Relationship between back squat strength to body mass ratio and muscle activity during single-leg landing tasks in varsity athletes

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ABSTRACT

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Sébastien Girard

The number of injuries sustained by female athletes has been on the rise. Female athletes are 4 to 8 times more at risk of suffering an anterior cruciate ligament injury (ACL). Strength is believed to be an important predictor of ACL injury in female athletes and has been a focus of improvement in injury prevention programs. However, there is a lack of consensus on the relationship between muscle strength and hip and knee kinematics during landing tasks. Only a few studies used a lower extremity relative strength measure and reported promising results, but none of them reported EMG activity. The goal of this study was to explore the relationship between back squat strength to body mass ratio and the lower limb muscle activity during single-leg landing tasks.

Twenty-eight varsity athletes were recruited (13 males and 15 females) from various sports from the universities in the Montreal, Québec region. Participants were asked to perform a standardized 1-RM back squat test followed by single-leg drop landings from 28cm and 44cm plyometric boxes. EMG data was collected 150ms pre-initial and 250ms post-initial contact for the following muscles: biceps femoris (BF), semitendinosus (ST), vatus lateralis (VL), vastus medialis (VMO), rectus femoris (RF), gluteus medius (GMED) and gluteus maximus (GMAX). Significant differences were found between male and female athletes on the back squat one-repetition maximum and squat to body mass ratio (SQ:BW). Females had significantly more neuromuscular activity of the quadriceps and GMAX, and significantly less activity of the biceps femoris in both landing phases. After controlling for strength, only significant differences in RF, BF and GMAX activity remained between sexes in the deceleration phase. Prior to landing, moderate negative correlations between VL, VMO and GMAX activity and SQ:BW were observed at both drop heights. During the post-initial contact phase, moderate negative correlations for VL and VMO activity were found at both drop heights. Our findings suggest that researchers looking at sex-based differences in muscle activity should control for relative strength differences between groups as it may influence muscle activity during landing tasks.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

ACL: Anterior Cruciate Ligament

BF: Biceps Femoris

EMG: Electromyography

nEMG: Normalized Electromyography

GMAX: Gluteus Maximus

GMED: Gluteus Medius

IQR: Inter-quartile Range

MVIC: Maximal Voluntary Isometric Contraction

NCAA: National Collegiate Athletic Association

SM: Semimembranosus

RF: Rectus Femoris

SQ:BW: Squat to Bodyweight Ratio

TIBANT: Tibialis Anterior

VL: Vastus Lateralis

VMO: Vastus Medialis Oblique

1RM: One-repetition Maximum

CHAPTER 1 - LITERATURE REVIEW

1.1 Prevalence of ACL injuries

Athletes who participate in competitive sports are exposed to stresses and strains that increase the risk of injury. A review of the injury data collected by the NCAA through its Injury Surveillance System over 16 years reported that more than 50% of all the injuries reported across 15 sports were lower extremity injuries, with knee and ankle injuries being the most prevalent. Moreover, ankle ligament sprains accounted for 14.9% of all injuries, while ACL injuries account for 2.6% (Hootman et al., 2007). Besides ACL injuries, a 15 years retrospective cohort study of injury reports did not find any significant differences in the overall pattern of injury between male and female athletes competing in basketball, cross-country, soccer, swimming, tennis, track and water polo (Sallis et al., 2001). Moreover, the rate of game injuries is 3.5 times higher than the rate of practice injuries, which represents 1 injury every 2 games and 1 injury every 5 practices for a team of 50 participants (Hootman et al., 2007).

ACL ligament tears are one of the most severe knee injuries as they result in prolonged post-operative recovery and time away from the athlete's sport. The consequences of such an injury are significant, as it may result in loss of entire seasons of sports participation, decreased scholarship funding, lowered academic performance, long term disability, and significantly greater risk of osteoarthritis later in life (Ruiz et al., 2002) (Shelbourne, 2008). It is estimated that a quarter of a million anterior cruciate ligament injuries occur each year in Canada and in the United States (Campbell et al., 2014). There is nearly 350 000 ACL reconstructions performed annually in the United States. The cost associated with each ACL tear is estimated to be between US $17 000 and $25 000, including surgery and rehabilitation (Hewett et al., 1999) (Loes et al., 2000). The annual cost of care related to ACL reconstructions in the United States is estimated to be more than 2 billion, with US $650 millions only for female high school and college athletes (Wojtys and Brower, 2010). Since the introduction of the Title IX of the Educational Assistance Act in 1972, women participation in sports has been growing every year. Consequently the number of injuries sustained by female athletes is also on the rise (Sallis et al., 2001) (Myer et al., 2005). The rate of ACL injuries increased significantly since the late 1980s (Hootman et al., 2007). The risk of ACL tears is 4 to 8 times greater in female athletes than male athletes (Arendt et al., 1999) (Toth and Cordasco, 2001) (Krosshaug et al., 2007). A meta-analysis of the literature published on the incidence of ACL tears reported the following male versus female ACL tears ratios by sport: wrestling, 4.05; basketball, 3.5; indoor soccer, 2.77; soccer, 2.67; rugby, 1.94; lacrosse, 1.18; and alpine skiing, 1.00 (Prodromos et al., 2007). Nearly 70% of ACL injuries in female athletes result from a non-contact mechanism (Silvers and Mandelbaum, 2007). The reasons for this sex difference are likely a combination of anatomical, biomechanical, neuromuscular and hormonal factors (Griffin et al., 2000) (Barber-Westin et al., 2009). Because the anatomical differences cannot be addressed for prevention, the focus of research on preventive strategies has been on biomechanical risk factors, neuromuscular training and the effects of the menstrual cycle on the incidence of ACL injuries.

1.2 Risk factors for ACL injuries

With the evidence showing higher incidence of ACL injuries in female athletes, several researchers tried to identify the different risk factors that place the ACL at a greater risk of injury. A better understanding of those risk factors will help us identify which athletes are at a high risk for this injury and will improve our ability to design and implement preventive strategies. Sex differences have been found when comparing anatomical, hormonal, biomechanical and neuromuscular risk factors.

1.2.1 Anatomical risk factors

Typically, a female athlete has greater femoral anteversion, increased Q angle, excessive tibial torsion and excessive subtalar pronation than a male athlete. These differences have been associated with a higher risk of ACL injury (Silvers and Mandelbaum, 2007). Other anatomical risk factors such as body mass index (BMI), knee hyperextension, joint laxity, genetic predisposition and prior injury history have been reported also been reported (Alentorn et al., 2009).

Women are more prone to have a greater posterior tibial slope (PTS), which has been suggested to lead to increased anterior translation of the tibia (Hashemi et al., 2008) (Hashemi e al., 2011) (Dejour and Bonnin, 1994). A meta-analysis examining studies from 1997 to 2011 reported a strong association between a narrow femoral notch and increased risk of ACL injury (Zeng et al., 2013). It has been suggested that women have smaller femoral notches and smaller ACL size, cross-sectional area, mass and density, but because of a lack of a standardized methods for measurement, further research is needed to support these allegations (Lipps et al., 2012). Differences in structural properties of the ACL have been observed between sexes, as female have lower fibril concentration and a lower percentage of collagen fibrils, resulting in a lower tensile strength to failure and modulus of elasticity (Chandrashekar et al., 2005).

1.2.2 Hormonal risk factors

Many studies found a correlation between reproductive hormones and the incidence of ACL injuries (Arendt et al., 1999) (Griffin et al., 2000) (Vauhnik et al., 2008) (Zazulak et al., 2006). A higher incidence of these injuries has occurred simultaneously with estrogen and progesterone surges during a normal 28- to 30- menstrual cycle. Receptors for these two hormones have been found in the anterior cruciate ligament leading to believe that these two hormones may predispose female athletes to non-contact ACL injuries by altering the structural and compositional properties of the ligament (Heitz et al., 1999). A positive relationship between the level of estrogen in blood and ACL laxity has been reported. (Liu et al., 1997) (Yu et al., 1999) (Shultz et al., 2007) (Hansen et al., 2009). However, these changes in hormonal concentrations cannot directly explain the increased incidence of ACL injuries at a specific time throughout the menstrual cycle (Silvers and Mandelbaum, 2007).

1.2.3 Biomechanical risk factors

Understanding the mechanisms of injury in sport is necessary to design effective preventive programs. The "position of no return", where the trunk is flexed forward and rotated toward the opposite side, hips adducted and internally rotated and knee in valgus may place the ACL to a high risk of rupture (Ireland, 1999). A review of the risk factors that may put an athlete at risk for an ACL injury reported the following biomechanical risk factors: knee abduction, anterior tibial shear, lateral trunk motion, tibial rotation, dynamic foot pronation, fatigue and ground reaction forces (Alentorn et al., 2009).

The trunk orientation can influence the muscular demands of the lower extremity. Landing with increased trunk flexion has been shown to increase knee and hip flexion angles, which has been associated with a reduced ACL injury risks (Blackburn and Padua, 2008)

(Griffin et al., 2008) (Hewett et al., 2000). Lateral displacement of the trunk is a high predictor of ligament injury therefore core stability may be an important component of a prevention program (Zazulak et al., 2007). Female athletes land with decreased hip abduction compared to their male counter-part, which may place an increased valgus stress over the knee. They also land with a greater frontal plane velocity (Jenkins et al., 2017) that represents a loss of control which has been suggested as a potential contributor to injury (Joseph et al., 2011). Females also tend to have a decreased hip external rotation and increased knee internal rotation (Ford et al., 2005).

1.2.4 Neuromuscular risk factors

The involuntary contraction of the stabilizing muscles surrounding a joint in reaction to a stimulus is referred as neuromuscular control. The neuromuscular has an influence on biomechanics as it generates movement. The differences in unconscious muscle action might partially explain why certain individuals are more at risk of suffering an ACL injury (Olsen et al., 2004). The following neuromuscular risk factors are related to increase risk of ACL injury: relative hamstring to quadriceps activation, hip abduction strength and trunk proprioception (Alentorn et al., 2009).

1.3 Influence of strength on ACL injury risk factors

1.3.1 Influence of strength on neuromuscular risk factors

Strength is believed to be an important predictor of ACL injury in female athletes and has been a focus of improvement in injury prevention programs. It may have effect on injury risk through its influence on neuromuscular activation patterns, joint stiffness, antagonist muscle balance, ground reaction forces and joint mechanics.

Muscle fatigue is a way to experimentally induce muscle weakness and study its effects on lower limb mechanics. Examining a movement pattern before and after inducing fatigue in a specific muscle can provide insight into the muscle's role in the execution of a task. For example, if the execution of a task is negatively affected after localized muscle fatigue, it may mean that reduced muscle strength is responsible for it. However, if the execution of the task is unaltered but a greater neuromuscular activity occurs, it suggests that muscle strength has little influence on the task execution and that improved neuromuscular control can compensate for the diminished strength. Following a fatigue protocol targeting the hip extensors, gluteus maximus activation was increased by 55% when performing three consecutive maximal vertical jumps. On the other hand, kinematics remained unchanged after a 25% reduction in hip extensor strength (Hollman et al., 2012). A potential reason for this is that a 25% reduction in hip extensor strength might be insufficient to alter knee and hip kinematics for a bilateral jump-landing task. A single-leg landing task might have been more appropriate to study the role of strength in preventing knee valgus as it is more sports-specific and more demanding on the lower extremity stabilizers. Similarly, individuals with lower hip abductors and external rotators strength have greater EMG amplitude for the gluteus maximus and gluteus medius when performing a double-leg jump landing. These findings suggest that a greater neural drive to the gluteal musculature is used to achieve the same kinematics as a compensation (Homan et al., 2013). This inverse relationship between hip strength and neuromuscular activity is also supported by Nguyen et al. (2011) during the single-leg squat.

A fatigue protocol targeting the gluteus medius resulting in a 43% decrease in peak hip abductor isometric strength failed to produce hip and knee kinematics changes at initial contact and at 60ms after landing in women. Fatigue caused a delay in the activation of the gluteus medius, suggesting a reduction in anticipatory muscle activation (Patrek et al., 2011). Regardless of the sex, peak hip flexion and adduction increased when performing single-leg landing following a 30 seconds hip-abduction endurance test (Jacobs et al., 2007). Following an overall lower extremity fatigue, an increase trunk flexion and in vastus lateralis, biceps femoris and gluteus maximus activity occurred in recreational athletes with this protocol. This increase in muscle activity is believed to be a strategy to reduce the load on the ACL in conjunction with the increase trunk flexion (Lessi & Serrao, 2015).

