle energy absorption is supported. When considering injury status, the multiple linear regression models were not able to predict energy absorption based off knee extension and flexion isometric strength at the hip, knee, or ankle joint. Therefore, the hypothesis that injury status will be able to predict energy absorption at the hip, knee, and ankle based off knee extension and flexion isometric strength is not supported.

Regarding the relationship between energy absorption, isometric strength, and sex, neither strength nor sex added to the prediction of energy absorption at the hip, knee, and ankle joints. These results disagree with the results from Schmitz and Shults (2010) which state that greater knee extensor strength does predict greater knee energy absorption in the adult female population. Our results indicate that sex does not impact the relationship between energy absorption and strength at any of the lower extremity joints. Although it has been suggested that adolescent females and males will develop strength differently throughout puberty (Barber-Westin et al., 2006; Myer et al., 2004; Parker et al., 1990; Quatman et al., 2006; Round et al., 1999; Shultz, 2008) and male and female adolescents do display significantly increased knee extension torque (*Manuscript 1*), these results suggest that it will not affect how the lower extremity absorbs energy upon landing in adolescents. Control adolescent males have few kinematic and kinetic differences during a DVJ compared to control females (*Manuscript 1*). It is possible that strength does not largely affect the body's range of motion upon landing and will therefore not have as much of an impact on how much energy is absorbed at each joint (Decker et al., 2003). Finally, both male and female adolescents absorb most of the energy at the hip, secondly at the knee, and lastly at the ankle, meaning that they are using a proximal to distal approach. This could explain why there is no significant effect of sex since they are absorbing the energy in a similar manner.

Similarly, injury status was not a predictor of energy absorption,which was unexpected. Additionally, injury status and isometric strength did not add significantly to the prediction. This was unexpected considering that injured individuals are expected to absorb energy differently (Boo et al., 2018; Garrison et al., 2018) and control individuals have displayed increased knee extension torque (*Manuscript 1)*. The results show that injured individuals absorb energy no differently at the hip, knee, and ankle at a similar torque, for knee flexion torques, compared to control individuals. This disagrees with the literature which states that the ankle will absorb less energy upon landing while the hip will absorb more energy in injured individuals compared to control adolescents (Boo et al., 2018; Garrison et al., 2018). However, this does agree with the literature with states that there will be no differences found in the energy absorbed at the knee joint between injured and control adolescents (Boo et al., 2018). It is possible that the results are contradictory due to the previous studies including individuals who have had an ACL-R, while the current study has currently injured individuals. Both the control and injured individuals use a proximal to distal strategy (i.e., hip to knee to ankle) when absorbing the energy according to the groups means, which could explain why there were few significant relationships found when predicting energy absorption based off injury status. This may explain why, in adolescents, injured individuals compared to control individuals display similar lower extremity kinematics and kinetics (*Manuscript 1*). This could also explain why the energy is not absorbed differently, as the kinematics and kinetics surrounding the movement are similar, leading to the energy being absorbed in a similar manner.

Methodological Considerations

This study used a small selection of participants from a larger study performed in the Clinical Biomechanics Research Unit to allow for equal sample sizes when performing the statistical analysis. It is important to note that within the ACL injured population there is a significant difference in height, which could have affected the isometric strength and energy absorption results. Future studies could gather more participants to eliminate this statistically significant difference, however since we were observing relationships over a wide range of strength and energy absorption values, this height effect is unlikely to have impacted our findings. Additionally, this study only looked at the dominant limb of the participants, eliminating the possibility of contralateral limb differences which may have important clinical implications and should be included in future studies. Finally, this study only included significant predictors in the statistical models, future studies should incorporate more variables surrounding lower extremity strength as predictors for energy absorption.

Conclusion

In conclusion, the overall goal of this study was to determine if there is a relationship between energy absorption and isometric strength, regardless of sex and injury status. There was no relationship found between energy absorption and isometric strength, nor was sex a variable that influenced this relationship. When injury status was considered, regardless of sex, the relationship was not affected. Although there is not a relationship between energy absorption and isometric strength, the results may be relevant to ACL injury risk. The proximal to distal energy absorption strategy is considered a risk to the ACL (Decker et al., 2003; DeVita & Skelly, 1992; Pollard et al., 2017; Schmitz et al., 2007) and is thought to be the most efficient for dispersion of energy (Gregoire et al., 1984; Jacobs et al., 1996). In terms of clinical implications when considering ACL risk, while strength and energy absorption remain important to consider in rehabilitation and injury prevention programs (Buckthorpe, 2019; Norcross et al., 2010; Pollard et al., 2017), it is unlikely that there is an ideal energy absorption strategy in relation to isometric strength measures that can be specifically promoted in such programs to improve the current rehabilitations practices.

References

Agel, J., Arendt, E. A., & Bershadsky, B. (2005). Anterior cruciate ligament injury in National Collegiate Athletic Association basketball and soccer: A 13-year review. In *American Journal of Sports Medicine* (Vol. 33, Issue 4, pp. 524–530). SAGE PublicationsSage CA: Los Angeles, CA. https://doi.org/10.1177/0363546504269937

Agel, J., Rockwood, T., & Klossner, D. (2016). Collegiate ACL Injury Rates Across 15 Sports: National Collegiate Athletic Association Injury Surveillance System Data Update (2004-2005 Through 2012-2013). *Clinical Journal of Sport Medicine*. https://doi.org/10.1097/JSM.0000000000000290

Alentorn-Geli, E., Myer, G. D., Silvers, H. J., Samitier, G., Romero, D., Lázaro-Haro, C., & Cugat, R. (2009). Prevention of non-contact anterior cruciate ligament injuries in soccer players. Part 1: Mechanisms of injury and underlying risk factors. *Knee Surgery, Sports Traumatology, Arthroscopy*, *17*(7), 705–729. https://doi.org/10.1007/s00167-009-0813-1

Alkjær, T., Henriksen, M., Dyhre-Poulsen, P., & Simonsen, E. B. (2009). Forward lunge as a functional performance test in ACL deficient subjects: Test-retest reliability. *Knee*, *16*(3), 176–182. https://doi.org/10.1016/j.knee.2008.11.011

Alkjar, T., Simonsen, E. B., Peter Magnusson, S., Aagaard, H., & Dyhre-Poulsen, P. (2002). Differences in the movement pattern of a forward lunge in two types of anterior cruciate ligament deficient patients: Copers and non-copers. *Clinical Biomechanics*, *17*(8), 586–593. https://doi.org/10.1016/S0268-0033(02)00098-0

Ardern, C. L., Taylor, N. F., Feller, J. A., & Webster, K. E. (2014). Fifty-five per cent return to competitive sport following anterior cruciate ligament reconstruction surgery: an updated systematic review and meta-analysis including aspects of physical functioning and contextual factors. *British Journal of Sports Medicine*, *48*(21), 1453–1552. https://doi.org/10.1136/bjsports-2013-093398

Barber-Westin, S. D., Noyes, F. R., & Galloway, M. (2006). Jump-land characteristics and muscle strength development in young athletes: A gender comparison of 1140 athletes 9 to 17 years of age. *American Journal of Sports Medicine*. https://doi.org/10.1177/0363546505281242

Beck, N. A., Todd, J., Lawrence, R., Nordin, J. D., Defor, T. A., & Tompkins, M. (2017). ACL Tears in School-Aged Children and Adolescents Over 20 Years. *PEDIATRICS*, *139*(3). https://doi.org/10.1542/peds.2016-1877

Bencke, J., Næsborg, H., Simonsen, E. B., & Klausen, K. (2000). Motor pattern of the knee joint muscles during side-step cutting in European team handball: Influence on muscular co-ordination after an intervention study. *Scandinavian Journal of Medicine and Science in Sports*. https://doi.org/10.1034/j.1600-0838.2000.010002068.x

Benjamini, Y., & Hochberg, Y. (1995). Controlling the False Discovery Rate: A Practical and Powerful Approach to Multiple Testing. *Journal of the Royal Statistical Society: Series B (Methodological)*, *57*(1), 289–300. https://doi.org/10.1111/J.2517-6161.1995.TB02031.X

Biscarini, A., Botti, F. M., & Pettorossi, V. E. (2013). Selective contribution of each hamstring muscle to anterior cruciate ligament protection and tibiofemoral joint stability in leg-extension exercise: A simulation study. *European Journal of Applied Physiology*, *113*(9), 2263–2273. https://doi.org/10.1007/s00421-013-2656-1

Bisseling, R. W., & Hof, A. L. (2006). Handling of impact forces in inverse dynamics. *Journal of Biomechanics*. https://doi.org/10.1016/j.jbiomech.2005.07.021

Bizzini, M., Impellizzeri, F. M., Dvorak, J., Bortolan, L., Schena, F., Modena, R., & Junge, A. (2013). Physiological and performance responses to the “FIFA 11+” (part 1): is it an appropriate warm-up? *Journal of Sports Sciences*, *31*(13), 1481–1490. https://doi.org/10.1080/02640414.2013.802922

Boden, B. P., Dean, C. S., Feagin, J. A., & Garrett, W. E. (2000). Mechanisms of anterior cruciate ligament injury. *Orthopedics*, *23*(6), 573–578. https://doi.org/10.3928/0147-7447-20000601-15

Boo, M. E., Garrison, J. C., Hannon, J. P., Creed, K. M., Goto, S., Grondin, A. N., & Bothwell, J. M. (2018). Energy Absorption Contribution and Strength in Female Athletes at Return to Sport After Anterior Cruciate Ligament Reconstruction: Comparison With Healthy Controls. *Orthopaedic Journal of Sports Medicine*, *6*(3). https://doi.org/10.1177/2325967118759522

Buckthorpe, M. (2019). Optimising the Late-Stage Rehabilitation and Return-to-Sport Training and Testing Process After ACL Reconstruction. *Sports Medicine*, *49*, 1043–1058. https://doi.org/10.1007/s40279-019-01102-z

Butler, D. (1980). Ligamentous restraints to anterior drawer in the human knee : a biomechanical study . J Bone Joint Surg. *The Journal of Bone and Joint Surgery*, *62*(November 2015), 259–270.

Cesar, G. M., Tomasevicz, C. L., & Burnfield, J. M. (2016). Frontal plane comparison between drop jump and vertical jump: implications for the assessment of ACL risk of injury. *Sports Biomechanics*, *15*(4), 440–449. https://doi.org/10.1080/14763141.2016.1174286

Decker, M. J., Torry, M. R., Wyland, D. J., Sterett, W. I., & Steadman, J. R. (2003). Gender differences in lower extremity kinematics, kinetics and energy absorption during landing. *Clinical Biomechanics*. https://doi.org/10.1016/S0268-0033(03)00090-1

Del Bel, M. J., Kemp, L. G., Girard, C. I., Rossignol, J., Goulet, S. F., Bourgon, J.-F., Carsen, S., & Benoit, D. L. (2020). Translation and Validation of the Hospital for Special Surgery Pediatric Functional Activity Brief Scale for French Paediatric Populations. *Physiotherapy Canada*. https://doi.org/10.3138/ptc-2019-0033

DeVita, P., & Skelly, W. A. (1992). Effect of landing stiffness on joint kinetics and energetics in the lower extremity. *Medicine and Science in Sports and Exercise*, *24*(1), 108–115. https://doi.org/10.1249/00005768-199201000-00018

Dodwell, E. R., Lamont, L. E., Green, D. W., Pan, T. J., Marx, R. G., & Lyman, S. (2014). 20 years of pediatric anterior cruciate ligament reconstruction in New York state. *American Journal of Sports Medicine*, *42*(3), 675–680. https://doi.org/10.1177/0363546513518412

Dunn, O. J. (1964). Multiple Comparisons Using Rank Sums. *Technometrics*, *6*(3), 241. https://doi.org/10.2307/1266041

Duthon, V. B., Barea, C., Abrassart, S., Fasel, J. H., Fritschy, D., & Ménétrey, J. (2006). Anatomy of the anterior cruciate ligament. In *Knee Surgery, Sports Traumatology, Arthroscopy* (Vol. 14, Issue 3, pp. 204–213). https://doi.org/10.1007/s00167-005-0679-9

Ekstrom, R. A., Donatelli, R. A., & Carp, K. C. (2007). Electromyographic analysis of core trunk, hip, and thigh muscles during 9 rehabilitation exercises. *Journal of Orthopaedic and Sports Physical Therapy*. https://doi.org/10.2519/jospt.2007.2471

Fabricant, P. D., Robles, A., Downey-Zayas, T., Do, H. T., Marx, R. G., Widmann, R. F., & Green, D. W. (2013). Development and validation of a pediatric sports activity rating scale: The hospital for special surgery pediatric functional activity brief scale (HSS Pedi-FABS). *American Journal of Sports Medicine*, *41*(10), 2421–2429. https://doi.org/10.1177/0363546513496548

Failla, M. J., Arundale, A. J. H., Logerstedt, D. S., & Snyder-Mackler, L. (2015). Controversies in knee rehabilitation. Anterior cruciate ligament injury. In *Clinics in Sports Medicine* (Vol. 34, Issue 2, pp. 301–312). W.B. Saunders. https://doi.org/10.1016/j.csm.2014.12.008

Field, A. (2013). Discovering statistics using IBM SPSS statistics. In *Statistics*.