1.3.2 Influence of strength on biomechanical risk factors

Most of the studies that investigated the relationship between strength and knee mechanics during landing maneuvers used single-joint isometric measures of strength. Lower extremity dynamic knee valgus is associated with reduced hip abduction, extension and external rotation strength during single-leg landing tasks for females. Six studies reported negative low-to-moderate correlations between hip abduction strength and frontal plane knee displacement during landing tasks in female (Jacobs and Mattcola, 2005) (Jacobs et al. 2007) (Wallace et al., 2008) (Munkh-Erdene et al., 2011) (McCurdy et al., 2014) (Suzuki et al., 2015). Two studies reported negative low-to-moderate correlations for hip extension strength and knee valgus (Munkh-Erdene et al., 2011) (McCurdy et al., 2014). Three studies reported similar correlations for hip external rotation strength and knee valgus (Munkh-Erdene et al., 2011) (McCurdy et al., 2014) (Suzuki et al., 2015). Three other studies did not report any significant correlations between hip abductors, external rotators and extensors strength and knee valgus (Lawrence et al., 2008) (Homan et al., 2013) (Martinez et al., 2018). Interestingly, one study reported that hip abduction strength positively correlates with knee valgus (Hollman et al., 2009) during a step-down maneuvers. This finding could possibly be explained by the contribution of the gluteus medius to internal rotation during hip flexion. As the stance leg hip is flexed, the internal rotation moment of the anterior fibers increases while the moment arm of the remaining fibers switches from external rotation to internal rotation (Delp et al., 1999).

Weight-bearing multi-joint measures of strength might demonstrate a stronger relationship with joint mechanics that occur during landing tasks than single-joint and non-weight bearing strength measures as they involve similar movement patterns. Typically, athletes train using multi-joint, free-weight exercises such as squats for injury prevention and performance based on the specificity principle. Sex differences exist in absolute strength measures between males and females, with females exhibiting a deficit of 50% in upper body strength and about 30% in lower body strength (Hakkinen & Hakkinen, 1995). The one-repetition maximum (1RM) barbell back squat has been shown to be an important predictor for traumatic knee injuries in youth female athletes. According to a recent study conducted by Augustsson and Ageberg (2017) where participants were split into a weak and strong group based on their squat to bodyweight ratio, weaker female athletes were 9.5 and 7.5 times more at risk of suffering a traumatic knee injury and an ACL injury respectively. The authors suggested a 1.05 ratio cut-off value to distinguish between high and low risk of injury in youth female athletes. Wallace et al. (2008) did not find any correlation between absolute back squat strength and the landing kinematics from a vertical jump in both sexes. There were limitations in this study that could explain the lack of correlation reported by the authors. First of all, to be included in the study male participants were required to squat at least 1.5 times their bodyweight while female participants had to squat one time their bodyweight. Only stronger individuals were included in the study, excluding a possible correlation for the weaker athletes. Also, absolute strength values were used instead of relative values relative to their body weight. On the other hand, strong correlations between knee valgus during landing tasks and absolute modified single-leg squat (MSLS) and bilateral squat (BS) strength were reported in recreationally active females (McCurdy et al., 2014). Squat strength strongly correlates with knee valgus in bilateral (60 cm) ($-0.77 \leq r \leq -0.81$) and unilateral (30 cm) ($-0.78 \leq r \leq -0.83$) drop jumps, which suggests that women with higher level of strength produce mechanics associated with a lower risk of ACL injury (McCurdy et al., 2014). Absolute strength measures might not be the ideal way to measure one's strength, as they do not take into account the body mass. Differences in body composition play a major role in strength divergence, with females requiring 12% of essential body fat as opposed to 3% for males (Abe et al., 1998). One study investigated the relationship between relative squat strength values and knee front-plane displacement during jump landings. They reported moderate correlations between men's and women's strength to body mass ratio and knee valgus during drop jumps from 30cm (0.448), 45cm (0.449) and 60cm (0.439) (Haines et al., 2011). None of the studies that investigated the relationship between squat strength and knee kinematics during landing tasks reported EMG activity data. Recording EMG activity could provide insightful information on the influence of squat strength on muscle activity during landing tasks and help understanding the relationship between knee kinematics and muscle activity.

1.4 Sex differences for neuromuscular risk factors

1.4.1 Muscle activity

One of the proposed risk factor to explain the greater injury rate in female athletes is the difference in muscle activity between sexes (Alentorn et al., 2009). Researchers looked at muscle activation differences between male and female when performing different landing and cutting tasks. A lot of attention has been put into the quadriceps and the hamstrings as they help stabilize the knee, as well as the gluteus medius, a major lateral stabilizer of the hip. Many researchers hypothesized that differences in gluteus medius activation might be a reason why female athletes display greater valgus angles when performing various athletic tasks (Zuzulak et al., 2005) (Russel et al. 2006) (Carcia et al., 2007). A common exercise to screen for poor hip strength and trunk control is the single-leg squat and is used in pre-participation examinations. When performing a single-leg squat, women display more ankle dorsiflexion and pronation, and hip adduction, flexion and external rotation (Zeller et al., 2003). Furthermore, they tend to recruit the rectus femoris muscle more than their male counterpart (Zeller et al., 2003). During cutting manoeuvres, women may use motor control strategies that may alter their knee kinematics. These strategies result in lower knee flexion angles, greater knee valgus angles, greater quadricep muscles activity and lower hamstring muscles activity (Malinzak et al., 2001). These alterations are likely to increase the load on the ACL. When performing side-step cutting manoeuvres, female athletes show greater vastus lateralis activity than their male counterpart (Hanson et al., 2008) (Sigward & Powers, 2006) (Malinzak et al., 2001). Greater gluteus medius activity during the preparatory phase has also been observed (Hanson et al. 2008). On the other hand, during the post-contact phase of bilateral jumps and 45° cuts, men recruit their lateral hamstrings more than their female counterpart. (Ebben et al., 2010).

When looking at soccer and basketball players, female athletes have more joint laxity at the knee than male athletes. The same study that reported these differences in joint laxity observed that female basketball and soccer players had greater hamstring activity (Rozzi et al, 1999). The authors suggested this increase in muscular activity to be a compensatory mechanism to the joint laxity (Rozzi et al, 1999). Differences in muscle activity and kinematics exist between male and female soccer players when performing a soccer kick. Female soccer players have lower iliacus activity in their kicking limb, as well as lower gluteus medius and vastus medialis activity in their supporting limb. Furthermore, female have greater hip adduction angles in the supporting limb (Brophy et al., 2010).

Potential differences in gluteus medius activity between sexes have been suggested to be a possible factor for the increased knee valgus during landing in female athletes, but no differences in activity have been reported during single-leg drops (Zuzulak et al., 2005) (Russel et al. 2006). These findings were supported by Carcia et al. (2007) experiment, which consisted of double-leg drop jump from a 30cm wooden box. Moreover, muscle activation for the gluteus maximus, quadriceps, hamstrings and gastrocnemius are similar between the two sexes when performing a jump-landing task from a 30cm box (Walsh et al., 2012). Although no difference was observed between sexes, there is greater variability in the EMG signal for female athletes (Carcia et al., 2007). Differences have been reported between sexes when performing common functional tasks such the step-up, step-down, lunges, etc., but there is a lack of consistency between the findings. This inconsistency might be due to the lack of standardization among studies. After adjusting the distances and step heights based on the participant's height, there are no more differences between sexes for the step-down, forward lunge and side-step lunge (Bouillon et al., 2012).

When performing jump-landing and landing tasks, a positive relationship exists between the drop height and the quadriceps muscle activation during the preparatory phase in female athletes, while the activation of the hamstring muscles remained constant regardless of the height

(Ford et al., 2011) (De Britto et al., 2014) (Zazulak et al., 2005) (Peng et al. 2011). There are inconsistent reports on a possible sex effect for the quadriceps activation during landing tasks. Zazulak et al. (2005) reported a sex effect for the quadriceps activation, while De Britto et al. (2014) did not report a sex effect for any muscle besides the medial hamstrings. The medial hamstrings showed greater pre-activation in female recreational athletes independently of the drop height. Ford et al. (2011) reported an inverse relationship between hip flexion angles and drop height in female athletes, while De Britto et al. (2014) did not support this relationship. Only one study looked at the gluteus maximus when investigating the effects of the drop height on muscle activation. Female collegiate athletes have lower gluteus maximus activation when performing single-leg landing from heights of 30.5cm and 45.8cm (Zazulak et al. 2005). According to a study by Marquez et al. (2017), males display more rectus femoris and tibialis anterior activity during the landing phase from a counter-movement jump than their females counter-part.

Few studies have looked to which extend gluteus maximus strength and activity contribute to frontal-plane knee kinematics. In healthy, active women with lower isometric hip-extensor strength and peak gluteus maximus recruitment were correlated with increased knee valgus during a jump-landing task (Hollman et al., 2013). Moreover, frontal plane knee motion correlated with frontal and transverse plane hip motions and with gluteus maximus recruitment during the single-leg squat (Hollman et al., 2014). Gluteus maximus recruitment might be more important than external rotation and abduction strength during a single-limb step-down, as it negatively correlates with knee valgus while the other two variables do not. Women land from jumps with less gluteus maximus activity than men, potentially exposing them to a greater risk of a noncontact knee injury (Zazulak et al., 2005).

1.4.2 Muscle activation timing

Differences in muscle activation timing between sexes might be a risk factors for ACL injury in female athletes. Contraction of the quadriceps initiate an anterior tibial drawer and place stress on the ACL, while the hamstrings initiate a posterior tibial drawer and negate the stress put on the ACL by the quadriceps (Markolf et al., 1990). When performing a single-leg landing, the semimembranosus muscle (SM) activates later in men suggesting a protective mechanism for the ACL (Cowling et al., 2001). This delayed activation of the SM is hypothesized to was to allow peak muscle activity to better coincide with high anterior forces, thereby acting as an ACL synergist via increased joint compression and posterior tibial drawer (Cowling et al., 2001). Rozzi et al. (1999) failed to find any differences in the timing of quadriceps and hamstrings activation during functional movements. Chappell et al. (2002) also failed to find any differences in the activation timing in recreational athletes performing stop-jump tasks. In a recent research conducted by Stearns-Reider and Powers (2018), earlier activation of the vastus lateralis and gluteus maximum was observed in females when performing a double-leg drop-jump task. The authors also investigated the rate of torque development (RTD) for the knee and hip extensors in both sexes and females demonstrated a significantly lower RTD for the hip extensors. A reduced RTD of the hip and knee extensors has been negatively correlated with vastus lateralis activation onset for women (Stearns-Reider & Powers, 2018). Divergently, Ebben et al. (2010) observed earlier activation of the vastus medialis and lateralis muscles in men compared to women during the pre-foot contact phase of a jump. When performing cutting manoeuvres, women demonstrated a longer duration of rectus femoris and vastus medialis muscle burst in the post-contact phase. The analysis of sex did not reveal any other significant differences.

CHAPTER 2 - RATIONALE, OBJECTIVES & HYPOTHESES

2.1.1 Rationale

Based on the current literature, there is a lack of consensus on the relationship between muscle strength and hip and knee kinematics during landing tasks. Most of these studies used single-joint isometric measures of strength, which show low-to-moderate correlations with frontal plane knee displacement or simply do not significantly correlate. This absence of correlation could be explained by the fact landing tasks are multi-joint in nature and involve eccentric contractions, while the strength measures used are single-joint and involve isometric contractions. Although there is ongoing research exploring the relationship between strength and hip and knee kinematics, there are very few studies that used multi-joint strength measures. Only the study by Haines et al. (2011) used a relative measure of strength, the strength to body weight mass ratio, which considers body composition and absolute strength differences between sexes. Unfortunately, the authors did not report any EMG data on muscle activity. Recording EMG activity could provide insightful information on the influence of strength on muscle activity during landing tasks. So far, the uses of the squat as a predictor for knee valgus during landing seems promising, as moderate to strong correlations have been reported. Moreover, an inverse relationship between muscle strength and neuromuscular activity in the gluteal musculature has been observed, suggesting greater neural drive as a compensation for the weakness. There is a lack of literature on the influence of the strength to body mass ratio on the muscle activity of the lower limbs during landing. Specifically, it is important to determine muscle activity to be able to target deficiencies in the injury prevention programs used by strength and conditioning coaches.