Flaxman, T. E., AlkjÆr, T., Simonsen, E. B., Krogsgaard, M. R., & Benoit, D. L. (2017). Predicting the Functional Roles of Knee Joint Muscles from Internal Joint Moments. *Medicine and Science in Sports and Exercise*. https://doi.org/10.1249/MSS.0000000000001125

Fleming, B. C., Beynnon, B. D., Nichols, C. E., Johnson, R. J., & Pope, M. H. (1993). An in vivo comparison of anterior tibial translation and strain in the anteromedial band of the anterior cruciate ligament. *Journal of Biomechanics*, *26*(1), 51–58. https://doi.org/10.1016/0021-9290(93)90612-I

Fleming, B. C., Renstrom, P. A., Beynnon, B. D., Engstrom, B., Peura, G. D., Badger, G. J., & Johnson, R. J. (2001). The effect of weightbearing and external loading on anterior cruciate ligament strain. *Journal of Biomechanics*, *34*(2), 163–170. https://doi.org/10.1016/S0021-9290(00)00154-8

Fleming, B. C., Renstrom, P. A., Ohlen, G., Johnson, R. J., Peura, G. D., Beynnon, B. D., & Badger, G. J. (2001). The gastrocnemius muscle is an antagonist of the anterior cruciate ligament. *Journal of Orthopaedic Research*, *19*(6), 1178–1184. https://doi.org/10.1016/S0736-0266(01)00057-2

Ford, K. R., Shapiro, R., Myer, G. D., Van Den Bogert, A. J., & Hewett, T. E. (2010). Longitudinal Sex Differences during Landing in Knee Abduction in Young Athletes. *Med Sci Sports Exerc*, *42*(10), 1923–1931. https://doi.org/10.1249/MSS.0b013e3181dc99b1

Garrison, J. C., Hannon, J., Goto, S., Giesler, L., Bush, C., & Bothwell, J. M. (2018). Participants at three months post-operative anterior cruciate ligament reconstruction (ACL-R) demonstrate differences in lower extremity energy absorption contribution and quadriceps strength compared to healthy controls. *Knee*, *25*(5), 782–789. https://doi.org/10.1016/j.knee.2018.06.014

Gianotti, S. M., Marshall, S. W., Hume, P. A., & Bunt, L. (2009). Incidence of anterior cruciate ligament injury and other knee ligament injuries: A national population-based study. *Journal of Science and Medicine in Sport*. https://doi.org/10.1016/j.jsams.2008.07.005

Gregoire, L., Veeger, H., Huijing, P., & van Ingen Schenau, G. (1984). Role of Mono-and Biarticular Muscles in Explosive Movements. In *Int J Sports Med* (Vol. 5, Issue 6).

Griffin, L. Y., Agel, J., Albohm, M. J., Arendt, E. A., Dick, R. W., Garrett, W. E., Garrick, J. G., Hewett, T. E., Huston, L., Ireland, M. L., Johnson, R. J., Kibler, W. B., Lephart, S., Lewis, J. L., Lindenfeld, T. N., Mandelbaum, B. R., Marchak, P., Teitz, C. C., & Wojtys, E. M. (2000). Noncontact anterior cruciate ligament injuries: risk factors and prevention strategies. In *The Journal of the American Academy of Orthopaedic Surgeons*. https://doi.org/10.5435/00124635-200005000-00001

Haddas, R., James, C. R., & Hooper, T. L. (2015). Lower extremity fatigue, sex, and landing performance in a population with recurrent low back pain. *Journal of Athletic Training*. https://doi.org/10.4085/1062-6050-49.3.61

Herzog, M. M., Marshall, S. W., Lund, J. L., Pate, V., Mack, C. D., & Spang, J. T. (2017). Incidence of anterior cruciate ligament reconstruction among adolescent females in the United States, 2002 through 2014. *JAMA Pediatrics*. https://doi.org/10.1001/jamapediatrics.2017.0740

Herzog, W., & Read, L. J. (1993). Lines of action and moment arms of the major force-carrying structures crossing the human knee joint. *Journal of Anatomy*, *182 (Pt 2)*(Pt 2), 213–230.

Hewett, T. E., Lindenfeld, T. N., Riccobene, J. v., & Noyes, F. R. (1999). The effect of neuromuscular training on the incidence of knee injury in female athletes. A prospective study. *American Journal of Sports Medicine*, *27*(6), 699–706. https://doi.org/10.1177/03635465990270060301

Hewett, T. E., Myer, G. D., & Ford, K. R. (2004). Decrease in Neuromuscular Control About the Knee with Maturation in female athletes. *J Bone Joint Surg Am*, *86-A*(8), 1601–1608. https://journals.lww.com/jbjsjournal/Abstract/2004/08000/Decrease_in_Neuromuscular_Control_About_the_Knee.1.aspx

Hewett, T. E., Myer, G. D., Ford, K. R., Heidt, R. S., Colosimo, A. J., McLean, S. G., Van Den Bogert, A. J., Paterno, M. V, & Succop, P. (2005). Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes: A prospective study. *American Journal of Sports Medicine*, *33*(4), 492–501. https://doi.org/10.1177/0363546504269591

Hewett, T. E., Myer, G. D., Kiefer, A. W., Ford, K. R., Myer, G. D., Kiefer, A. W., & Ford, K. R. (2015). Longitudinal Increases in Knee Abduction Moments in Females during Adolescent

Growth. *Med. Sci. Sports Exerc*, *47*(12), 2579–2585. https://doi.org/10.1249/MSS.0000000000000700

Hewett, T. E., Stroupe, A. L., Nance, T. A., & Noyes, F. R. (1996). Plyometric training in female athletes: Decreased impact forces and increased hamstring torques. *American Journal of Sports Medicine*, *24*(6), 765–773. https://doi.org/10.1177/036354659602400611

Hirokawa, S., Solomonow, M., Yun lu, Lou, Z. P., & D'Ambrosia, R. (1992). Anterior-posterior and rotational displacement of the tibia elicited by quadriceps contraction. *The American Journal of Sports Medicine*. https://doi.org/10.1177/036354659202000311

Hoch, J. M., Baez, S. E., & Hoch, M. C. (2019). Examination of ankle function in individuals with a history of ACL reconstruction. *Physical Therapy in Sport : Official Journal of the Association of Chartered Physiotherapists in Sports Medicine*, *36*, 55–61. https://doi.org/10.1016/J.PTSP.2019.01.002

Huston, L. J., & Wojtys, E. M. (1996). Neuromuscular Performance Characteristics in Elite Female Athletes. *The American Journal of Sports Medicine*, *24*(4), 427–436. https://doi.org/10.1177/036354659602400405

Impellizzeri, F. M., Bizzini, M., Dvorak, J., Pellegrini, B., Schena, F., & Junge, A. (2013). Physiological and performance responses to the FIFA 11+ (part 2): a randomised controlled trial on the training effects. *Journal of Sports Sciences*, *31*(13), 1491–1502. https://doi.org/10.1080/02640414.2013.802926

Ireland, M. L. (2002). The female ACL: Why is it more prone to injury? *Journal of Orthopaedics*, *33*(4), 637–651. https://doi.org/10.1016/S0972-978X(16)00023-4

Jacobs, R., Bobbert, M. F., & van Ingen Schenau, G. J. (1996). Mechanical output from individual muscles during explosive leg extensions: The role of biarticular muscles. *Journal of Biomechanics*, *29*(4), 513–523. https://doi.org/10.1016/0021-9290(95)00067-4

Kain, C. C., McCarthy, J. A., Arms, S., Pope, M. H., Steadman, J. R., Manske, P. R., & Shively, R. A. (1988). An in vivo analysis of the effect of transcutaneous electrical stimulation of the quadriceps and hamstrings on anterior cruciate ligament deformation. *The American Journal of Sports Medicine*, *16*(2), 147–152. https://doi.org/10.1177/036354658801600210

Karanikas, K., Arampatzis, A., & Brüggemann, G. P. (2009). Motor task and muscle strength followed different adaptation patterns after anterior cruciate ligament reconstruction. *European Journal of Physical and Rehabilitation Medicine*, *45*(1).

Kline, P. W., Morgan, K., Johnson, D. L., Ireland, M. L., & Noehren, B. (n.d.). *Impaired quadriceps rate of torque development and knee mechanics after anterior cruciate ligament reconstruction with patellar tendon autograft*. https://doi.org/10.1177/0363546515595834

Kocher, M. S., Smith, J. T., Iversen, M. D., Brustowicz, K., Ogunwole, O., Andersen, J., Yoo, W. J., McFeely, E. D., Anderson, A. F., & Zurakowski, D. (2011). Reliability, validity, and responsiveness of a modified International Knee Documentation Committee Subjective Knee

Form (Pedi-IKDC) in children with knee disorders. *The American Journal of Sports Medicine, 39*(5), 933–939. https://doi.org/10.1177/0363546510383002

Kristianslund, E., Krosshaug, T., & Van den Bogert, A. J. (2012). Effect of low pass filtering on joint moments from inverse dynamics: Implications for injury prevention. *Journal of Biomechanics*. https://doi.org/10.1016/j.jbiomech.2011.12.011

Landry, S. C., McKean, K. A., Hubley-Kozey, C. L., Stanish, W. D., & Deluzio, K. J. (2007a). Neuromuscular and lower limb biomechanical differences exist between male and female elite adolescent soccer players during an unanticipated run and crosscut maneuver. *American Journal of Sports Medicine*, *35*(11). https://doi.org/10.1177/0363546507307400

Landry, S. C., McKean, K. A., Hubley-Kozey, C. L., Stanish, W. D., & Deluzio, K. J. (2007b). Neuromuscular and lower limb biomechanical differences exist between male and female elite adolescent soccer players during an unanticipated side-cut maneuver. *American Journal of Sports Medicine*, *35*(11). https://doi.org/10.1177/0363546507300823

Li, G., Rudy, T. W., Sakane, M., Kanamori, A., Ma, C. B., & Woo, S. L. Y. (1999). The importance of quadriceps and hamstring muscle loading on knee kinematics and in-situ forces in the ACL. *Journal of Biomechanics*, *32*(4), 395–400. https://doi.org/10.1016/S0021-9290(98)00181-X

Liederbach, M., Kremenic, I. J., Orishimo, K. F., Pappas, E., & Hagins, M. (2014). Comparison of landing biomechanics between male and female dancers and athletes, part 2: Influence of fatigue and implications for anterior cruciate ligament injury. *American Journal of Sports Medicine*, *42*(5), 1089–1095. https://doi.org/10.1177/0363546514524525