The purpose of the study was to explore the relationship between the squat strength to body mass ratio and the lower limb muscle activity during a single-leg landing. This would improve the existing knowledge on the association between strength and muscular activity during landing tasks. We looked at the influence of sex on the relationship between relative strength and muscle activity. Our results provided us more information on the possible neuromuscular compensation strategies used by weaker individuals and helped clarify the importance of strength in ACL injury prevention programs. For this study, we wanted participants with a wide range of strength to body weight ratio to determine if there's a correlation between strength and muscle activity. Therefore, we used participants from various sports as the need for strength varies among sports.

2.2 Objectives

1. Assess the squat strength to body weight ratio of male and female athletes using a 1RM back squat protocol.
2. Measure muscle activity prior and after initial contact of the non-dominant limb using EMG during single-leg landing tasks.
3. To identify the relationship between relative squat strength and muscle activity during single-leg landing tasks.
4. To determine if sex has an influence on the relationship between relative strength and muscle activity during single-leg landing tasks.

2.3 Hypotheses

1. Male athletes will have greater squat strength to body weight ratio than female athletes.

2. Female athletes will display greater quadriceps and lower gluteus maximus activity when performing the single-leg landing tasks than their male counterparts.
3. There will be a positive correlation between squat strength to body weight ratio and gluteus maximus activity during both landing phases.
4. There will be no sex effect on the relationship between relative squat strength and muscle activity during single-leg landing tasks.

CHAPTER 3 - SIGNIFICANCE OF RESEARCH PROPOSAL

The purpose of this study is to explore the relationship between relative strength and muscle activity during landing tasks in male and female varsity athletes. To date, there is a lack of published studies on the effects of relative squat strength on lower extremity muscle activity during landing tasks. By exploring this relationship, this study will contribute to the literature regarding the importance of strength in injury prevention programs. Moreover, it will build on the existing body of literature on the relationship between single-joint strength measures and muscle activity during landing tasks.

A few studies used the squat to body weight ratio as a predictor for knee valgus during landing tasks, but none of them recorded EMG activity. This study will help us to understand why stronger individuals on the squat exercise are less likely to suffer from an ACL injury their weaker counterpart during landing. Specifically, this will help to identify neuromuscular compensation strategies used by weaker individuals and will allow strength and conditioning coaches to update the injury prevention programs based on muscle activity.

CHAPTER 4 - METHODS AND PROCEDURES

4.1 Participants

All the 28 participants recruited (13 males and 15 females) were varsity athletes from various sports from the universities in the Montreal, Québec region (Table 1). The participants met the following inclusion criteria: (1) age 18 to 24 years old; (2) active member of a varsity team; (3) physically active at least 5 days a week; (4) 1 year of experience in weight lifting. Exclusion criteria for participation in the study were: (1) Recent or prior history of major lower extremity injury; (2) Regular use of a knee brace for stability during physical activity; (3) previous enrolment in an injury prevention exercise intervention. Participants were not compensated their participations in this study and the institute's ethical review board approved this study.

Table 1. Anthropometrics characteristics and strength measurements of participants

	Males (n = 13)	Females (n = 15)	*p* value
Age (years)	22.62 ± 1.76	22.27 ± 1.75	0.604
Height (cm)	183.32 ± 5.81	165.70 ± 6.38	< .0005*
Body weight (kg)	95.79 ± 3.77	64.79 ± 1.67	< .0005*
Squat 1RM (kg)	181.26 ± 26.01	91.47 ± 18.93	< .0005*
Squat to body weight ratio	1.92 ± 0.29	1.41 ± 0.22	< .0005*

* Statistical difference between sexes ($p < 0.05$).

4.2 Material and Apparatus

Muscle activity data was recorded using a Myopac® system (1000 Hz) and amplified (MPRD-101 Receiver/Decoder unit). Raw EMG data were bandpass filtered (Butterworth) at 100 Hz (high) and 500 Hz (low), full-wave rectified and then root mean squared (RMS) with a

100ms time constant using DATAPAC 2K2 software (RUN Technologies). The interelectrode distance was 2cm. A foot switch was used to start recording EMG activity upon landing. Maximal voluntary isometric contraction (MVIC) was be found using the maximal amplitude of the processed signal. A goniometer was be used to measure the squat depth at 120° knee flexion that is required for the one-repetition back squat strength test. An elastic band was used to give feedback on the depth on the squat. Drop landings were performed from plyometric boxes of 28 cm and 44 cm.

4.3 Procedures

4.3.1 Drop landing test

Participants were asked to perform single-leg drop landings from various heights (28cm and 44cm). Three practice trials with a rest period of 30 seconds between each trial were performed to minimize potential learning effect across trials. Following the practice trials, subjects performed three trials at each height in a randomized order. Subjects were instructed step off the box with their non-dominant limb without stepping down or jumping up before the drop. Subjects landed on their non-dominant foot and will be asked to hold that position for at least one second. A one-minute rest period was given between each recording trial. The non-dominant leg was used for EMG data recording and was determined by asking the participants which leg they would use to kick a ball and testing the opposite leg (Gstöttner et al., 2009).

4.3.2 One-repetition strength test

A one-repetition maximum squat test was used to assess the absolute strength of the athletes (McMaster et al., 2014). Participants performed a warm up using light resistance that easily allows 5 to 10 repetitions with a one-minute rest period. Then, a warm up set of 3 to 5 repetitions was performed after adding 10-20% of weight followed by a two-minute rest period. A third and final warm up set was performed after adding 10-20% of weight for 2 to 3 repetitions followed by a 2- to 4-minute rest. After increasing the weight by 10-20%, a first 1RM attempt was performed. If the attempt was successful, a 2- to 4-minute rest period was provided and the previous step was repeated. If the athlete failed, the load was decreased by subtracting 5 to 10% of the weight and a new 1RM attempt was performed following a 2- to 4-minute rest period. The load was increased or decreased until the athlete could complete one repetition with proper exercise technique. For an attempt to be valid, the participant had to reach a squat depth at 120° of knee flexion previously measured with a goniometer. An elastic band across the squat rack placed at the measured height was used to give tactile feedback to the participant.

4.3.3 Experimental procedures

The participants who accepted to take part in the study after receiving the information in person or via email reported to the Athletic Therapy Lab for a testing session of 90 minutes. Once the informed consent was signed, then the testing procedures began. During the first half of the session, information such as age, sport, activity level, weight and height was obtained followed by placement of the EMG electrodes and manual muscle testing procedures. EMG data was collected for the following muscles: biceps femoris (BF), semitendinosus (ST), vatus lateralis (VL), vastus medialis (VMO), rectus femoris (RF), gluteus medius (GMED) and gluteus maximus (GMAX). Electrode placement was done according to the recommendations of the Surface ElectroMyoGraphy for the Non-Invasive Assessment of Muscles (SENIAM). The muscles were located according to the manual muscle testing procedures by Kendall et al.

(2005). To decrease skin impedance and ensure a stable electrode contact, the skin was abraded and cleaned using gauze and alcohol prior the electrode placement. The MVICs were recorded for each of the selected muscles by using Kendall et al. (2005) manual muscle testing procedures. The participant was instructed to meet the examiner's resistance for 5 seconds, until they are told to relax. Once the set-up was complete, a warm-up consisting of 5 minutes of stationary bike at low intensity and a series of dynamic stretches. The participants performed three practice trials to get familiar with the drop landing. Then, EMG data was recorded for 150-ms pre-initial contact and 250ms post-initial contact for each of the three trials at the different heights to study the preparatory activity and muscle response during the single leg drop landing task. Once the EMG data collection was completed, all the electrodes were removed, and the skin was checked for irritation.

The second half of the session consisted of a one-repetition maximum squat. Once the test 1RM value was obtained, the participant was debriefed about the purpose of the project and all the questions were answered.

4.4 Data Analysis

The EMG readings were normalized to the MVIC and were reported as percentage of the MVIC (%MVIC). The EMG readings of the three trials at each height were averaged to determine the mean muscle activity of each muscle. The mean value over a 150ms and 250ms window before and after initial contact, respectively, were used for comparison. For the relative strength value, the strength to body weight ratio was calculated by dividing the 1RM value (kg) by the body mass (kg).

4.5 Statistical Analysis

For this study, the independent variables are sex (male and female) and drop height (28cm and 44cm), while the dependent variables were strength to body weight mass and mean EMG activity. Differences between characteristics of the males and females were analyzed using student's t-tests (age, weight, squat 1RM and strength to body weight ratio). The mean muscle activity data was screened for outliers using the inter-quartile range (IQR) rule and 6 subjects whose EMG amplitudes for at least one muscle were identified as statistical outliers (≥ 3x IQR for extreme outliers). These subjects were eliminated from the final analysis for the affected muscles. The mean EMG data for each muscle were analyzed using a 2x2 (sex x height) mixed-model analysis of variance (ANOVA). Furthermore, the EMG data were analyzed using a 2x2 (sex x height) mixed-model analysis of covariance (ANCOVA) to control for the SQ:BW. Mean EMG data was then arranged into halves using the median (n = 14 per half) based on the SQ:BW, thus creating High vs. Low strength groups. The same analysis for the sex groups was performed on the newly formed strength groups (APPENDIX G). Pearson's correlations between muscle activity and squat to body mass ratio were performed for both heights and for males and females combined and separately. The time to peak to EMG activity after initial contact were analyzed using a 2x2 (sex x strength group) mixed-model analysis of variance (ANOVA). These statistical analyses will be performed at a 5% level of significance using SPSS (IBM, Armonk, NY, USA).

4.6 Power Analysis

To our knowledge, there is no published study that looked at sex differences in the relationship between relative strength and muscle activity in landing tasks. Previous studies that focused on the relationship between strength measures and knee kinematics used sample sizes of ±30 participant to obtain significant differences (Malinzak et al., 2001)(Clairborne et al.,s 2006)(Haines et al., 2011)(McCurdy et al., 2014). A sample size close to 30 participants will be used for this study and data collected from pilot participants will be used for power calculation.

CHAPTER 5 - RESULTS

5.1 Anthropometrics Characteristics and Strength Measurements

There were significant differences in height ($t_{(26)}$ = 7.587, $p < 0.005$) and body weight ($t_{(26)}$ = 7.883, $p < 0.005$) between male (weight: *M* = 95.79kg, SD = 3.77; height: *M* = 183.32 cm, SD = 5.81) and female (weight: *M* = 64.79 kg, SD = 1.67; height: *M* = 165.70 cm, SD = 6.38) participants. Male mean weight and height were 17.61cm (SE = 2.32) and 31kg (SE = 3.93) higher than their female counterpart respectively. Descriptive statistics are displayed in Table 1.

Significant differences were also found in the strength measures between the sexes in one repetition-maximum ($t_{(26)}$ = 7.883, $p < 0.005$) (Figure A-1) and squat to body weight ratio ($t_{(26)}$ = 5.184, $p < 0.005$) (Figure A-2). In terms of absolute strength, the male group had an average squat 1RM of 181.26 kg (SD = 26.01) versus 91.47 kg (SD = 18.93) for the female group. Mean male squat was 89.79kg (SE = 8.52) heavier than females. Regarding relative strength, the male group had an average SQ:BW of 1.92 (SD = 0.29) and the female group had an average SQ:BW of 1.41 (SD = 0.22). These higher numbers resulted in a difference of 0.51 (SE = 0.10) in SQ:BW, with males scoring higher. The distribution of SQ:BW among sexes is presented in Figure 1.

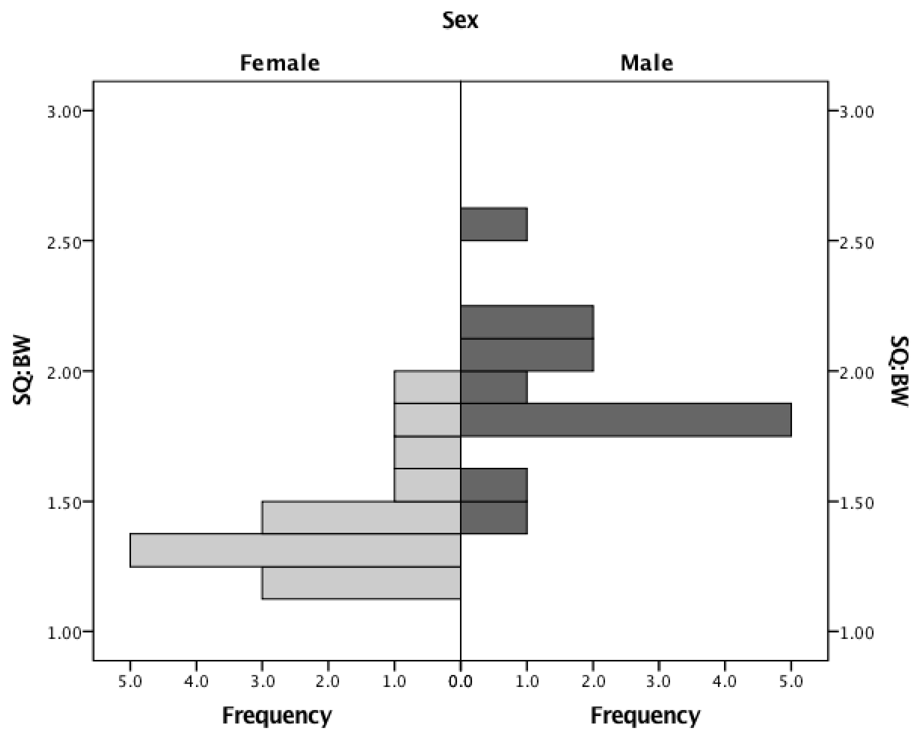


Figure 1. Distribution of squat to bodyweight ratio by sex. (Male n=13, Female n=15).

5.2 Mean EMG values during landing tasks

For all of the eight muscles analyzed, there was no statistical interaction effects between sex and height for muscle activity. During the pre-landing (Figure 2) phase, there was a main effect of sex on muscle activity for the VL ($F_{1,52}$ = 11.052, p = .002), VMO ($F_{1,48}$ = 11.123, p = .002), RF ($F_{1,50}$ = 7.362, p = .009), BF ($F_{1,50}$ = 8.033, p = .007) and GMAX ($F_{1,52}$ = 12.269, p = .001) muscles, such that muscle pre-activity was significantly higher for women (VL: *M* = 14.87%, *SD* = 7.54; VMO: *M* = 19.71.80%, *SD* = 8.50; RF: *M* = 12.88%, *SD* = 7.96; GMAX: *M* = 16.53%, *SD* = 6.50) than for men (VL: *M* = 9.16%, *SD* = 5.31; VMO: *M* = 12.96%, *SD* = 6.08; RF: *M* = 9.68%, *SD* = 5.77; GMAX: *M* = 10.98%, *SD* = 5.16) for most muscles. Only BF muscle activity was statistically less in female athletes (BF: *M* = 5.55%, *SD* = 2.56) compared to male athletes (BF: *M* = 8.45%, *SD* = 4.64). A main effect of drop height on muscle activity was observed for the VL ($F_{1,52}$ = 4.997, p = .030), VMO ($F_{1,48}$ = 4.895, p = .032) and TIBANT ($F_{1,48}$ = 4.120, p = .048) muscles pre-activity. The mean muscle activity of the VL, VMO and TIBANT was significantly higher for drop landing tasks at 44cm (VL: *M* = 14.16%, *SD* = 8.17; VMO: *M* = 18.85%, *SD* = 9.03; TIBANT: *M* = 12.47%, *SD* = 5.46) than at 28cm (VL: *M* = 10.27%, *SD* = 5.43; VMO: *M* = 14.34%, *SD* = 6.60; TIBANT: *M* = 9.69%, *SD* = 3.74).

During the post-landing (Figure 3) phase, there was a main effect of sex on muscle activity for the VL ($F_{1,52}$ = 13.283, p = .001), VMO ($F_{1,48}$ = 8.644, p = .005), RF ($F_{1,50}$ = 21.344, p < 0.001), BF ($F_{1,50}$ = 8.481, p = .005) and GMAX ($F_{1,52}$ = 12.957, p = .001) muscles. Muscle activity of the VL, VMO, RF and GMAX was significantly higher for women (VL: *M* = 46.94%, *SD* = 17.20; VMO: *M* = 53.84%, *SD* = 19.00; RF: *M* = 28.84%, *SD* = 13.13; GMAX: *M* = 34.17%, *SD* = 14.27) than for men (VL: *M* = 32.73%, *SD* = 12.03; VMO: *M* = 40.98%, *SD* = 11.71; RF: *M* = 16.14%, *SD* = 7.15; GMAX: *M* = 21.83%, *SD* = 10.74). On the other hand, BF activity was statistically less in female athletes (*M* = 8.01%, SD = 3.17) compared to male athletes (*M* = 12.56%, SD = 7.44) during the deceleration phase. A main effect of drop height on muscle activity was observed for the VL ($F_{1,52}$ = 4.558, p = .037) and RF ($F_{1,48}$ = 8.409, p = .006) muscles. The mean muscle activity of the VL and RF was significantly higher for drop landing tasks at 44cm (VL: *M* = 44.63%, *SD* = 18.57; RF: *M* = 27.39%, *SD* = 14.80) than at 28cm (VL: *M* = 36.06%, *SD* = 13.16; RF: *M* = 19.00%, *SD* = 8.04). The descriptive statistics for the main effects of sex and height are shown in Table B-1.

A two-way (sex x height) analysis of covariance (ANCOVA) with SQ:BW as a covariate was performed to determine if the sex differences in muscle activity were caused by the discrepancies in SQ:BW between sexes. After controlling relative strength, there was no main effect for sex for any of the muscles in the pre-landing phase. During the post-landing phase, there was a main effect of sex on muscle activity for the RF ($F_{1,49}$ = 11.93, p = 0.01), BF ($F_{1,49}$ =7.425, p = 0.009) and GMAX ($F_{1,52}$ = 8.041, p = 0.007), such that female athletes had significantly less BF activity (Female: *M* = 7.33%, *SE* = 1.31; Male: *M* = 13.30%, *SE* = 1.38) and significantly more RF (Female: *M* = 29.15%, *SE* = 2.21; Male: *M* = 15.75%, *SE* = 2.56) and GMAX (Female: *M* = 34.93%, *SE* = 2.87; Male: *M* = 20.95%, *SE* = 3.15) activity than male athletes. The main effects for height remained unchanged. The unadjusted and adjusted mean values are displayed in Table B-2 and Table B-3 for the pre-landing and post-landing phases respectively.

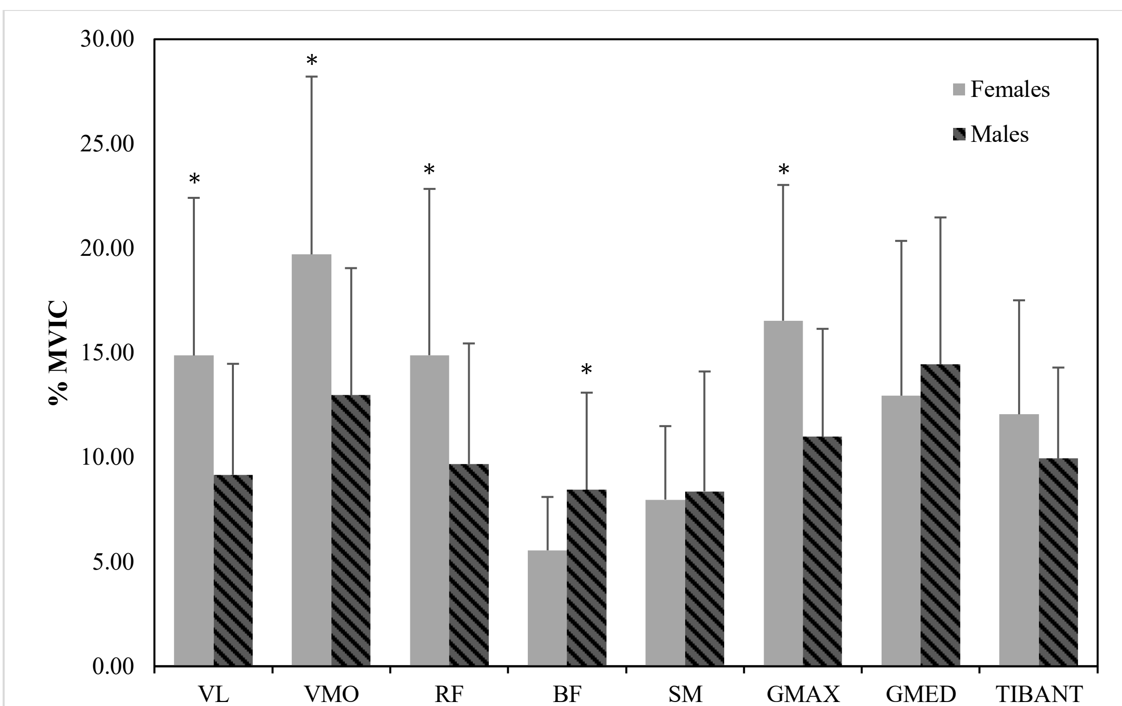


Figure 2. Mean muscle EMG activity during the pre-landing phase. Data are mean ± SD.* Significant differences between sexes (p < 0.05)

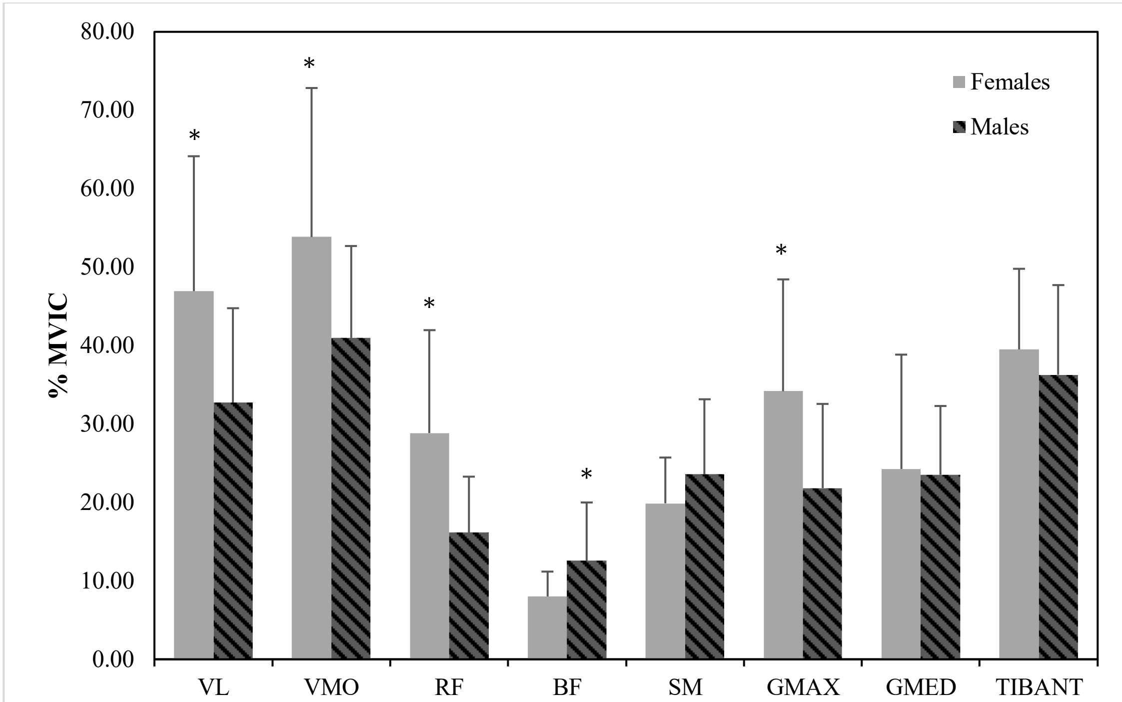


Figure 3. Mean muscle EMG activity during the post-landing phase. Data are mean ± SD. * Significant differences between sexes ($p < 0.05$)

5.3 Relationship between squat to body weight ratio and muscle activity

Pearson product-moment correlations between muscle activity and squat to body weight ratio at each height for males and females combined displayed significant negative relationships during the pre-landing (Table 2) and post-landing (Table 3) phases. Prior to landing, there were moderate negative correlations between VL, VMO and GMAX activity and SQ:BW at both drop heights. At 28cm, there was a positive moderate correlation between BF activity and SQ:BW. During the post-landing phase, moderate negative correlations for VL and VMO activity were found at both drop heights. There was a moderate negative correlation for RF activity only during the 28cm drop landing task. The scatter graphs for the significant correlations are displayed in APPENDIX C.