Lisee, C., Birchmeier, T., Yan, A., & Kuenze, C. (2019). Associations between isometric quadriceps strength characteristics, knee flexion angles, and knee extension moments during single leg step down and landing tasks after anterior cruciate ligament reconstruction. *Clinical Biomechanics*, *70*, 231–236. https://doi.org/10.1016/J.CLINBIOMECH.2019.10.012

Lloyd, D. G., & Buchanan, T. S. (2001). Strategies of muscular support of varus and valgus isometric loads at the human knee. *Journal of Biomechanics*. https://doi.org/10.1016/S0021-9290(01)00095-1

Lloyd, D. G., Buchanan, T. S., & Besier, T. F. (2005). Neuromuscular biomechanical modeling to understand knee ligament loading. *Medicine and Science in Sports and Exercise*, *37*(11), 1939–1947. https://doi.org/10.1249/01.MSS.0000176676.49584.BA

MacWilliams, B. A., Wilson, D. R., Desjardins, J. D., Romero, J., & Chao, E. Y. S. (1999). Hamstrings cocontraction reduces internal rotation, anterior translation, and anterior cruciate ligament load in weight-bearing flexion. *Journal of Orthopaedic Research*, *17*(6), 817–822. https://doi.org/10.1002/jor.1100170605

Mantovani, G., & Lamontagne, M. (2017). How Different Marker Sets Affect Joint Angles in Inverse Kinematics Framework. *Journal of Biomechanical Engineering*. https://doi.org/10.1115/1.4034708

Markatos, K., Kaseta, M. K., Lallos, S. N., Korres, D. S., & Efstathopoulos, N. (2013). The anatomy of the ACL and its importance in ACL reconstruction. In *European Journal of Orthopaedic Surgery and Traumatology* (Vol. 23, Issue 7, pp. 747–752). Eur J Orthop Surg Traumatol. https://doi.org/10.1007/s00590-012-1079-8

Markolf, K. L., Graff-Radford, A., & Amstutz, H. C. (1978). In vivo knee stability. A quantitative assessment using an instrumented clinical testing apparatus. *Journal of Bone and Joint Surgery - Series A*. https://doi.org/10.2106/00004623-197860050-00014

Markolf, K. L., O'Neill, G., Jackson, S. R., & McAllister, D. R. (2004). Effects of applied quadriceps and hamstrings muscle loads on forces in the anterior and posterior cruciate ligaments. *American Journal of Sports Medicine*. https://doi.org/10.1177/0363546503262198

McLean, S. G., Huang, X., & Van Den Bogert, A. J. (2005). Association between lower extremity posture at contact and peak knee valgus moment during sidestepping: Implications for ACL injury. *Clinical Biomechanics*. https://doi.org/10.1016/j.clinbiomech.2005.05.007

Mokhtarzadeh, H., Yeow, C. H., Hong Goh, J. C., Oetomo, D., Malekipour, F., & Lee, P. V. S. (2013). Contributions of the Soleus and Gastrocnemius muscles to the anterior cruciate ligament loading during single-leg landing. *Journal of Biomechanics*, *46*(11), 1913–1920. https://doi.org/10.1016/j.jbiomech.2013.04.010

Montgomery, C., Blackburn, J., Withers, D., Tierney, G., Moran, C., & Simms, C. (2018). Mechanisms of ACL injury in professional rugby union: A systematic video analysis of 36 cases. *British Journal of Sports Medicine*, *52*(15), 994–1001. https://doi.org/10.1136/bjsports-2016-096425

Montgomery, M. M., Shultz, S. J., & Schmitz, R. J. (2014). The effect of equalizing landing task demands on sex differences in lower extremity energy absorption. *Clinical Biomechanics*, *29*(7), 760–766. https://doi.org/10.1016/j.clinbiomech.2014.06.004

Morgan, K. D., Donnelly, C. J., & Reinbolt, J. A. (2014). Elevated gastrocnemius forces compensate for decreased hamstrings forces during the weight-acceptance phase of single-leg jump landing: Implications for anterior cruciate ligament injury risk. *Journal of Biomechanics*, *47*(13), 3295–3302. https://doi.org/10.1016/j.jbiomech.2014.08.016

Myer, G. D., Ford, K. R., & Hewett, T. E. (2004). Rationale and clinical techniques for anterior cruciate ligament injury prevention among female athletes. *Journal of Athletic Training*.

Myer, G. D., Ford, K. R., McLean, S. G., & Hewett, T. E. (2006). The effects of plyometric versus dynamic stabilization and balance training on lower extremity biomechanics. *American Journal of Sports Medicine*. https://doi.org/10.1177/0363546505281241

Myklebust, G., Maehlum, S., Holm, I., & Bahr, R. (2007). A prospective cohort study of anterior cruciate ligament injuries in elite Norwegian team handball. *Scandinavian Journal of Medicine & Science in Sports*, *8*(3), 149–153. https://doi.org/10.1111/j.1600-0838.1998.tb00185.x

Navacchia, A., Ueno, R., Ford, K. R., DiCesare, C. A., Myer, G. D., & Hewett, T. E. (2019). EMG-Informed Musculoskeletal Modeling to Estimate Realistic Knee Anterior Shear Force During Drop Vertical Jump in Female Athletes. *Annals of Biomedical Engineering*, *47*(12), 2416–2430. https://doi.org/10.1007/S10439-019-02318-W

Nogaro, M. C., Abram, S. G. F., Alvand, A., Bottomley, N., Jackson, W. F. M., & Price, A. (2020). Paediatric and adolescent anterior cruciate ligament reconstruction surgery. *The Bone & Joint Journal*, *102-B*(2), 239–245. https://doi.org/10.1302/0301-620X.102B2.BJJ-2019-0420.R2

Norcross, M. F., Blackburn, J. T., Goerger, B. M., & Padua, D. A. (2010). The association between lower extremity energy absorption and biomechanical factors related to anterior cruciate ligament injury. *Clinical Biomechanics*, *25*(10), 1031–1036. https://doi.org/10.1016/j.clinbiomech.2010.07.013

Padua, D. A., Marshall, S. W., Boling, M. C., Thigpen, C. A., William E. Garrett, J., & Beutler, A. I. (2009). The Landing Error Scoring System (LESS) Is a Valid and Reliable Clinical Assessment Tool of Jump-Landing Biomechanics: The JUMP-ACL Study. *Https://Doi.Org/10.1177/0363546509343200*, *37*(10), 1996–2002. https://doi.org/10.1177/0363546509343200

Parker, D. F., Round, J. M., Sacco, P., & Jones, D. A. (1990). A Cross-sectional survey of upper and lower limb strength in boys and girls during childhood and adolescence. *Annals of Human Biology*, *17*(3), 199–211. https://doi.org/10.1080/03014469000000962

Pataky, T. C., Robinson, M. A., & Vanrenterghem, J. (2013). Vector field statistical analysis of kinematic and force trajectories. *Journal of Biomechanics*, *46*(14), 2394–2401. https://doi.org/10.1016/j.jbiomech.2013.07.031

Petushek, E. J., Sugimoto, D., Stoolmiller, M., Smith, G., & Myer, G. D. (2019). Evidence-Based Best-Practice Guidelines for Preventing Anterior Cruciate Ligament Injuries in Young Female Athletes: A Systematic Review and Meta-analysis. *American Journal of Sports Medicine*, *47*(7), 1744–1753. https://doi.org/10.1177/0363546518782460

Pollard, C. D., Sigward, S. M., & Powers, C. M. (2017). ACL Injury Prevention Training Results in Modification of Hip and Knee Mechanics During a Drop-Landing Task. *Orthopaedic Journal of Sports Medicine*, *5*(9). https://doi.org/10.1177/2325967117726267

Powell, J. W., & Barber-Foss, K. D. (2000a). Sex-related injury patterns among selected high school sports. *American Journal of Sports Medicine*. https://doi.org/10.1177/03635465000280031801

Powell, J. W., & Barber-Foss, K. D. (2000b). Sex-related injury patterns among selected high school sports. *American Journal of Sports Medicine*. https://doi.org/10.1177/03635465000280031801

Quatman, C. E., Ford, K. R., Myer, G. D., & Hewett, T. E. (2006). Maturation leads to gender differences in landing force and vertical jump performance: A longitudinal study. *American Journal of Sports Medicine*. https://doi.org/10.1177/0363546505281916

Renstrom, P., Ljungqvist, A., Arendt, E., Beynnon, B., Fukubayashi, T., Garrett, W., Georgoulis, T., Hewett, T. E., Johnson, R., Krosshaug, T., Mandelbaum, B., Micheli, L., Myklebust, G., Roos, E., Roos, H., Schamasch, P., Shultz, S., Werner, S., Wojtys, E., & Engebretsen, L. (2008a). Non-contact ACL injuries in female athletes: An International Olympic Committee current concepts. *British Journal of Sports Medicine*. https://doi.org/10.1136/bjsm.2008.048934

Renstrom, P., Ljungqvist, A., Arendt, E., Beynnon, B., Fukubayashi, T., Garrett, W., Georgoulis, T., Hewett, T. E., Johnson, R., Krosshaug, T., Mandelbaum, B., Micheli, L., Myklebust, G., Roos, E., Roos, H., Schamasch, P., Shultz, S., Werner, S., Wojtys, E., & Engebretsen, L. (2008b). Non-contact ACL injuries in female athletes: An International Olympic Committee current concepts. *British Journal of Sports Medicine*. https://doi.org/10.1136/bjsm.2008.048934

Report Card Development Team. (2018). *The 2018 ParticipACTION Report Card on Physical Activity for Children and Youth*.

Romanchuk, N. J., Bel, M. J. Del, & Benoit, D. L. (2020). SEX-SPECIFIC ENERGY ABSORPTION STRATEGIES DURING UNANTICIPATED SINGLE-LEG LANDINGS IN ADOLESCENTS: IMPLICATIONS FOR KNEE INJURIES. *Orthopaedic Journal of Sports Medicine*, *8*(4_suppl3), 2325967120S0023. https://doi.org/10.1177/2325967120s00237

Romanchuk, N. J., del Bel, M. J., & Benoit, D. L. (2020). Sex-specific landing biomechanics and energy absorption during unanticipated single-leg drop-jumps in adolescents: implications for knee injury mechanics. *Journal of Biomechanics*, 110064. https://doi.org/10.1016/j.jbiomech.2020.110064

Round, J. M., Jones, D. A., Honour, J. W., & Nevill, A. M. (1999). Hormonal factors in the development of differences in strength between boys and girls during adolescence: A longitudinal study. *Annals of Human Biology*, *26*(1), 49–62. https://doi.org/10.1080/030144699282976

Sale, D., Quinlan, J., Marsh, E., McComas, A. J., & Belanger, A. Y. (1982). Influence of joint position on ankle plantarflexion in humans. *Journal of Applied Physiology Respiratory Environmental and Exercise Physiology*. https://doi.org/10.1152/jappl.1982.52.6.1636

Sanders, T. L., Maradit Kremers, H., Bryan, A. J., Larson, D. R., Dahm, D. L., Levy, B. A., Stuart, M. J., & Krych, A. J. (2016). Incidence of anterior cruciate ligament tears and reconstruction: A 21-year population-based study. *American Journal of Sports Medicine*, *44*(6), 1502–1507. https://doi.org/10.1177/0363546516629944

Scheffler, S. (2012). The cruciate ligaments: Anatomy, biology, and biomechanics. In *The Knee Joint: Surgical Techniques and Strategies* (Vol. 9782287993, pp. 11–21). https://doi.org/10.1007/978-2-287-99353-4_2

Schmitz, R. J., Kulas, A. S., Perrin, D. H., Riemann, B. L., & Shultz, S. J. (2007). Sex differences in lower extremity biomechanics during single leg landings. *Clinical Biomechanics*, *22*(6), 681–688. https://doi.org/10.1016/j.clinbiomech.2007.03.001

Sepúlveda, F., Sánchez, L., Amy, E., & Micheo, W. (2017). Anterior cruciate ligament injury: Return to play, function and long-term considerations. *Current Sports Medicine Reports*, *16*(3), 172–178. https://doi.org/10.1249/JSR.0000000000000356

Shea, K. G., Pfeiffer, R., Jo, H. W., Curtin, M., & Apel, P. J. (2004). Anterior cruciate ligament injury in pediatric and adolescent soccer players: An analysis of insurance data. *Journal of Pediatric Orthopaedics*. https://doi.org/10.1097/01241398-200411000-00005

Shultz, S. J. (2008). Differences in Lower Extremity Anatomical and Postural Characteristics in Males and Females Between Maturation Groups. *J Orthop Sports Phys Ther*, *38*(3), 137–149. https://doi.org/10.2519/jospt.2008.2645

Sinclair, J., Brooks, D., & Stainton, · Philip. (2019). Sex differences in ACL loading and strain during typical athletic movements: a musculoskeletal simulation analysis. *European Journal of Applied Physiology*, *119*(3), 713–721. https://doi.org/10.1007/s00421-018-04062-w

Slauterbeck, J. R., Hickox, J. R., Beynnon, B., & Hardy, D. M. (2006). Anterior Cruciate Ligament Biology and Its Relationship to Injury Forces. In *Orthopedic Clinics of North America* (Vol. 37, Issue 4, pp. 585–591). https://doi.org/10.1016/j.ocl.2006.09.001

Snyder-Mackler, L., Delitto, A., Stralka, S. W., & Bailey, S. L. (1994). Use of electrical stimulation to enhance recovery of quadriceps femoris muscle force production in patients following anterior cruciate ligament reconstruction. *Physical Therapy*, *74*(10), 901–907. https://doi.org/10.1093/ptj/74.10.901

Steffen, K., Nilstad, A., Kristianslund, E. K., Myklebust, G., Bahr, R., & Krosshaug, T. (2016). Association between lower extremity muscle strength and noncontact ACL injuries. *Medicine and Science in Sports and Exercise*, *48*(11), 2082–2089. https://doi.org/10.1249/MSS.0000000000001014

Takahashi, S., Nagano, Y., Ito, W., Kido, Y., & Okuwaki, T. (2019). A retrospective study of mechanisms of anterior cruciate ligament injuries in high school basketball, handball, judo, soccer, and volleyball. *Medicine*, *98*(26), e16030. https://doi.org/10.1097/MD.0000000000016030

Taylor, S. J. C., Whincup, P. H., Hindmarsh, P. C., Lampe, F., Odoki, K., & Cook, D. G. (2001). Performance of a new pubertal self-assessment questionnaire: A preliminary study. *Paediatric and Perinatal Epidemiology*, *15*(1), 88–94. https://doi.org/10.1046/j.1365-3016.2001.00317.x

Tegner, Y., & Lysholm, J. (1985). Rating systems in the evaluation of knee ligament injuries. *Clinical Orthopaedics and Related Research*. https://doi.org/10.1097/00003086-198509000-00007

Tengman, E., Brax Olofsson, L., Stensdotter, A. K., Nilsson, K. G., & Häger, C. K. (2014). Anterior cruciate ligament injury after more than 20 years. II. Concentric and eccentric knee muscle strength. *Scandinavian Journal of Medicine and Science in Sports*, *24*(6), e501-509. https://doi.org/10.1111/SMS.12215

Thomas, A. C., Villwock, M., Wojtys, E. M., & Palmieri-Smith, R. M. (2013). Lower Extremity Muscle Strength After Anterior Cruciate Ligament Injury and Reconstruction. *Journal of Athletic Training*, *48*(5), 610–620. https://doi.org/10.4085/1062-6050-48.3.23

Torzilli, P. A., Xianghua Deng, & Warren, R. F. (1994). The Effect of Joint-Compressive Load and Quadriceps Muscle Force on Knee Motion in the Intact and Anterior Cruciate Ligament-Sectioned Knee. *The American Journal of Sports Medicine*, *22*(1), 105–112. https://doi.org/10.1177/036354659402200117

van Melick, N., H van Cingel, R. E., Brooijmans, F., Neeter, C., van Tienen, T., Hullegie, W., & G Nijhuis-van der Sanden, M. W. (2016). Evidence-based clinical practice update: practice guidelines for anterior cruciate ligament rehabilitation based on a systematic review and multidisciplinary consensus. *British Journal of Sports Medicine*, *50*, 1506–1515. https://doi.org/10.1136/bjsports-2015-095898

van Melick, N., Meddeler, B. M., Hoogeboom, T. J., Nijhuis-van der Sanden, M. W. G., & van Cingel, R. E. H. (2017). How to determine leg dominance: The agreement between self-reported and observed performance in healthy adults. *PLoS ONE*. https://doi.org/10.1371/journal.pone.0189876

Waldén, M., Krosshaug, T., Bjørneboe, J., Andersen, T. E., Faul, O., & Hägglund, M. (2015). Three distinct mechanisms predominate in noncontact anterior cruciate ligament injuries in male professional football players: A systematic video analysis of 39 cases. *British Journal of Sports Medicine*, *49*(22), 1452–1460. https://doi.org/10.1136/bjsports-2014-094573

Webster, K. E., Feller, J. A., & Lambros, C. (2008). Development and preliminary validation of a scale to measure the psychological impact of returning to sport following anterior cruciate ligament reconstruction surgery. *Physical Therapy in Sport*, *9*, 9–15. https://doi.org/10.1016/j.ptsp.2007.09.003

Werner, B. C., Yang, S., Looney, A. M., & Gwathmey, F. W. (2016). Trends in pediatric and adolescent anterior cruciate ligament injury and reconstruction. *Journal of Pediatric Orthopaedics*. https://doi.org/10.1097/BPO.0000000000000482

Wiggins, A. J., Grandhi, R. K., Schneider, D. K., Stanfield, D., Webster, K. E., & Myer, G. D. (2016). Risk of Secondary Injury in Younger Athletes after Anterior Cruciate Ligament Reconstruction. In *American Journal of Sports Medicine* (Vol. 44, Issue 7, pp. 1861–1876). https://doi.org/10.1177/0363546515621554

Wild, C. Y., Steele, J. R., & Munro, B. J. (2013). Musculoskeletal and Estrogen Changes during the Adolescent Growth Spurt in Girls. *Medicine & Science in Sports & Exercise*, *45*(1), 138–145. https://doi.org/10.1249/MSS.0b013e31826a507e

Wingfield, K. (2013). Neuromuscular Training to prevent knee injuries in adolescent female soccer players. *Clinical Journal of Sport Medicine*. https://doi.org/10.1097/01.jsm.0000433153.51313.6b

Winter, D. A. (2009). Mechanical Work, Energy, and Power. In *Biomechanics and Motor Control of Human Movement*. https://doi.org/10.1002/9780470549148.ch6

Worrell, T. W., Karst, G., Adamczyk, D., Moore, R., Stanley, C., Steimel, B., & Steimel, S. (2001). Influence of joint position on electromyographic and torque generation during maximal voluntary isometric contractions of the hamstrings and gluteus maximus muscles. *Journal of Orthopaedic and Sports Physical Therapy*. https://doi.org/10.2519/jospt.2001.31.12.730

Wright, R. W., Haas, A. K., Anderson, J., Calabrese, G., Cavanaugh, J., Hewett, T. E., Lorring, D., McKenzie, C., Preston, E., Williams, G., & MOON Group. (2015). Anterior Cruciate Ligament Reconstruction Rehabilitation: MOON Guidelines. *Sports Health*, *7*(3), 239–243. https://doi.org/10.1177/1941738113517855

Yanagawa, T., Shelburne, K., Serpas, F., & Pandy, M. (2002). Effect of hamstrings muscle action on stability of the ACL-deficient knee in isokinetic extension exercise. *Clinical Biomechanics*, *17*(9–10), 705–712. https://doi.org/10.1016/S0268-0033(02)00104-3

Yasuda, K., & Sasaki, T. (1987). Exercise after anterior cruciate ligament reconstruction. The force exerted on the tibia by the separate isometric contractions of the quadriceps or the hamstrings. *Clinical Orthopaedics and Related Research*, *No. 220*, 275–283. https://doi.org/10.1097/00003086-198707000-00038

Yu, B., & Garrett, W. E. (2007). Mechanisms of non-contact ACL injuries. In *British Journal of Sports Medicine* (Vol. 41, Issue SUPPL. 1, pp. 47–51). https://doi.org/10.1136/bjsm.2007.037192

Zhang, S. N., Bates, B. T., & Dufek, J. S. (2000). Contributions of lower extremity joints to energy dissipation during landings. *Medicine and Science in Sports and Exercise*. https://doi.org/10.1097/00005768-200004000-00014

CHAPTER 7: GENERAL DISCUSSION

The overall aim of my Master's thesis was to evaluate energy absorption strategies in males and female with and without ACL injuries. To address Aim-1, I examined the differences in strength and energy absorption strategies in adolescent males and females with and without ACL injuries during two functional tasks typically used to assess functional capacity during rehabilitation and Aim-2 determined if there was a relationship between strength and energy absorption strategies in males and females with and without ACL injuries.

We hypothesized that hypothesized that (H1) females and ACL injured would display lower peak torque values during knee extension and ankle plantarflexion compared to males and control individuals (Huston & Wojtys, 1996; Kain et al., 1988; Mokhtarzadeh et al., 2013), (H2), females would absorb a higher percentage of energy at the ankle compared to male counterparts; while the knee would absorb the highest percentage of energy, regardless of sex (DeVita & Skelly, 1992; Zhang et al., 2000). And finally, we hypothesized that (H3) injured individuals, regardless of sex, would absorb more energy at the hip and ankle compared to matched controls while the knee would not be affected (Boo et al., 2018; Garrison et al., 2018). Based on our findings, (H1) females display lower knee extension torque compared to males and ACL injured display lower knee extension and ankle plantarflexion torque compared to uninjured. It is thought that the injured individuals will display lower torque values as the injury will compromise muscular strength due to lack of use (Barber-Westin et al., 2006; Myer et al., 2004; Parker et al., 1990; Quatman et al., 2006; Round et al., 1999). Furthermore, muscular strength will contribute to knee stabilization during dynamic weight bearing movements and potentially protect the ACL from injury (Snyder-Mackler et al., 1994). In terms of sex, females have been suggested to lack the pubertal muscular development that has been observed in males, potentially explaining why they have significantly lower knee extension strength (Barber-Westin et al., 2006; Myer et al., 2004; Parker et al., 1990; Quatman et al., 2006; Round et al., 1999). Taken together, both variables of knee extension and ankle plantarflexion are important in determining appropriate rehabilitation strategies.

Next, our findings show that for H2 there were no differences in energy absorbed at the ankle between males and females and the knee did not absorb the greatest amount of energy. It is possible that because the females displayed greater ankle plantarflexion moments compared to males, this allowed them to dissipate the energy to the larger muscles in the lower extremity, allowing the ankle joint to stabilize itself instead of attempt to absorb an increased amount of energy. Additionally, it is likely that because the hip joint is associated with larger muscle groups, it had the ability to absorb more energy and protect the distal joints and therefore the ACL (Zhang et al., 2000). Finally, (H3) the results show that there were no significant differences at the hip and ankle joints between ACL injured and uninjured individuals in terms of energy absorption. Literature suggest that the injured individuals will rely on an increased amount of energy absorbed at the hip and ankle to avoid absorbing energy at the knee and risk injury (Boo et al., 2018). It is interesting how the energy is absorbed similarly between the injured and control, however, another possible speculation is that the control group is avoiding injury by relying on the hip and ankle joint and the injured group is avoiding pain and re-injury by doing the same. For the knee joint, the only significant difference was found between the male and female control groups where the males were found to absorb more energy at the knee compared to the females.