Table 2. Correlation in neuromuscular pre-landing activity and SQ:BW. Pearson's correlation coefficients are displayed by drop height for both sexes.

	Height (cm)	VL	VMO	RF	BF	SM	GMAX	GMED	TIBANT
SQ:BW	28	-.496*	-.585*	-.244	.595*	-.069	-.485*	.050	-.192
	44	-.483*	-.526*	-.305	.271	-.255	-.544*	.012	-.382

* Significant correlation ($p < 0.05$)

Table 3. Correlation in neuromuscular post-landing activity and SQ:BW. Pearson's correlation coefficients are displayed by drop height for both sexes.

	Height (cm)	VL	VMO	RF	BF	SM	GMAX	GMED	TIBANT
SQ:BW	28	-.447*	-.422*	-.418*	.277	.214	-.341	.063	-.087
	44	-.465*	-.463*	-.345	.104	.119	-.215	.074	-.154

* Significant correlation ($p < 0.05$)

Pearson product-moment correlations between muscle activity and SQ:BW for females displayed significant negative correlations for VMO, BF and SM in the pre-landing phase (VMO: *r* = -.555, *p* = .002; BF: *r* = -.402, *p* = .034; SM: *r* = -.447, *p* = .017) and significant negative correlations for VL, VMO and SM post landing (VL: *r* = -.376, *p* = 0.40; VMO: *r* = -.413, *p* = .029; SM: *r* = -.454, *p* = .015) phases. Only a strong positive correlation between BF muscle activity and SQ:BW was present for males during the pre-landing phase (*r* = .546, *p* = .004).

CHAPTER 6 - Discussion

The goal of this study was to explore the relationship between the SQ:BW and the lower limb muscle activity during a single-leg landing. The main findings of this investigation are:

1. Male varsity athletes have a significant higher SQ:BW than female varsity athletes.
2. Females have significantly more neuromuscular activity of the quadriceps and GMAX, and significantly less activity of the BF in pre- and post-landing phases.
3. There is a negative correlation between SQ:BW and muscle activity of the GMAX during both phases of landing for all participants.
4. There is a sex effect on muscle activity of the RF, BF and GMAX during the post-landing phase.

6.1 Strength measurements

The absolute weight lifted on the 1RM back squat may not be representative of someone's strength as it does not consider the body mass. For example, if we have two athletes lifting 100kg on their 1RM back squat with one weighting 62kg and the other 57kg, the latter would be considered stronger in terms of relative strength since his SQ:BW is slightly higher. Body mass is particularly important when performing single-leg landing tasks as it will dictate the impact upon landing. We used the SQ:BW in our study to investigate the relationship between muscle activity and strength during landing tasks

There are disparities in strength measures between sexes. When looking at absolute strength, females exhibit a deficit of 50% in upper body strength and about 30% in lower body strength compared to males (Hakkinen & Hakkinen, 1995). As for the SQ:BW, males have significantly higher scores than females (Haines et al., 2011). This gap in absolute and relative strength can be partly explained by differences in body composition between sexes. Men typically have more muscle mass while women have more fat mass (Schorr et al., 2018). Unlike men, who require only 3% of essential body fat, women need 12% of essential body fat because of child bearing and hormonal function (Abe et al., 1998). For example, when using the squat to fat-free mass ratio instead of the SQ:BW, the gap in strength between sexes is reduced due to women having a higher percentage of fat mass (Haines et al., 2011). The greater proportion of muscle mass allows men to potentially generate more force at an equal body mass. In our study, males scored higher on the absolute and relative measures of strength in as expected. Our findings agree with a greater SQ:BW for males reported by Haines et al. (2011), supporting our first hypothesis that male athletes will have greater squat strength to body weight ratio compared to female athletes.

6.2 Differences in muscle activity during landing

6.2.1 Sex differences

An interesting finding of this study was that females demonstrated more gluteus maximus activity than males in the pre-landing and post-landing phases, in contrary to what we hypothesized. We expected females to have lower gluteus maximus activity during landing as reported previously by Zazulak et al. (2005), but we observed significantly higher level of activation. Conversely, Hughes & Dally (2015) found no significant difference in GMAX activity during single-leg landing task in the post-landing phase. Differences in MVIC tests, tasks performed, and electrode placement may be responsible for these conflicting results. For example, Hughes & Dally (2015) tested GMAX MVIC using side-lying hip abduction, focusing on the portion of the muscle involved in abduction of the hip joint. In the current study, we measured GMAX MVIC using prone-lying hip extension as it is a powerful extensor of the hip joint. This difference in methods may have resulted in different levels of GMAX activation used for normalization purposes. Zazulak provides little information about this aspect of their study. Moreover, Hughes & Dally (2015) performed a maximum height vertical jump with a single-leg landing instead of a drop landing task, which may elicit different levels of EMG activation as the intensity is relative to the participants ability to generate height. In our investigation, the pre-determined drop landing heights does not consider the participant's maximal jumping height may be more challenging for some than others, thus resulting in higher EMG activity in certain participants.

Our female group scored significantly lower on the 1RM back squat and the SQ:BW. This may play an important role on the level of gluteal activation upon landing as previous literature reported a negative relationship between strength measures and neuromuscular activity a during double-leg jump landing task and the single-leg squat (Nguyen et al., 2011) (Homan et al., 2013). In our investigation we observed the same negative relationship between strength and muscle activity during single-leg landing tasks for the quadriceps and the gluteus maximus. Our findings along those previous studies (Nguyen et al., 2011) (Homan et al., 2013) suggest that weaker individuals may compensate for their lack of force production via greater gluteal activity.

In our study, females preferentially activated their quadriceps over their hamstrings, potentially increasing the stress on the ACL due to anterior translation of the tibia (Hewett at al., 2010). A decreased activation ratio of the hamstrings relative to the quadriceps may contribute to the increased risk of an ACL injury (Ford et al., 2011) (Alentorn et al., 2009). Our female group showed significantly higher mean quadriceps activation in both landing phases, which supports the first part of our second hypothesis which suggested that female athletes will display greater quadriceps activation than males when performing the single-leg landing tasks. This supports previous research reporting greater quadriceps activity in females during landing tasks (Hughes & Dally, 2015)(Zazulak et al., 2005). Our female group demonstrated lower recruitment of the biceps femoris than their male counter-part during landing. Activation of the hamstrings during landing tasks is important as they initiate a posterior tibial drawer and negate the stress put on the ACL by the quadriceps. Previous research investigating sex differences in hamstrings activity during landing tasks have shown conflicting results, but our findings agree with those of Hughes & Dally (2015) and Chappell et al. (2007) who reported higher lateral hamstring activity in males during the deceleration phase. In our investigation there was a moderate positive correlation between BF pre-activity and SQ:BW, which may be a factor contributing to the higher BF activation observed in males during the pre-landing phase as they were significantly stronger.

Differences in GMED activity between sexes have been hypothesized as a potential risk factor of ACL injuries in females because of its role as a major hip lateral stabilizer during landing. In our study, the female and male groups had similar level of GMED activity between in both phases. Our findings support previous literature reporting no sex differences in GMED activity during single-leg landing (Zazulak et al., 2005) (Russel et al., 2006).

Overall, females in this investigation used an activation strategy that is a hypothesized risk factor for ACL injuries. They showed higher quadriceps to hamstrings co-activation ratio and higher GMAX activity prior to landing, a neuromuscular activation pattern that is typically associated with smaller knee flexion angles at initial contact (Walsh et al., 2012). Our female group showed quadriceps dominance after the initial contact, a limiting factor for knee flexion motion during the deceleration phase (Walsh et al., 2012). Smaller knee flexion angles during landing produce higher impact forces at the knee and might increase the stress on the ACL (Malinzak et al., 2001).

6.2.2 Sex differences after controlling for strength differences

Our fourth hypothesis was that there will be no sex effect on the relationship between relative squat strength and muscle activity during single-leg landing tasks. When separating the groups based on sex, we observed a significant strength gap and muscle activity differences between groups. After controlling for differences in SQ:BW

(ANCOVA), there was no more main effects of sex on the quadriceps, BF and GMAX muscle activity during the preparation phase. The muscle activity difference between sexes for the RF muscle was not statistically significant after controlling for SQ:BW ($p = 0.089$) even if the correlation between the two variables was low (28cm: $R^2 = 0.06$; 44cm: $R^2 = 0.09$). These differences in significance reinforce the importance of controlling for SQ:BW disparity between groups when investigating sex differences in muscle pre-activation. In contrast, when examining results during the post-landing phase a main effect of sex on muscle activity of the BF, RF and GMAX muscles was still observed after controlling for the strength gap between groups. The correlations between SQ:BW and BF (28cm: $R^2 = 0.08$; 44cm: $R^2 = 0.01$), RF (28cm: $R^2 = 0.17$; 44cm: $R^2 = 0.12$), and GMAX (28cm: $R^2 = 0.12$; 44cm: $R^2 = 0.05$) activity were low during the post-landing phase, which may explain why there was still a significant difference in muscle activity between sexes after controlling for SQ:BW differences. Similar to the pre-landing phase, we did not observe a difference in muscle activity for the VL and VMO after controlling for strength.

Overall, our results suggest that the differences observed between sexes in the pre-landing phase may have been influenced by the strength gap between the groups. When taking strength into account, we did not observe differences in muscle activity for any of eight muscles measured. The differences in methodology and potential strength differences between the groups may be responsible for the conflicting results reported in muscle pre-activation. On the other hand, we observed sex differences in RF, BF and GMAX activity during the post-landing phase that the strength gap alone could not explain. These findings contradict our fourth hypothesis, which is that will be no effect of sex on the relation between SQ:BW and muscle activity.

6.3 Relationship between the squat to body weight ratio and muscle activity

In our study the SQ:BW demonstrated significant negative moderate correlations with VL (28cm: R^2 = 0.25; 44cm: R^2 = 0.23), VMO (28cm: R^2 = 0.34; 44cm: R^2 = 0.28) and GMAX (28cm: R^2 = 0.23; 44cm: R^2 = 0.30) activity during the preparation phase at both drop heights. The SQ:BW had a positive moderate correlation with BF (R^2 = 0.35) activity at a drop height of 28cm. These findings suggest that individuals with lower SQ:BW may compensate for their lack of strength by preferentially recruiting their quadriceps over their hamstring. Higher activation of the quadriceps and GMAX have been associated with smaller knee flexion at landing, which induces an anterior shear stress to the ACL (Walsh et al., 2012). The correlations observed in the pre-landing phase suggest that we may potentially lower the quadriceps to hamstring co-activation ratio by increasing someone's SQ:BW, thus reducing ACL injury risk. During the post-landing phase, we observed similar relationships to the pre-landing phase between the SQ:BW and VL (28cm: R^2 = 0.20; 44cm: R^2 = 0.22) and VMO (28cm: R^2 = 0.18; 44cm: R^2 = 0.21) activity. The negative relationship between SQ:BW and GMAX activity was non-significant during the deceleration phase. Contrary to our original hypothesis, we did not observe a positive relationship between SQ:BW and GMAX activity during landing. These findings highlight the importance of controlling for strength differences when investigating the effect of sex on muscle activity during single-leg landing tasks as it may have an influence on the results. The potential strength gap between the sexes may contribute to the absence of a consensus in the current literature on a sex effect on the quadriceps activation during landing tasks.