Aim2 Determine if there was a relationship between strength and energy absorption strategies in males and females with and without ACL injuries

We hypothesized that (H4) sex will not be a relevant variable to predict energy absorption at the hip, knee, and ankle based off knee extension and flexion isometric strength and we hypothesized that (H5) injury status will be relevant in the prediction of energy absorption at the hip, knee, and ankle based off knee extension and flexion isometric strength (Decker et al., 2003; DeVita & Skelly, 1992; Pollard et al., 2017; Schmitz et al., 2007). Based on our findings, (H4) sex was not a relevant variable to predict energy absorption at the hip, knee, and ankle based off knee extension and flexion isometric strength. It was thought that strength may not have largely affect the ROM in the body and there will not have a large impact of how much energy is absorbed at each joint (Decker et al., 2003). Additionally, the results from *Manuscript 1* suggest that males and females do not display many significant differences in terms of kinematics and kinetics. Finally, both males and females used a similar proximal to distal approach when absorbing the energy upon landing, explaining why sex was not a relevant predictor of energy absorption. Next, the finding suggest (H5) injury status was not a relevant variable to predict energy absorption at the hip, knee, and ankle based off knee extension and flexion isometric strength. This was unexpected, however, similarly to above, the ACL injured and controls both absorbed energy in a proximal to distal manner, possibly explaining why injury status was not a relevant predictor. Additionally, injured and controls did not display any significant kinematics or kinetic differences, which explains the lack of relationship present (*Manuscript 1*).

Conclusion

Overall, the goal of this study was to evaluate the energy absorption strategies in males and females with and without ACL injuries, with the hope that the findings could be beneficial in developing improved rehabilitation and injury prevention programs for adolescents. The findings did suggest that there are clear strength differences in injured individuals compared to controls for knee extension and ankle plantarflexion, and differences between males and females for knee extension. This suggests that strength is important to continue to consider when designing adolescent rehabilitation and injury prevention programs, especially when you consider that there are currently limited evidence-based return-to-activity programs. Unexpectedly, the results suggest limited differences in energy absorption between sexes and injury status. This suggested that energy absorption may not be as important to consider when designing such programs as was initially expected. Furthermore, according to Cohen’s D, there is a small relationship between strength and energy absorption at the hip, knee, and ankle joints when sex and injury status are considered. This research leads us to suggest that an ideal energy absorption strategy to consider in developing improved ACL injury rehabilitation and prevention programs is not related to isometric strength measures. However, it is possible that the most ideal combination of energy, kinematics, and strength was simply not identified in this research and more research will need to be done to understand what is an ideal practice for adolescents.

REFERENCES

Agel, J., Arendt, E. A., & Bershadsky, B. (2005). Anterior cruciate ligament injury in National Collegiate Athletic Association basketball and soccer: A 13-year review. In *American Journal of Sports Medicine* (Vol. 33, Issue 4, pp. 524–530). SAGE PublicationsSage CA: Los Angeles, CA. https://doi.org/10.1177/0363546504269937

Agel, J., Rockwood, T., & Klossner, D. (2016). Collegiate ACL Injury Rates Across 15 Sports: National Collegiate Athletic Association Injury Surveillance System Data Update (2004-2005 Through 2012-2013). *Clinical Journal of Sport Medicine*. https://doi.org/10.1097/JSM.0000000000000290

Alentorn-Geli, E., Myer, G. D., Silvers, H. J., Samitier, G., Romero, D., Lázaro-Haro, C., & Cugat, R. (2009). Prevention of non-contact anterior cruciate ligament injuries in soccer players. Part 1: Mechanisms of injury and underlying risk factors. *Knee Surgery, Sports Traumatology, Arthroscopy*, *17*(7), 705–729. https://doi.org/10.1007/s00167-009-0813-1

Alkjær, T., Henriksen, M., Dyhre-Poulsen, P., & Simonsen, E. B. (2009). Forward lunge as a functional performance test in ACL deficient subjects: Test-retest reliability. *Knee*, *16*(3), 176–182. https://doi.org/10.1016/j.knee.2008.11.011

Alkjar, T., Simonsen, E. B., Peter Magnusson, S., Aagaard, H., & Dyhre-Poulsen, P. (2002). Differences in the movement pattern of a forward lunge in two types of anterior cruciate ligament deficient patients: Copers and non-copers. *Clinical Biomechanics*, *17*(8), 586–593. https://doi.org/10.1016/S0268-0033(02)00098-0

Ardern, C. L., Taylor, N. F., Feller, J. A., & Webster, K. E. (2014). Fifty-five per cent return to competitive sport following anterior cruciate ligament reconstruction surgery: an updated systematic review and meta-analysis including aspects of physical functioning and contextual factors. *British Journal of Sports Medicine*, *48*(21), 1453–1552. https://doi.org/10.1136/bjsports-2013-093398

Barber-Westin, S. D., Noyes, F. R., & Galloway, M. (2006). Jump-land characteristics and muscle strength development in young athletes: A gender comparison of 1140 athletes 9 to 17 years of age. *American Journal of Sports Medicine*. https://doi.org/10.1177/0363546505281242

Beck, N. A., Todd, J., Lawrence, R., Nordin, J. D., Defor, T. A., & Tompkins, M. (2017). ACL Tears in School-Aged Children and Adolescents Over 20 Years. *PEDIATRICS*, *139*(3). https://doi.org/10.1542/peds.2016-1877

Bencke, J., Næsborg, H., Simonsen, E. B., & Klausen, K. (2000). Motor pattern of the knee joint muscles during side-step cutting in European team handball: Influence on muscular co-ordination after an intervention study. *Scandinavian Journal of Medicine and Science in Sports*. https://doi.org/10.1034/j.1600-0838.2000.010002068.x

Benjamini, Y., & Hochberg, Y. (1995). Controlling the False Discovery Rate: A Practical and Powerful Approach to Multiple Testing. *Journal of the Royal Statistical Society: Series B (Methodological)*, *57*(1), 289–300. https://doi.org/10.1111/J.2517-6161.1995.TB02031.X

Biscarini, A., Botti, F. M., & Pettorossi, V. E. (2013). Selective contribution of each hamstring muscle to anterior cruciate ligament protection and tibiofemoral joint stability in leg-extension exercise: A simulation study. *European Journal of Applied Physiology*, *113*(9), 2263–2273. https://doi.org/10.1007/s00421-013-2656-1

Bisseling, R. W., & Hof, A. L. (2006). Handling of impact forces in inverse dynamics. *Journal of Biomechanics*. https://doi.org/10.1016/j.jbiomech.2005.07.021

Bizzini, M., Impellizzeri, F. M., Dvorak, J., Bortolan, L., Schena, F., Modena, R., & Junge, A. (2013). Physiological and performance responses to the “FIFA 11+” (part 1): is it an appropriate warm-up? *Journal of Sports Sciences*, *31*(13), 1481–1490. https://doi.org/10.1080/02640414.2013.802922

Boden, B. P., Dean, C. S., Feagin, J. A., & Garrett, W. E. (2000). Mechanisms of anterior cruciate ligament injury. *Orthopedics*, *23*(6), 573–578. https://doi.org/10.3928/0147-7447-20000601-15

Boo, M. E., Garrison, J. C., Hannon, J. P., Creed, K. M., Goto, S., Grondin, A. N., & Bothwell, J. M. (2018). Energy Absorption Contribution and Strength in Female Athletes at Return to Sport After Anterior Cruciate Ligament Reconstruction: Comparison With Healthy Controls. *Orthopaedic Journal of Sports Medicine*, *6*(3). https://doi.org/10.1177/2325967118759522

Buckthorpe, M. (2019). Optimising the Late-Stage Rehabilitation and Return-to-Sport Training and Testing Process After ACL Reconstruction. *Sports Medicine*, *49*, 1043–1058. https://doi.org/10.1007/s40279-019-01102-z

Butler, D. (1980). Ligamentous restraints to anterior drawer in the human knee : a biomechanical study . J Bone Joint Surg. *The Journal of Bone and Joint Surgery*, *62*(November 2015), 259–270.

Cesar, G. M., Tomasevicz, C. L., & Burnfield, J. M. (2016). Frontal plane comparison between drop jump and vertical jump: implications for the assessment of ACL risk of injury. *Sports Biomechanics*, *15*(4), 440–449. https://doi.org/10.1080/14763141.2016.1174286

Decker, M. J., Torry, M. R., Wyland, D. J., Sterett, W. I., & Steadman, J. R. (2003). Gender differences in lower extremity kinematics, kinetics and energy absorption during landing. *Clinical Biomechanics*. https://doi.org/10.1016/S0268-0033(03)00090-1

Del Bel, M. J., Kemp, L. G., Girard, C. I., Rossignol, J., Goulet, S. F., Bourgon, J.-F., Carsen, S., & Benoit, D. L. (2020). Translation and Validation of the Hospital for Special Surgery Pediatric Functional Activity Brief Scale for French Paediatric Populations. *Physiotherapy Canada*. https://doi.org/10.3138/ptc-2019-0033

DeVita, P., & Skelly, W. A. (1992). Effect of landing stiffness on joint kinetics and energetics in the lower extremity. *Medicine and Science in Sports and Exercise*, *24*(1), 108–115. https://doi.org/10.1249/00005768-199201000-00018

Dodwell, E. R., Lamont, L. E., Green, D. W., Pan, T. J., Marx, R. G., & Lyman, S. (2014). 20 years of pediatric anterior cruciate ligament reconstruction in New York state. *American Journal of Sports Medicine*, *42*(3), 675–680. https://doi.org/10.1177/0363546513518412

Dunn, O. J. (1964). Multiple Comparisons Using Rank Sums. *Technometrics*, *6*(3), 241. https://doi.org/10.2307/1266041

Duthon, V. B., Barea, C., Abrassart, S., Fasel, J. H., Fritschy, D., & Ménétrey, J. (2006). Anatomy of the anterior cruciate ligament. In *Knee Surgery, Sports Traumatology, Arthroscopy* (Vol. 14, Issue 3, pp. 204–213). https://doi.org/10.1007/s00167-005-0679-9

Ekstrom, R. A., Donatelli, R. A., & Carp, K. C. (2007). Electromyographic analysis of core trunk, hip, and thigh muscles during 9 rehabilitation exercises. *Journal of Orthopaedic and Sports Physical Therapy*. https://doi.org/10.2519/jospt.2007.2471

Fabricant, P. D., Robles, A., Downey-Zayas, T., Do, H. T., Marx, R. G., Widmann, R. F., & Green, D. W. (2013). Development and validation of a pediatric sports activity rating scale: The hospital for special surgery pediatric functional activity brief scale (HSS Pedi-FABS). *American Journal of Sports Medicine*, *41*(10), 2421–2429. https://doi.org/10.1177/0363546513496548

Failla, M. J., Arundale, A. J. H., Logerstedt, D. S., & Snyder-Mackler, L. (2015). Controversies in knee rehabilitation. Anterior cruciate ligament injury. In *Clinics in Sports Medicine* (Vol. 34, Issue 2, pp. 301–312). W.B. Saunders. https://doi.org/10.1016/j.csm.2014.12.008

Field, A. (2013). Discovering statistics using IBM SPSS statistics. In *Statistics*.

Flaxman, T. E., AlkjÆr, T., Simonsen, E. B., Krogsgaard, M. R., & Benoit, D. L. (2017). Predicting the Functional Roles of Knee Joint Muscles from Internal Joint Moments. *Medicine and Science in Sports and Exercise*. https://doi.org/10.1249/MSS.0000000000001125

Fleming, B. C., Beynnon, B. D., Nichols, C. E., Johnson, R. J., & Pope, M. H. (1993). An in vivo comparison of anterior tibial translation and strain in the anteromedial band of the anterior cruciate ligament. *Journal of Biomechanics*, *26*(1), 51–58. https://doi.org/10.1016/0021-9290(93)90612-I

Fleming, B. C., Renstrom, P. A., Beynnon, B. D., Engstrom, B., Peura, G. D., Badger, G. J., & Johnson, R. J. (2001). The effect of weightbearing and external loading on anterior cruciate ligament strain. *Journal of Biomechanics*, *34*(2), 163–170. https://doi.org/10.1016/S0021-9290(00)00154-8

Fleming, B. C., Renstrom, P. A., Ohlen, G., Johnson, R. J., Peura, G. D., Beynnon, B. D., & Badger, G. J. (2001). The gastrocnemius muscle is an antagonist of the anterior cruciate ligament. *Journal of Orthopaedic Research*, *19*(6), 1178–1184. https://doi.org/10.1016/S0736-0266(01)00057-2

Ford, K. R., Shapiro, R., Myer, G. D., Van Den Bogert, A. J., & Hewett, T. E. (2010). Longitudinal Sex Differences during Landing in Knee Abduction in Young Athletes. *Med Sci Sports Exerc*, *42*(10), 1923–1931. https://doi.org/10.1249/MSS.0b013e3181dc99b1

Garrison, J. C., Hannon, J., Goto, S., Giesler, L., Bush, C., & Bothwell, J. M. (2018). Participants at three months post-operative anterior cruciate ligament reconstruction (ACL-R) demonstrate differences in lower extremity energy absorption contribution and quadriceps strength compared to healthy controls. *Knee*, *25*(5), 782–789. https://doi.org/10.1016/j.knee.2018.06.014

Gianotti, S. M., Marshall, S. W., Hume, P. A., & Bunt, L. (2009). Incidence of anterior cruciate ligament injury and other knee ligament injuries: A national population-based study. *Journal of Science and Medicine in Sport*. https://doi.org/10.1016/j.jsams.2008.07.005

Gregoire, L., Veeger, H., Huijing, P., & van Ingen Schenau, G. (1984). Role of Mono-and Biarticular Muscles in Explosive Movements. In *Int J Sports Med* (Vol. 5, Issue 6).

Griffin, L. Y., Agel, J., Albohm, M. J., Arendt, E. A., Dick, R. W., Garrett, W. E., Garrick, J. G., Hewett, T. E., Huston, L., Ireland, M. L., Johnson, R. J., Kibler, W. B., Lephart, S., Lewis, J. L., Lindenfeld, T. N., Mandelbaum, B. R., Marchak, P., Teitz, C. C., & Wojtys, E. M. (2000). Noncontact anterior cruciate ligament injuries: risk factors and prevention strategies. In *The Journal of the American Academy of Orthopaedic Surgeons*. https://doi.org/10.5435/00124635-200005000-00001

Haddas, R., James, C. R., & Hooper, T. L. (2015). Lower extremity fatigue, sex, and landing performance in a population with recurrent low back pain. *Journal of Athletic Training*. https://doi.org/10.4085/1062-6050-49.3.61

Herzog, M. M., Marshall, S. W., Lund, J. L., Pate, V., Mack, C. D., & Spang, J. T. (2017). Incidence of anterior cruciate ligament reconstruction among adolescent females in the United States, 2002 through 2014. *JAMA Pediatrics*. https://doi.org/10.1001/jamapediatrics.2017.0740

Herzog, W., & Read, L. J. (1993). Lines of action and moment arms of the major force-carrying structures crossing the human knee joint. *Journal of Anatomy*, *182 (Pt 2)*(Pt 2), 213–230.

Hewett, T. E., Lindenfeld, T. N., Riccobene, J. v., & Noyes, F. R. (1999). The effect of neuromuscular training on the incidence of knee injury in female athletes. A prospective study. *American Journal of Sports Medicine*, *27*(6), 699–706. https://doi.org/10.1177/03635465990270060301

Hewett, T. E., Myer, G. D., & Ford, K. R. (2004). Decrease in Neuromuscular Control About the Knee with Maturation in female athletes. *J Bone Joint Surg Am*, *86-A*(8), 1601–1608. https://journals.lww.com/jbjsjournal/Abstract/2004/08000/Decrease_in_Neuromuscular_Control_About_the_Knee.1.aspx

Hewett, T. E., Myer, G. D., Ford, K. R., Heidt, R. S., Colosimo, A. J., McLean, S. G., Van Den Bogert, A. J., Paterno, M. V, & Succop, P. (2005). Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes: A prospective study. *American Journal of Sports Medicine*, *33*(4), 492–501. https://doi.org/10.1177/0363546504269591

Hewett, T. E., Myer, G. D., Kiefer, A. W., Ford, K. R., Myer, G. D., Kiefer, A. W., & Ford, K. R. (2015). Longitudinal Increases in Knee Abduction Moments in Females during Adolescent

Growth. *Med. Sci. Sports Exerc*, *47*(12), 2579–2585. https://doi.org/10.1249/MSS.0000000000000700

Hewett, T. E., Stroupe, A. L., Nance, T. A., & Noyes, F. R. (1996). Plyometric training in female athletes: Decreased impact forces and increased hamstring torques. *American Journal of Sports Medicine*, *24*(6), 765–773. https://doi.org/10.1177/036354659602400611

Hirokawa, S., Solomonow, M., Yun lu, Lou, Z. P., & D’Ambrosia, R. (1992). Anterior-posterior and rotational displacement of the tibia elicited by quadriceps contraction. *The American Journal of Sports Medicine*. https://doi.org/10.1177/036354659202000311

Hoch, J. M., Baez, S. E., & Hoch, M. C. (2019). Examination of ankle function in individuals with a history of ACL reconstruction. *Physical Therapy in Sport : Official Journal of the Association of Chartered Physiotherapists in Sports Medicine*, *36*, 55–61. https://doi.org/10.1016/J.PTSP.2019.01.002

Huston, L. J., & Wojtys, E. M. (1996). Neuromuscular Performance Characteristics in Elite Female Athletes. *The American Journal of Sports Medicine*, *24*(4), 427–436. https://doi.org/10.1177/036354659602400405

Impellizzeri, F. M., Bizzini, M., Dvorak, J., Pellegrini, B., Schena, F., & Junge, A. (2013). Physiological and performance responses to the FIFA 11+ (part 2): a randomised controlled trial on the training effects. *Journal of Sports Sciences*, *31*(13), 1491–1502. https://doi.org/10.1080/02640414.2013.802926

Ireland, M. L. (2002). The female ACL: Why is it more prone to injury? *Journal of Orthopaedics*, *33*(4), 637–651. https://doi.org/10.1016/S0972-978X(16)00023-4

Jacobs, R., Bobbert, M. F., & van Ingen Schenau, G. J. (1996). Mechanical output from individual muscles during explosive leg extensions: The role of biarticular muscles. *Journal of Biomechanics*, *29*(4), 513–523. https://doi.org/10.1016/0021-9290(95)00067-4

Kain, C. C., McCarthy, J. A., Arms, S., Pope, M. H., Steadman, J. R., Manske, P. R., & Shively, R. A. (1988). An in vivo analysis of the effect of transcutaneous electrical stimulation of the quadriceps and hamstrings on anterior cruciate ligament deformation. *The American Journal of Sports Medicine*, *16*(2), 147–152. https://doi.org/10.1177/036354658801600210

Karanikas, K., Arampatzis, A., & Brüggemann, G. P. (2009). Motor task and muscle strength followed different adaptation patterns after anterior cruciate ligament reconstruction. *European Journal of Physical and Rehabilitation Medicine*, *45*(1).

Kline, P. W., Morgan, K., Johnson, D. L., Ireland, M. L., & Noehren, B. (n.d.). *Impaired quadriceps rate of torque development and knee mechanics after anterior cruciate ligament reconstruction with patellar tendon autograft*. https://doi.org/10.1177/0363546515595834

Kocher, M. S., Smith, J. T., Iversen, M. D., Brustowicz, K., Ogunwole, O., Andersen, J., Yoo, W. J., McFeely, E. D., Anderson, A. F., & Zurakowski, D. (2011). Reliability, validity, and responsiveness of a modified International Knee Documentation Committee Subjective Knee

Form (Pedi-IKDC) in children with knee disorders. *The American Journal of Sports Medicine*, *39*(5), 933–939. https://doi.org/10.1177/0363546510383002

Kristianslund, E., Krosshaug, T., & Van den Bogert, A. J. (2012). Effect of low pass filtering on joint moments from inverse dynamics: Implications for injury prevention. *Journal of Biomechanics*. https://doi.org/10.1016/j.jbiomech.2011.12.011

Landry, S. C., McKean, K. A., Hubley-Kozey, C. L., Stanish, W. D., & Deluzio, K. J. (2007a). Neuromuscular and lower limb biomechanical differences exist between male and female elite adolescent soccer players during an unanticipated run and crosscut maneuver. *American Journal of Sports Medicine*, *35*(11). https://doi.org/10.1177/0363546507307400

Landry, S. C., McKean, K. A., Hubley-Kozey, C. L., Stanish, W. D., & Deluzio, K. J. (2007b). Neuromuscular and lower limb biomechanical differences exist between male and female elite adolescent soccer players during an unanticipated side-cut maneuver. *American Journal of Sports Medicine*, *35*(11). https://doi.org/10.1177/0363546507300823

Li, G., Rudy, T. W., Sakane, M., Kanamori, A., Ma, C. B., & Woo, S. L. Y. (1999). The importance of quadriceps and hamstring muscle loading on knee kinematics and in-situ forces in the ACL. *Journal of Biomechanics*, *32*(4), 395–400. https://doi.org/10.1016/S0021-9290(98)00181-X

Liederbach, M., Kremenic, I. J., Orishimo, K. F., Pappas, E., & Hagins, M. (2014). Comparison of landing biomechanics between male and female dancers and athletes, part 2: Influence of fatigue and implications for anterior cruciate ligament injury. *American Journal of Sports Medicine*, *42*(5), 1089–1095. https://doi.org/10.1177/0363546514524525

Lisee, C., Birchmeier, T., Yan, A., & Kuenze, C. (2019). Associations between isometric quadriceps strength characteristics, knee flexion angles, and knee extension moments during single leg step down and landing tasks after anterior cruciate ligament reconstruction. *Clinical Biomechanics*, *70*, 231–236. https://doi.org/10.1016/J.CLINBIOMECH.2019.10.012

Lloyd, D. G., & Buchanan, T. S. (2001). Strategies of muscular support of varus and valgus isometric loads at the human knee. *Journal of Biomechanics*. https://doi.org/10.1016/S0021-9290(01)00095-1

Lloyd, D. G., Buchanan, T. S., & Besier, T. F. (2005). Neuromuscular biomechanical modeling to understand knee ligament loading. *Medicine and Science in Sports and Exercise*, *37*(11), 1939–1947. https://doi.org/10.1249/01.MSS.0000176676.49584.BA

MacWilliams, B. A., Wilson, D. R., Desjardins, J. D., Romero, J., & Chao, E. Y. S. (1999). Hamstrings cocontraction reduces internal rotation, anterior translation, and anterior cruciate ligament load in weight-bearing flexion. *Journal of Orthopaedic Research*, *17*(6), 817–822. https://doi.org/10.1002/jor.1100170605

Mantovani, G., & Lamontagne, M. (2017). How Different Marker Sets Affect Joint Angles in Inverse Kinematics Framework. *Journal of Biomechanical Engineering*. https://doi.org/10.1115/1.4034708

Markatos, K., Kaseta, M. K., Lallos, S. N., Korres, D. S., & Efstathopoulos, N. (2013). The anatomy of the ACL and its importance in ACL reconstruction. In *European Journal of Orthopaedic Surgery and Traumatology* (Vol. 23, Issue 7, pp. 747–752). Eur J Orthop Surg Traumatol. https://doi.org/10.1007/s00590-012-1079-8