6.4 Limitations

We acknowledge the present study had several limitations. In our investigation, the SQ:BW range from 1.15 to 2.57. A bigger sample size may have been needed to achieve higher statistical power due to our wide range of SQ:BW values. Also, there was a significant difference in strength between sexes, with males scoring higher on the relative and absolute strength measurements. This difference resulted in a majority of male athletes at the higher end of the SQ:BW scale, while having mostly females at the lower end. Future studies should include male and female participants of similar strength values to have a better understanding of the effect of sex on the relationship between SQ:BW and muscle activity. Moreover, the mean SQ:BW of both males (1.92) and females (1.41) were high in this study, which confine our sample to strong athletes. Consequently, these observations may not apply to the general population who are of average fitness and strength levels.

Our data was obtained during controlled single-leg drop landing tasks at two pre-determined heights. A maximal height vertical jump with a single-leg landing may have been more representative of the muscle activity associated with ACL injuries as it is present in many sports disciplines such as volleyball, soccer, and basketball. The pre-determined drop landing height might not be representative of the participant's maximal vertical jump height and may be more challenging for some than others. Also, we used

MVIC to normalize the EMG data obtained during the drop landing tasks. This method assumes a maximal effort from the participant, but it is not possible to confirm a maximal effort during this test. A submaximal effort would result in higher normalized values potentially affecting the relationship observed between SQ:BW and muscle activity. Lastly, we did not record any kinematics data during this investigation. Therefore, we cannot make direct correlations between the neuromuscular activity patterns observed and vulnerable landing positions.

CHAPTER 7 - Conclusions

In conclusion, increasing one's strength through a higher SQ:BW may play a potential role in reducing neuromuscular risk factors during landing. In our sex-based groups, females recruited significantly more their quadricep and GMAX muscles while showing less BF activity than males in both landing phases. A decreased activation ratio of the hamstrings relative to the quadriceps has been suggested to increased risk of an ACL injury (Ford et al., 2005) (Alentorn et al., 2009). Higher pre-activation of the quadriceps and GMAX is typically associated with smaller knee flexion angles at initial contact (Walsh et al., 2012), thus potentially increasing the stress on the ACL (Malinzak et al., 2001). However, we observed a significant difference in both absolute and relative strength measurements with females scoring lower than males. After controlling for strength, only significant differences in RF, BF and GMAX activity remained between sexes in the post-landing phase. The sex differences observed for these muscles could not be explained solely by differences in SQ:BW suggesting that there might be other factors influencing muscle activity after initial contact. During the pre-landing phase, negative correlations between SQ:BW and muscle activity of the quadriceps and GMAX muscles were observed, yet hamstrings activity was positively correlated with SQ:BW. Therefore, by increasing someone's strength, it may increase the hamstring to quadriceps coactivation ratio and reduce GMAX activity in the preparatory phase, thus potentially reducing ACL injury risk. Furthermore, the SQ:BW negatively correlated with the quadriceps muscles post initial-contact.

Based on our findings, researchers looking at sex-based differences in muscle activity should control for relative strength differences between groups as it may influence muscle activity during landing tasks. The results of this study highlight the importance of accounting for strength when investigating ACL injuries, but more studies are needed to have a better understanding of the relationship between SQ:BW and muscle activity during landing tasks. In our study we had a significant difference in strength between sexes resulting in most male athletes being at the higher end of the SQ:BW scale, while having mostly females at the lower end. To have a more accurate understanding of the SQ:BW influence on muscle activity during landing tasks future studies should include male and female participants of similar strength values. This would help clarify a potential sex effect on the relationship between relative strength and muscle activity during landing tasks.

REFERENCES

Abe, T., Brechue, W. F., Fujita, S., & Brown, J. B. (1998). Gender differences in FFM accumulation and architectural characteristics of muscle. *Medicine and Science in Sports and Exercise, 30*(7), 1066-1070.

Alentorn-Geli, E., ha, G. D., Silvers, H. J., Samitier, G., Romero, D., Lazaro-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 : Official Journal of the ESSKA, 17*(7), 705-729. doi:10.1007/s00167-009-0813-1 [doi]

Arendt, E. A., Agel, J., & Dick, R. (1999). Anterior cruciate ligament injury patterns among collegiate men and women. *Journal of Athletic Training, 34*(2), 86-92.

Augustsson, S. R., & Ageberg, E. (2017). Weaker lower extremity muscle strength predicts traumatic knee injury in youth female but not male athletes. *BMJ Open Sport & Exercise Medicine, 3*(1). doi:10.1136/bmjsem-2017-000222

Barber-Westin, S. D., Noyes, F. R., Smith, S. T., & Campbell, T. M. (2009). Reducing the risk of noncontact anterior cruciate ligament injuries in the female athlete. *The Physician and Sportsmedicine, 37*(3), 49-61. doi:10.3810/psm.2009.10.1729 [doi]

Blackburn, J. T., & Padua, D. A. (2008). Influence of trunk flexion on hip and knee joint kinematics during a controlled drop landing. *Clinical Biomechanics (Bristol, Avon), 23*(3), 313-319. doi:S0268-0033(07)00224-0 [pii]

Bouillon, L. E., Wilhelm, J., Eisel, P., Wiesner, J., Rachow, M., & Hatteberg, L. (2012). Electromyographic assessment of muscle activity between genders during unilateral weight-bearing tasks using adjusted distances. *International Journal of Sports Physical Therapy, 7*(6), 595-605.

Brophy, R., Silvers, H. J., Gonzales, T., & Mandelbaum, B. R. (2010). Gender influences: The role of leg dominance in ACL injury among soccer players. *British Journal of Sports Medicine, 44*(10), 694-697. doi:10.1136/bjsm.2008.051243 [doi]

Campbell, C. J., Carson, J. D., Diaconescu, E. D., Celebrini, R., Rizzardo, M. R., Godbout, V., . . . Canadian Academy of Sport and Exercise Medicine. (2014). Canadian academy of sport and exercise medicine position statement: Neuromuscular training programs can decrease anterior cruciate ligament injuries in youth soccer players. *Clinical Journal of Sport Medicine : Official Journal of the Canadian Academy of Sport Medicine, 24*(3), 263-267. doi:10.1097/JSM.0000000000000068 [doi]

Carcia, C. R., & Martin, R. L. (2007). The influence of gender on gluteus medius activity during a drop jump. Physical Therapy in Sport, 8(4), 169-176.

Chandrashekar, N., Slauterbeck, J., & Hashemi, J. (2005). Sex-based differences in the anthropometric characteristics of the anterior cruciate ligament and its relation to intercondylar notch geometry: A cadaveric study. *The American Journal of Sports Medicine, 33*(10), 1492-1498. doi:0363546504274149 [pii]

Chappell, Jonathan D., et al. Kinematics and Electromyography of Landing Preparation in Vertical Stop-Jump. The American Journal of Sports Medicine, vol. 35, no. 2, 2007, pp. 235–241., doi:10.1177/0363546506294077.

Chappell, J. D., Yu, B., Kirkendall, D. T., & Garrett, W. E. (2002). A comparison of knee kinetics between male and female recreational athletes in stop-jump tasks. *The American Journal of Sports Medicine, 30*(2), 261-267.

Cowling, E. J., & Steele, J. R. (2001). Is lower limb muscle synchrony during landing affected by gender? implications for variations in ACL injury rates. *Journal of Electromyography and Kinesiology : Official Journal of the International Society of Electrophysiological Kinesiology, 11*(4), 263-268. doi:S1050-6411(00)00056-0 [pii]

De Britto, M. A., Carpes, F. P., Koutras, G., & Pappas, E. (2014). Quadriceps and hamstrings prelanding myoelectric activity during landing from different heights among male and female athletes. *Journal of Electromyography and Kinesiology : Official Journal of the International Society of Electrophysiological Kinesiology, 24*(4), 508-512. doi:10.1016/j.jelekin.2014.04.009 [doi]

Dejour, H., & Bonnin, M. (1994). Tibial translation after anterior cruciate ligament rupture. two radiological tests compared. *The Journal of Bone and Joint Surgery.British Volume, 76*(5), 745-749.

Delp, S. L., Hess, W. E., Hungerford, D. S., & Jones, L. C. (1999). Variation of rotation moment arms with hip flexion. *Journal of Biomechanics, 32*(5), 493-501. doi:S0021-9290(99)00032-9 [pii]

Ebben, W. P., Fauth, M. L., Petushek, E. J., Garceau, L. R., Hsu, B. E., Lutsch, B. N., & Feldmann, C. R. (2010). Gender-based analysis of hamstring and quadriceps muscle activation during jump landings and cutting. *Journal of Strength and Conditioning Research / National Strength & Conditioning Association, 24*(2), 408-415. doi:10.1519/JSC.0b013e3181c509f4 [doi]

Ford, K. R., Myer, G. D., Schmitt, L. C., Uhl, T. L., & Hewett, T. E. (2011). Preferential quadriceps activation in female athletes with incremental increases in landing intensity. *Journal of Applied Biomechanics, 27*(3), 215-222.

Ford, K. R., Myer, G. D., Toms, H. E., & Hewett, T. E. (2005). Gender differences in the kinematics of unanticipated cutting in young athletes. *Medicine and Science in Sports and Exercise, 37*(1), 124-129. doi:00005768-200501000-00020 [pii]

Gstöttner, M., Neher, A., Scholtz, A., Millonig, M., Lembert, S., & Raschner, C. (2009). Balance ability and muscle response of the preferred and nonpreferred leg in soccer players. *Motor Control*, *13*(2), 218-231.

Griffin, L. Y., Agel, J., Albohm, M. J., Arendt, E. A., Dick, R. W., Garrett, W. E., . . . Wojtys, E. M. (2000). Noncontact anterior cruciate ligament injuries: Risk factors and prevention strategies. *The Journal of the American Academy of Orthopaedic Surgeons, 8*(3), 141-150.

Haines, T. L., McBride, J. M., Triplett, N. T., Skinner, J. W., Fairbrother, K. R., & Kirby, T. J. (2011). A comparison of men's and women's strength to body mass ratio and varus/valgus knee angle during jump landings. *Journal of Sports Sciences, 29*(13), 1435-1442. doi:10.1080/02640414.2011.599039 [doi]

Hakkinen, K., & Hakkinen, A. (1995). Neuromuscular adaptations during intensive strength training in middle-aged and elderly males and females. *Electromyography and Clinical Neurophysiology, 35*(3), 137-147.

Hansen, M., Kongsgaard, M., Holm, L., Skovgaard, D., Magnusson, S. P., Qvortrup, K., . . . Kjaer, M. (2009). Effect of estrogen on tendon collagen synthesis, tendon structural characteristics, and biomechanical properties in postmenopausal women. *Journal of Applied Physiology (Bethesda, Md.: 1985), 106*(4), 1385-1393. doi:10.1152/japplphysiol.90935.2008 [doi]

Hansen, M., Kongsgaard, M., Holm, L., Skovgaard, D., Magnusson, S. P., Qvortrup, K., . . . Kjaer, M. (2009). Effect of estrogen on tendon collagen synthesis, tendon structural characteristics, and biomechanical properties in postmenopausal women. *Journal of Applied Physiology (Bethesda, Md.: 1985), 106*(4), 1385-1393. doi:10.1152/japplphysiol.90935.2008 [doi]

Hanson, A. M., Padua, D. A., Troy Blackburn, J., Prentice, W. E., & Hirth, C. J. (2008). Muscle activation during side-step cutting maneuvers in male and female soccer athletes. *Journal of Athletic Training, 43*(2), 133-143. doi:10.4085/1062-6050-43.2.133 [doi]

Hashemi, J., Chandrashekar, N., Mansouri, H., Slauterbeck, J. R., & Hardy, D. M. (2008). The human anterior cruciate ligament: Sex differences in ultrastructure and correlation with biomechanical properties. *Journal of Orthopaedic Research : Official Publication of the Orthopaedic Research Society, 26*(7), 945-950. doi:10.1002/jor.20621 [doi]

Hashemi, J., Mansouri, H., Chandrashekar, N., Slauterbeck, J. R., Hardy, D. M., & Beynnon, B. D. (2011). Age, sex, body anthropometry, and ACL size predict the structural properties of the human anterior cruciate ligament. *Journal of Orthopaedic Research : Official Publication of the Orthopaedic Research Society, 29*(7), 993-1001. doi:10.1002/jor.21245 [doi]

Heitz, N. A., Eisenman, P. A., Beck, C. L., & Walker, J. A. (1999). Hormonal changes throughout the menstrual cycle and increased anterior cruciate ligament laxity in females. *Journal of Athletic Training, 34*(2), 144-149.

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. The American Journal of Sports Medicine, 27(6), 699-706. doi:10.1177/03635465990270060301

Hewett, T. E., Ford, K. R., Hoogenboom, B. J., & Myer, G. D. (2010). Understanding and preventing acl injuries: Current biomechanical and epidemiologic considerations - update 2010. *North American Journal of Sports Physical Therapy : NAJSPT, 5*(4), 234-251.

Hollman, J. H., Galardi, C. M., Lin, I. H., Voth, B. C., & Whitmarsh, C. L. (2014). Frontal and transverse plane hip kinematics and gluteus maximus recruitment correlate with frontal plane knee kinematics during single-leg squat tests in women. *Clinical Biomechanics (Bristol, Avon), 29*(4), 468-474. doi:10.1016/j.clinbiomech.2013.12.017 [doi]

Hollman, J. H., Ginos, B. E., Kozuchowski, J., Vaughn, A. S., Krause, D. A., & Youdas, J. W. (2009). Relationships between knee valgus, hip-muscle strength, and hip-muscle recruitment during a single-limb step-down. *Journal of Sport Rehabilitation, 18*(1), 104-117.

Hollman, J. H., Hohl, J. M., Kraft, J. L., Strauss, J. D., & Traver, K. J. (2012). Effects of hip extensor fatigue on lower extremity kinematics during a jump-landing task in women: A controlled laboratory study. *Clinical Biomechanics (Bristol, Avon), 27*(9), 903-909. doi:10.1016/j.clinbiomech.2012.07.004 [doi]

Hollman, J. H., Hohl, J. M., Kraft, J. L., Strauss, J. D., & Traver, K. J. (2013). Modulation of frontal-plane knee kinematics by hip-extensor strength and gluteus maximus recruitment during a jump-landing task in healthy women. *Journal of Sport Rehabilitation, 22*(3), 184-190. doi:2012-0073 [pii]

Homan, K. J., Norcross, M. F., Goerger, B. M., Prentice, W. E., & Blackburn, J. T. (2013). The influence of hip strength on gluteal activity and lower extremity kinematics. *Journal of Electromyography and*

Kinesiology : Official Journal of the International Society of Electrophysiological Kinesiology, 23(2), 411-415. doi:10.1016/j.jelekin.2012.11.009 [doi]

Hootman, J. M., Dick, R., & Agel, J. (2007). Epidemiology of collegiate injuries for 15 sports: Summary and recommendations for injury prevention initiatives. *Journal of Athletic Training, 42*(2), 311-319.

Hughes, G., & Dally, N. (2015). Gender difference in lower limb muscle activity during landing and rapid change of direction. Science & Sports, 30(3), 163-168. doi:10.1016/j.scispo.2015.02.009 Huston, L. J., & Wojtys, E. M. (1996). Neuromuscular performance characteristics in elite female athletes. *The American Journal of Sports Medicine, 24*(4), 427-436.

Ireland, M. L. (1999). Anterior cruciate ligament injury in female athletes: Epidemiology. *Journal of Athletic Training, 34*(2), 150-154.

Jacobs, C., & Mattacola, C. (2005). Sex Differences in Eccentric Hip-Abductor Strength and Knee-Joint Kinematics When Landing from a Jump. *Journal of Sport Rehabilitation, 14*(4), 346-355. doi:10.1123/jsr.14.4.346

Jacobs, C. A., Uhl, T. L., Mattacola, C. G., Shapiro, R., & Rayens, W. S. (2007). Hip abductor function and lower extremity landing kinematics: Sex differences. *Journal of Athletic Training, 42*(1), 76-83.

Jenkins, W. L., Williams, D., Williams, K., Hefner, J., & Welch, H. (2017). Sex differences in total frontal plane knee movement and velocity during a functional single-leg landing. *Physical Therapy in Sport, 24*, 1-6. doi:10.1016/j.ptsp.2016.09.005

Krosshaug, T., Nakamae, A., Boden, B. P., Engebretsen, L., Smith, G., Slauterbeck, J. R., . . . Bahr, R. (2007). Mechanisms of anterior cruciate ligament injury in basketball: Video analysis of 39 cases. *The American Journal of Sports Medicine, 35*(3), 359-367. doi:0363546506293899 [pii]

Lawrence, R. K.,3rd, Kernozek, T. W., Miller, E. J., Torry, M. R., & Reuteman, P. (2008). Influences of hip external rotation strength on knee mechanics during single-leg drop landings in females. *Clinical Biomechanics (Bristol, Avon), 23*(6), 806-813. doi:10.1016/j.clinbiomech.2008.02.009 [doi]

Lessi, G. C., & Serrao, F. V. (2015). Effects of fatigue on lower limb, pelvis and trunk kinematics and lower limb muscle activity during single-leg landing after anterior cruciate ligament reconstruction. *Knee Surgery, Sports Traumatology, Arthroscopy : Official Journal of the ESSKA,* doi:10.1007/s00167-015-3762-x [doi]

Lipps, D. B., Oh, Y. K., Ashton-Miller, J. A., & Wojtys, E. M. (2012). Morphologic characteristics help explain the gender difference in peak anterior cruciate ligament strain during a simulated pivot landing. *The American Journal of Sports Medicine, 40*(1), 32-40. doi:10.1177/0363546511422325 [doi]

Loes, M. D., Dahlstedt, L. J., & Thomee, R. (2000). A 7-year study on risks and costs of knee injuries in male and female youth participants in 12 sports. Scandinavian Journal of Medicine and Science in Sports, 10(2), 90-97. doi:10.1034/j.1600-0838.2000.010002090.x

Liu, S. H., Al-Shaikh, R. A., Panossian, V., Finerman, G. A., & Lane, J. M. (1997). Estrogen affects the cellular metabolism of the anterior cruciate ligament. A potential explanation for female athletic injury. *The American Journal of Sports Medicine, 25*(5), 704-709.

Malinzak, R. A., Colby, S. M., Kirkendall, D. T., Yu, B., & Garrett, W. E. (2001). A comparison of knee joint motion patterns between men and women in selected athletic tasks. *Clinical Biomechanics (Bristol, Avon), 16*(5), 438-445. doi:S0268-0033(01)00019-5 [pii]

Markolf, K. L., Gorek, J. F., Kabo, J. M., & Shapiro, M. S. (1990). Direct measurement of resultant forces in the anterior cruciate ligament. An in vitro study performed with a new experimental technique. The Journal of Bone & Joint Surgery, 72(4), 557-567. doi:10.2106/00004623-199072040-00014

Márquez, G., Alegre, L. M., Jaén, D., Martin-Casado, L., & Aguado, X. (2017). Sex differences in kinetic and neuromuscular control during jumping and landing. *Journal of Musculoskeletal & Neuronal Interactions*, *17*(1), 409–416.

Martinez, A. F., Lessi, G. C., Carvalho, C., & Serrao, F. V. (2018). Association of Hip and Trunk Strength With Three-Dimensional Trunk, Hip, and Knee Kinematics During a Single-Leg Drop Vertical Jump. *Journal of Strength and Conditioning Research, 32*(7), 1902-1908. doi:10.1519/jsc.0000000000002564

McCurdy, K., Walker, J., Armstrong, R., & Langford, G. (2014). Relationship between selected measures of strength and hip and knee excursion during unilateral and bilateral landings in women. *Journal of Strength and Conditioning Research / National Strength & Conditioning Association, 28*(9), 2429-2436. doi:10.1519/JSC.0000000000000583 [doi]

McMaster, D. T., Gill, N., Cronin, J., & McGuigan, M. (2014). A brief review of strength and ballistic assessment methodologies in sport. *Sports Medicine*, *44*(5), 603-623.

Munkh-Erdene, B., Sakamoto, M., Nakazawa, R., Aoyagi, M., & Kasuyama, T. (2011). Relationship Between Hip Muscle Strength and Kinematics of the Knee Joint during Single Leg Squatting and Dropping. *Journal of Physical Therapy Science, 23*(2), 205-207. doi:10.1589/jpts.23.205

Myer, G. D., Ford, K. R., & Hewett, T. E. (2005). The effects of gender on quadriceps muscle activation strategies during a maneuver that mimics a high ACL injury risk position. *Journal of Electromyography and Kinesiology : Official Journal of the International Society of Electrophysiological Kinesiology, 15*(2), 181-189. doi:S1050-6411(04)00081-1 [pii]

Nguyen, A. D., Shultz, S. J., Schmitz, R. J., Luecht, R. M., & Perrin, D. H. (2011). A preliminary multifactorial approach describing the relationships among lower extremity alignment, hip muscle activation, and lower extremity joint excursion. *Journal of Athletic Training, 46*(3), 246-256.

Olsen, O. E., Myklebust, G., Engebretsen, L., & Bahr, R. (2004). Injury mechanisms for anterior cruciate ligament injuries in team handball: A systematic video analysis. *The American Journal of Sports Medicine, 32*(4), 1002-1012.

Patrek, M. F., Kernozek, T. W., Willson, J. D., Wright, G. A., & Doberstein, S. T. (2011). Hip-abductor fatigue and single-leg landing mechanics in women athletes. *Journal of Athletic Training, 46*(1), 31-42. doi:10.4085/1062-6050-46.1.31 [doi]

Peng, H. T., Kernozek, T. W., & Song, C. Y. (2011). Quadricep and hamstring activation during drop jumps with changes in drop height. *Physical Therapy in Sport : Official Journal of the Association of Chartered Physiotherapists in Sports Medicine, 12*(3), 127-132. doi:10.1016/j.ptsp.2010.10.001 [doi]

Prodromos, C. C., Han, Y., Rogowski, J., Joyce, B., & Shi, K. (2007). A meta-analysis of the incidence of anterior cruciate ligament tears as a function of gender, sport, and a knee injury-reduction regimen. *Arthroscopy : The Journal of Arthroscopic & Related Surgery : Official Publication of the Arthroscopy Association of North America and the International Arthroscopy Association, 23*(12), 1320-1325.e6. doi:S0749-8063(07)00686-X [pii]

Rozzi, S. L., Lephart, S. M., Gear, W. S., & Fu, F. H. (1999). Knee joint laxity and neuromuscular characteristics of male and female soccer and basketball players. *The American Journal of Sports Medicine, 27*(3), 312-319.

Ruiz, A., Kelly, M., & Nutton, R. (2002). Arthroscopic ACL reconstruction: A 5–9 year follow-up. *The Knee, 9*(3), 197-200. doi:10.1016/s0968-0160(02)00019-4

Russell, K. A., Palmieri, R. M., Zinder, S. M., & Ingersoll, C. D. (2006). Sex differences in valgus knee angle during a single-leg drop jump. *Journal of Athletic Training, 41*(2), 166-171.