Markolf, K. L., Graff-Radford, A., & Amstutz, H. C. (1978). In vivo knee stability. A quantitative assessment using an instrumented clinical testing apparatus. *Journal of Bone and Joint Surgery - Series A*. https://doi.org/10.2106/00004623-197860050-00014

Markolf, K. L., O'Neill, G., Jackson, S. R., & McAllister, D. R. (2004). Effects of applied quadriceps and hamstrings muscle loads on forces in the anterior and posterior cruciate ligaments. *American Journal of Sports Medicine*. https://doi.org/10.1177/0363546503262198

McLean, S. G., Huang, X., & Van Den Bogert, A. J. (2005). Association between lower extremity posture at contact and peak knee valgus moment during sidestepping: Implications for ACL injury. *Clinical Biomechanics*. https://doi.org/10.1016/j.clinbiomech.2005.05.007

Mokhtarzadeh, H., Yeow, C. H., Hong Goh, J. C., Oetomo, D., Malekipour, F., & Lee, P. V. S. (2013). Contributions of the Soleus and Gastrocnemius muscles to the anterior cruciate ligament loading during single-leg landing. *Journal of Biomechanics*, *46*(11), 1913–1920. https://doi.org/10.1016/j.jbiomech.2013.04.010

Montgomery, C., Blackburn, J., Withers, D., Tierney, G., Moran, C., & Simms, C. (2018). Mechanisms of ACL injury in professional rugby union: A systematic video analysis of 36 cases. *British Journal of Sports Medicine*, *52*(15), 994–1001. https://doi.org/10.1136/bjsports-2016-096425

Montgomery, M. M., Shultz, S. J., & Schmitz, R. J. (2014). The effect of equalizing landing task demands on sex differences in lower extremity energy absorption. *Clinical Biomechanics*, *29*(7), 760–766. https://doi.org/10.1016/j.clinbiomech.2014.06.004

Morgan, K. D., Donnelly, C. J., & Reinbolt, J. A. (2014). Elevated gastrocnemius forces compensate for decreased hamstrings forces during the weight-acceptance phase of single-leg jump landing: Implications for anterior cruciate ligament injury risk. *Journal of Biomechanics*, *47*(13), 3295–3302. https://doi.org/10.1016/j.jbiomech.2014.08.016

Myer, G. D., Ford, K. R., & Hewett, T. E. (2004). Rationale and clinical techniques for anterior cruciate ligament injury prevention among female athletes. *Journal of Athletic Training*.

Myer, G. D., Ford, K. R., McLean, S. G., & Hewett, T. E. (2006). The effects of plyometric versus dynamic stabilization and balance training on lower extremity biomechanics. *American Journal of Sports Medicine*. https://doi.org/10.1177/0363546505281241

Myklebust, G., Maehlum, S., Holm, I., & Bahr, R. (2007). A prospective cohort study of anterior cruciate ligament injuries in elite Norwegian team handball. *Scandinavian Journal of Medicine & Science in Sports*, *8*(3), 149–153. https://doi.org/10.1111/j.1600-0838.1998.tb00185.x

Navacchia, A., Ueno, R., Ford, K. R., DiCesare, C. A., Myer, G. D., & Hewett, T. E. (2019). EMG-Informed Musculoskeletal Modeling to Estimate Realistic Knee Anterior Shear Force During Drop Vertical Jump in Female Athletes. *Annals of Biomedical Engineering*, *47*(12), 2416–2430. https://doi.org/10.1007/S10439-019-02318-W

Nogaro, M. C., Abram, S. G. F., Alvand, A., Bottomley, N., Jackson, W. F. M., & Price, A. (2020). Paediatric and adolescent anterior cruciate ligament reconstruction surgery. *The Bone & Joint Journal*, *102-B*(2), 239–245. https://doi.org/10.1302/0301-620X.102B2.BJJ-2019-0420.R2

Norcross, M. F., Blackburn, J. T., Goerger, B. M., & Padua, D. A. (2010). The association between lower extremity energy absorption and biomechanical factors related to anterior cruciate ligament injury. *Clinical Biomechanics*, *25*(10), 1031–1036. https://doi.org/10.1016/j.clinbiomech.2010.07.013

Padua, D. A., Marshall, S. W., Boling, M. C., Thigpen, C. A., William E. Garrett, J., & Beutler, A. I. (2009). The Landing Error Scoring System (LESS) Is a Valid and Reliable Clinical Assessment Tool of Jump-Landing Biomechanics: The JUMP-ACL Study. *Https://Doi.Org/10.1177/0363546509343200*, *37*(10), 1996–2002. https://doi.org/10.1177/0363546509343200

Parker, D. F., Round, J. M., Sacco, P., & Jones, D. A. (1990). A Cross-sectional survey of upper and lower limb strength in boys and girls during childhood and adolescence. *Annals of Human Biology*, *17*(3), 199–211. https://doi.org/10.1080/03014469000000962

Pataky, T. C., Robinson, M. A., & Vanrenterghem, J. (2013). Vector field statistical analysis of kinematic and force trajectories. *Journal of Biomechanics*, *46*(14), 2394–2401. https://doi.org/10.1016/j.jbiomech.2013.07.031

Petushek, E. J., Sugimoto, D., Stoolmiller, M., Smith, G., & Myer, G. D. (2019). Evidence-Based Best-Practice Guidelines for Preventing Anterior Cruciate Ligament Injuries in Young Female Athletes: A Systematic Review and Meta-analysis. *American Journal of Sports Medicine*, *47*(7), 1744–1753. https://doi.org/10.1177/0363546518782460

Pollard, C. D., Sigward, S. M., & Powers, C. M. (2017). ACL Injury Prevention Training Results in Modification of Hip and Knee Mechanics During a Drop-Landing Task. *Orthopaedic Journal of Sports Medicine*, *5*(9). https://doi.org/10.1177/2325967117726267

Powell, J. W., & Barber-Foss, K. D. (2000a). Sex-related injury patterns among selected high school sports. *American Journal of Sports Medicine*. https://doi.org/10.1177/03635465000280031801

Powell, J. W., & Barber-Foss, K. D. (2000b). Sex-related injury patterns among selected high school sports. *American Journal of Sports Medicine*. https://doi.org/10.1177/03635465000280031801

Quatman, C. E., Ford, K. R., Myer, G. D., & Hewett, T. E. (2006). Maturation leads to gender differences in landing force and vertical jump performance: A longitudinal study. *American Journal of Sports Medicine*. https://doi.org/10.1177/0363546505281916

Renstrom, P., Ljungqvist, A., Arendt, E., Beynnon, B., Fukubayashi, T., Garrett, W., Georgoulis, T., Hewett, T. E., Johnson, R., Krosshaug, T., Mandelbaum, B., Micheli, L., Myklebust, G., Roos, E., Roos, H., Schamasch, P., Shultz, S., Werner, S., Wojtys, E., & Engebretsen, L. (2008a). Non-contact ACL injuries in female athletes: An International Olympic Committee current concepts. *British Journal of Sports Medicine*. https://doi.org/10.1136/bjsm.2008.048934

Renstrom, P., Ljungqvist, A., Arendt, E., Beynnon, B., Fukubayashi, T., Garrett, W., Georgoulis, T., Hewett, T. E., Johnson, R., Krosshaug, T., Mandelbaum, B., Micheli, L., Myklebust, G., Roos, E., Roos, H., Schamasch, P., Shultz, S., Werner, S., Wojtys, E., & Engebretsen, L. (2008b). Non-contact ACL injuries in female athletes: An International Olympic Committee current concepts. *British Journal of Sports Medicine*. https://doi.org/10.1136/bjsm.2008.048934

Report Card Development Team. (2018). *The 2018 ParticipACTION Report Card on Physical Activity for Children and Youth*.

Romanchuk, N. J., Bel, M. J. Del, & Benoit, D. L. (2020). SEX-SPECIFIC ENERGY ABSORPTION STRATEGIES DURING UNANTICIPATED SINGLE-LEG LANDINGS IN ADOLESCENTS: IMPLICATIONS FOR KNEE INJURIES. *Orthopaedic Journal of Sports Medicine*, *8*(4_suppl3), 2325967120S0023. https://doi.org/10.1177/2325967120s00237

Romanchuk, N. J., del Bel, M. J., & Benoit, D. L. (2020). Sex-specific landing biomechanics and energy absorption during unanticipated single-leg drop-jumps in adolescents: implications for knee injury mechanics. *Journal of Biomechanics*, 110064. https://doi.org/10.1016/j.jbiomech.2020.110064

Round, J. M., Jones, D. A., Honour, J. W., & Nevill, A. M. (1999). Hormonal factors in the development of differences in strength between boys and girls during adolescence: A longitudinal study. *Annals of Human Biology*, *26*(1), 49–62. https://doi.org/10.1080/030144699282976

Sale, D., Quinlan, J., Marsh, E., McComas, A. J., & Belanger, A. Y. (1982). Influence of joint position on ankle plantarflexion in humans. *Journal of Applied Physiology Respiratory Environmental and Exercise Physiology*. https://doi.org/10.1152/jappl.1982.52.6.1636

Sanders, T. L., Maradit Kremers, H., Bryan, A. J., Larson, D. R., Dahm, D. L., Levy, B. A., Stuart, M. J., & Krych, A. J. (2016). Incidence of anterior cruciate ligament tears and reconstruction: A 21-year population-based study. *American Journal of Sports Medicine*, *44*(6), 1502–1507. https://doi.org/10.1177/0363546516629944

Scheffler, S. (2012). The cruciate ligaments: Anatomy, biology, and biomechanics. In *The Knee Joint: Surgical Techniques and Strategies* (Vol. 9782287993, pp. 11–21). https://doi.org/10.1007/978-2-287-99353-4_2

Schmitz, R. J., Kulas, A. S., Perrin, D. H., Riemann, B. L., & Shultz, S. J. (2007). Sex differences in lower extremity biomechanics during single leg landings. *Clinical Biomechanics*, *22*(6), 681–688. https://doi.org/10.1016/j.clinbiomech.2007.03.001

Sepúlveda, F., Sánchez, L., Amy, E., & Micheo, W. (2017). Anterior cruciate ligament injury: Return to play, function and long-term considerations. *Current Sports Medicine Reports*, *16*(3), 172–178. https://doi.org/10.1249/JSR.0000000000000356

Shea, K. G., Pfeiffer, R., Jo, H. W., Curtin, M., & Apel, P. J. (2004). Anterior cruciate ligament injury in pediatric and adolescent soccer players: An analysis of insurance data. *Journal of Pediatric Orthopaedics*. https://doi.org/10.1097/01241398-200411000-00005

Shultz, S. J. (2008). Differences in Lower Extremity Anatomical and Postural Characteristics in Males and Females Between Maturation Groups. *J Orthop Sports Phys Ther*, *38*(3), 137–149. https://doi.org/10.2519/jospt.2008.2645

Sinclair, J., Brooks, D., & Stainton, · Philip. (2019). Sex differences in ACL loading and strain during typical athletic movements: a musculoskeletal simulation analysis. *European Journal of Applied Physiology*, *119*(3), 713–721. https://doi.org/10.1007/s00421-018-04062-w

Slauterbeck, J. R., Hickox, J. R., Beynnon, B., & Hardy, D. M. (2006). Anterior Cruciate Ligament Biology and Its Relationship to Injury Forces. In *Orthopedic Clinics of North America* (Vol. 37, Issue 4, pp. 585–591). https://doi.org/10.1016/j.ocl.2006.09.001

Snyder-Mackler, L., Delitto, A., Stralka, S. W., & Bailey, S. L. (1994). Use of electrical stimulation to enhance recovery of quadriceps femoris muscle force production in patients following anterior cruciate ligament reconstruction. *Physical Therapy*, *74*(10), 901–907. https://doi.org/10.1093/ptj/74.10.901

Steffen, K., Nilstad, A., Kristianslund, E. K., Myklebust, G., Bahr, R., & Krosshaug, T. (2016). Association between lower extremity muscle strength and noncontact ACL injuries. *Medicine and Science in Sports and Exercise*, *48*(11), 2082–2089. https://doi.org/10.1249/MSS.0000000000001014

Takahashi, S., Nagano, Y., Ito, W., Kido, Y., & Okuwaki, T. (2019). A retrospective study of mechanisms of anterior cruciate ligament injuries in high school basketball, handball, judo, soccer, and volleyball. *Medicine*, *98*(26), e16030. https://doi.org/10.1097/MD.0000000000016030

Taylor, S. J. C., Whincup, P. H., Hindmarsh, P. C., Lampe, F., Odoki, K., & Cook, D. G. (2001). Performance of a new pubertal self-assessment questionnaire: A preliminary study. *Paediatric and Perinatal Epidemiology*, *15*(1), 88–94. https://doi.org/10.1046/j.1365-3016.2001.00317.x

Tegner, Y., & Lysholm, J. (1985). Rating systems in the evaluation of knee ligament injuries. *Clinical Orthopaedics and Related Research*. https://doi.org/10.1097/00003086-198509000-00007

Tengman, E., Brax Olofsson, L., Stensdotter, A. K., Nilsson, K. G., & Häger, C. K. (2014). Anterior cruciate ligament injury after more than 20 years. II. Concentric and eccentric knee muscle strength. *Scandinavian Journal of Medicine and Science in Sports*, *24*(6), e501-509. https://doi.org/10.1111/SMS.12215

Thomas, A. C., Villwock, M., Wojtys, E. M., & Palmieri-Smith, R. M. (2013). Lower Extremity Muscle Strength After Anterior Cruciate Ligament Injury and Reconstruction. *Journal of Athletic Training*, *48*(5), 610–620. https://doi.org/10.4085/1062-6050-48.3.23

Torzilli, P. A., Xianghua Deng, & Warren, R. F. (1994). The Effect of Joint-Compressive Load and Quadriceps Muscle Force on Knee Motion in the Intact and Anterior Cruciate Ligament-Sectioned Knee. *The American Journal of Sports Medicine*, *22*(1), 105–112. https://doi.org/10.1177/036354659402200117

van Melick, N., H van Cingel, R. E., Brooijmans, F., Neeter, C., van Tienen, T., Hullegie, W., & G Nijhuis-van der Sanden, M. W. (2016). Evidence-based clinical practice update: practice guidelines for anterior cruciate ligament rehabilitation based on a systematic review and multidisciplinary consensus. *British Journal of Sports Medicine*, *50*, 1506–1515. https://doi.org/10.1136/bjsports-2015-095898

van Melick, N., Meddeler, B. M., Hoogeboom, T. J., Nijhuis-van der Sanden, M. W. G., & van Cingel, R. E. H. (2017). How to determine leg dominance: The agreement between self-reported and observed performance in healthy adults. *PLoS ONE*. https://doi.org/10.1371/journal.pone.0189876

Waldén, M., Krosshaug, T., Bjørneboe, J., Andersen, T. E., Faul, O., & Hägglund, M. (2015). Three distinct mechanisms predominate in noncontact anterior cruciate ligament injuries in male professional football players: A systematic video analysis of 39 cases. *British Journal of Sports Medicine*, *49*(22), 1452–1460. https://doi.org/10.1136/bjsports-2014-094573

Webster, K. E., Feller, J. A., & Lambros, C. (2008). Development and preliminary validation of a scale to measure the psychological impact of returning to sport following anterior cruciate ligament reconstruction surgery. *Physical Therapy in Sport*, *9*, 9–15. https://doi.org/10.1016/j.ptsp.2007.09.003

Werner, B. C., Yang, S., Looney, A. M., & Gwathmey, F. W. (2016). Trends in pediatric and adolescent anterior cruciate ligament injury and reconstruction. *Journal of Pediatric Orthopaedics*. https://doi.org/10.1097/BPO.0000000000000482

Wiggins, A. J., Grandhi, R. K., Schneider, D. K., Stanfield, D., Webster, K. E., & Myer, G. D. (2016). Risk of Secondary Injury in Younger Athletes after Anterior Cruciate Ligament Reconstruction. In *American Journal of Sports Medicine* (Vol. 44, Issue 7, pp. 1861–1876). https://doi.org/10.1177/0363546515621554

Wild, C. Y., Steele, J. R., & Munro, B. J. (2013). Musculoskeletal and Estrogen Changes during the Adolescent Growth Spurt in Girls. *Medicine & Science in Sports & Exercise*, *45*(1), 138–145. https://doi.org/10.1249/MSS.0b013e31826a507e

Wingfield, K. (2013). Neuromuscular Training to prevent knee injuries in adolescent female soccer players. *Clinical Journal of Sport Medicine*. https://doi.org/10.1097/01.jsm.0000433153.51313.6b

Winter, D. A. (2009). Mechanical Work, Energy, and Power. In *Biomechanics and Motor Control of Human Movement*. https://doi.org/10.1002/9780470549148.ch6

Worrell, T. W., Karst, G., Adamczyk, D., Moore, R., Stanley, C., Steimel, B., & Steimel, S. (2001). Influence of joint position on electromyographic and torque generation during maximal voluntary isometric contractions of the hamstrings and gluteus maximus muscles. *Journal of Orthopaedic and Sports Physical Therapy*. https://doi.org/10.2519/jospt.2001.31.12.730

Wright, R. W., Haas, A. K., Anderson, J., Calabrese, G., Cavanaugh, J., Hewett, T. E., Lorring, D., McKenzie, C., Preston, E., Williams, G., & MOON Group. (2015). Anterior Cruciate Ligament Reconstruction Rehabilitation: MOON Guidelines. *Sports Health*, *7*(3), 239–243. https://doi.org/10.1177/1941738113517855

Yanagawa, T., Shelburne, K., Serpas, F., & Pandy, M. (2002). Effect of hamstrings muscle action on stability of the ACL-deficient knee in isokinetic extension exercise. *Clinical Biomechanics*, *17*(9–10), 705–712. https://doi.org/10.1016/S0268-0033(02)00104-3

Yasuda, K., & Sasaki, T. (1987). Exercise after anterior cruciate ligament reconstruction. The force exerted on the tibia by the separate isometric contractions of the quadriceps or the hamstrings. *Clinical Orthopaedics and Related Research*, *No. 220*, 275–283. https://doi.org/10.1097/00003086-198707000-00038

Yu, B., & Garrett, W. E. (2007). Mechanisms of non-contact ACL injuries. In *British Journal of Sports Medicine* (Vol. 41, Issue SUPPL. 1, pp. 47–51). https://doi.org/10.1136/bjsm.2007.037192

Zhang, S. N., Bates, B. T., & Dufek, J. S. (2000). Contributions of lower extremity joints to energy dissipation during landings. *Medicine and Science in Sports and Exercise*. https://doi.org/10.1097/00005768-200004000-00014

APPENDIX A

Table A.1

Summary of all tasks performed by participants during each data collection

Task	Description
Max Anterior Hop	Max anterior hops consisted of jumping as far forward as possible on one leg
Max Lateral Hop	Max lateral hops consisted of jumping as far laterally as possible on one leg
Timed Hop	Timed hop consisted of hopping on one leg for six meters as fast as possible
Cross Hop	Cross hop consisted of performing three consecutive hops while jumping across a midline, all as far as possible
Triple Hop	Triple hop consisted of jumping as far as possible on a single leg three consecutive times
Squats	Squats consisted of standing in a comfortable position and squatting down as far as comfortable and returning to the original position
Counter-Movement Jump	Counter-movement jumps consisted of standing in a comfortable position and jumping as high as possible and then returning to the original position
Lunges	Lunges consisted of stepping forward with one to a force plate in front of them and lunging down without touching the force plate with their front knee and then returning to the starting position
Side-Cut	Side-cut consisted of running and then cutting at a 45º angle as fast as possible
Drop-Vertical Jump	Drop-vertical jumps consisted of stepping off a raised platform (aligned to the participant’s tibial plateau), immediately performing a two-legged maximal vertical jump, and landing onto a force platform

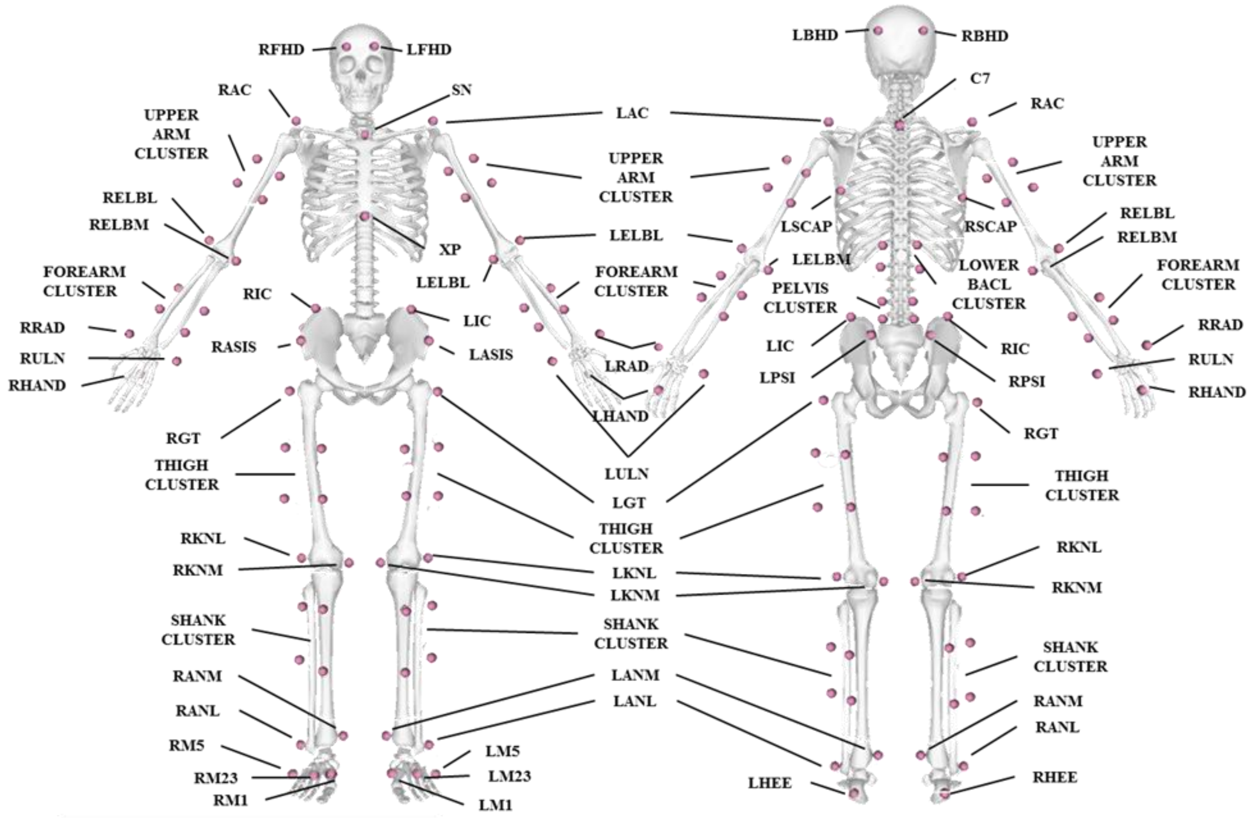

Figure A.1. Clinical Biomechanics Research Unit (CBRU) cluster marker set, adapted from the Human Movement Biomechanics Laboratory cluster marker set. Plug-in-Gait marker set acted as the basis with the additions of medial knee, ankle and elbow markers (LMKN, RMKN, LMAN, RMAN, LELBM, RELBM), three thigh,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