Sallis, R. E., Jones, K., Sunshine, S., Smith, G., & Simon, L. (2001). Comparing sports injuries in men and women. *International Journal of Sports Medicine, 22*(6), 420-423. doi:10.1055/s-2001-16246 [doi]

Schorr, M., Dichtel, L. E., Gerweck, A. V., Valera, R. D., Torriani, M., Miller, K. K., & Bredella, M. A. (2018). Sex differences in body composition and association with cardiometabolic risk. Biology of Sex Differences, 9(1). doi:10.1186/s13293-018-0189-3

The SENIAM project [homepage on the Internet] SENIAM 8. European Recommendations for Surface ElectroMyoGraphy. [Accessed October 30, 2018]. Available from: http://www.seniam.org/

Shelbourne, K. D. (2008). Anterior Cruciate Ligament Injury Combined with Medial Collateral Ligament, Posterior Cruciate Ligament, and/or Lateral-Side Injury. The Anterior Cruciate Ligament: Reconstruction and Basic Science, 477-485. doi:10.1016/b978-1-4160-3834-4.10061-7

Shultz, S. J., Kirk, S. E., Johnson, M. L., Sander, T. C., & Perrin, D. H. (2004). Relationship between sex hormones and anterior knee laxity across the menstrual cycle. *Medicine and Science in Sports and Exercise, 36*(7), 1165-1174. doi:00005768-200407000-00011 [pii]

Sigward, S. M., & Powers, C. M. (2006). The influence of gender on knee kinematics, kinetics and muscle activation patterns during side-step cutting. *Clinical Biomechanics (Bristol, Avon), 21*(1), 41-48. doi:S0268-0033(05)00179-8 [pii]

Silvers, H. J., & Mandelbaum, B. R. (2007). Prevention of anterior cruciate ligament injury in the female athlete. *British Journal of Sports Medicine, 41 Suppl 1*, i52-9. doi:bjsm.2007.037200 [pii]

Stearns-Reider, K. M., & Powers, C. M. (2017). Rate of Torque Development and Feedforward Control of the Hip and Knee Extensors: Gender Differences. *Journal of Motor Behavior, 50*(3), 321-329. doi:10.1080/00222895.2017.1363692

Suzuki, H., Omori, G., Uematsu, D., Nishino, K., & Endo, N. (2015). THE INFLUENCE OF HIP STRENGTH ON KNEE KINEMATICS DURING A SINGLE-LEGGED MEDIAL DROP LANDING AMONG COMPETITIVE COLLEGIATE BASKETBALL PLAYERS. *International Journal of Sports Physical Therapy*, *10*(5), 592–601.

Toth, A. P., & Cordasco, F. A. (2001). Anterior cruciate ligament injuries in the female athlete. *The Journal of Gender-Specific Medicine : JGSM : The Official Journal of the Partnership for Women's Health at Columbia, 4*(4), 25-34.

Vauhnik, R., Perme, M. P., Barcellona, M. G., Morrissey, M. C., Sevsek, F., & Rugelj, D. (2015). Effect of repeated passive anterior loading on human knee anterior laxity. *Manual Therapy, 20*(5), 709-714. doi:10.1016/j.math.2015.02.007 [doi]

Wallace, B. J., Kernozek, T. W., Mikat, R. P., Wright, G. A., Simons, S. Z., & Wallace, K. L. (2008). A comparison between back squat exercise and vertical jump kinematics: Implications for determining anterior cruciate ligament injury risk. *Journal of Strength and Conditioning Research / National Strength & Conditioning Association, 22*(4), 1249-1258. doi:10.1519/JSC.0b013e31816d66a4 [doi]

Walsh, M., Boling, M. C., McGrath, M., Blackburn, J. T., & Padua, D. A. (2012). Lower extremity muscle activation and knee flexion during a jump-landing task. *Journal of Athletic Training, 47*(4), 406-413. doi:10.4085/1062-6050-47.4.17 [doi]

Jenkins, W. L., Williams, D., Williams, K., Hefner, J., & Welch, H. (2017). Sex differences in total frontal plane knee movement and velocity during a functional single-leg landing. *Physical Therapy in Sport, 24*, 1-6. doi:10.1016/j.ptsp.2016.09.005

Yu, W. D., Liu, S. H., Hatch, J. D., Panossian, V., & Finerman, G. A. (1999). Effect of estrogen on cellular metabolism of the human anterior cruciate ligament. *Clinical Orthopaedics and Related Research, (366)*(366), 229-238.

Zazulak, B. T., Hewett, T. E., Reeves, N. P., Goldberg, B., & Cholewicki, J. (2007). Deficits in neuromuscular control of the trunk predict knee injury risk: A prospective biomechanical-epidemiologic study. *The American Journal of Sports Medicine, 35*(7), 1123-1130. doi:0363546507301585 [pii]

Zazulak, B. T., Paterno, M., Myer, G. D., Romani, W. A., & Hewett, T. E. (2006). The effects of the menstrual cycle on anterior knee laxity: A systematic review. *Sports Medicine (Auckland, N.Z.), 36*(10), 847-862. doi:36104 [pii]

Zazulak, B. T., Ponce, P. L., Straub, S. J., Medvecky, M. J., Avedisian, L., & Hewett, T. E. (2005). Gender comparison of hip muscle activity during single-leg landing. *The Journal of Orthopaedic and Sports Physical Therapy, 35*(5), 292-299. doi:10.2519/jospt.2005.35.5.292 [doi]

Zeller, B. L., McCrory, J. L., Kibler, W. B., & Uhl, T. L. (2003). Differences in Kinematics and Electromyographic Activity Between Men and Women during the Single-Legged Squat*. *The American journal of sports medicine, 31*(3), 449-456.

Zeng, C., Gao, S. G., Wei, J., Yang, T. B., Cheng, L., Luo, W., . . . Lei, G. H. (2013). The influence of the intercondylar notch dimensions on injury of the anterior cruciate ligament: A meta-analysis. *Knee Surgery, Sports Traumatology, Arthroscopy : Official Journal of the ESSKA, 21*(4), 804-815. doi:10.1007/s00167-012-2166-4 [doi]

APPENDIX A - Additional figures

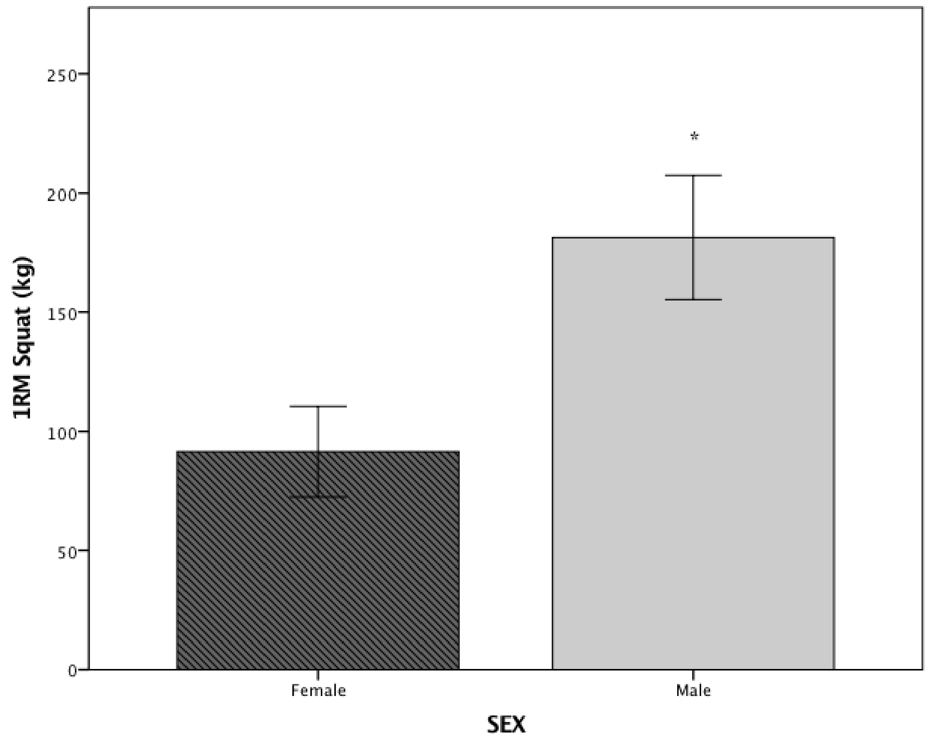


Figure A-1. Differences in squat one-repetition maximum (1RM) between sexes.* Significant differences between sexes ($p < 0.05$)

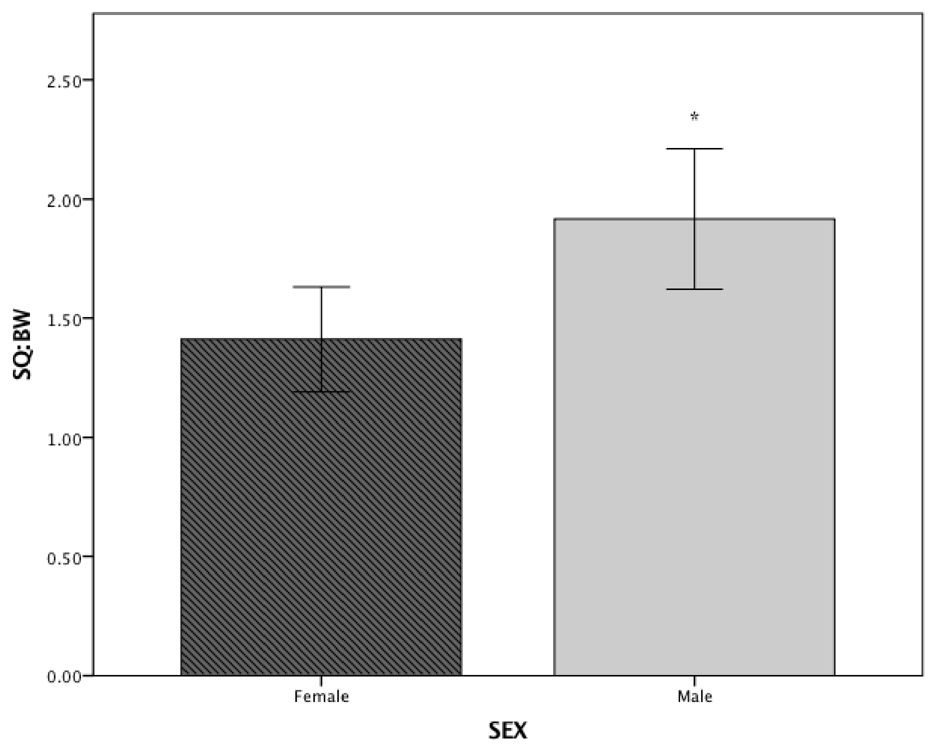


Figure A-2. Differences in squat to body weight ratio (SQ:BW) between sexes. * Significant differences between sexes ($p < 0.05$)

APPENDIX B - Mean normalized EMG tables

Table B-1. Normalized EMG (%MVIC) for pre and post-landing phases by sex.

Muscle	Height (cm)	Pre-landing Males (n = 13) Mean ± SD	Pre-landing Females (n = 15) Mean ± SD	Post-landing Males (n = 13) Mean ± SD	Post-landing Females (n = 15) Mean ± SD
Vastus lateralis[a,b,c,d]	28	7.62 ± 3.72	12.56 ± 5.73	30.33 ± 11.22	42.04 ± 14.92
	44	10.70 ± 6.31	17.16 ± 8.59	35.13 ± 12.77	52.85 ± 19.21
Vastus medialis[a,b,d]	28	10.96 ± 4.46	17.24 ± 6.89	38.25 ± 12.02	48.28 ± 16.16
	44	14.97 ± 6.99	22.18 ± 9.47	43.72 ± 11.22	59.39 ± 20.55
Rectus femoris[b,c,d]	28	7.83 ± 4.21	13.42 ± 7.61	14.02 ± 5.45	22.98 ± 7.64
	44	11.52 ± 6.67	16.35 ± 8.29	18.26 ± 7.15	34.69 ± 15.00
Biceps femoris[b,d]	28	8.31 ± 4.85	4.98 ± 1.77	12.31 ± 6.33	7.37 ± 2.97
	44	8.58 ± 4.62	6.11 ± 3.12	12.80 ± 8.66	8.66 ± 4.62
Semimembranosus	28	8.58 ± 6.20	7.30 ± 2.85	22.69 ± 8.47	17.88 ± 5.34
	44	8.16 ± 5.47	8.65 ± 4.07	24.45 ± 10.86	21.90 ± 5.79
Gluteus maximus[b,d]	28	10.32 ± 4.87	15.11 ± 5.92	19.61 ± 9.63	32.06 ± 14.99
	44	11.65 ± 5.55	17.95 ± 6.92	24.04 ± 11.70	36.29 ± 13.69
Gluteus medius	28	13.25 ± 5.95	12.95 ± 7.41	21.54 ± 7.08	21.65 ± 14.00
	44	15.63 ± 8.04	16.32 ± 7.38	25.51 ± 10.07	25.51 ± 15.16
Tibialis anterior[a]	28	8.77 ± 4.32	10.47 ± 4.32	35.80 ± 13.45	38.06 ± 10.96
	44	11.10 ± 5.36	13.64 ± 6.13	36.77 ± 9.56	40.86 ± 9.71

[a,b] Significant main effect for height and sex respectively for pre-landing ($p < .05$)

[c,d] Significant main effect for height and sex respectively for post-landing ($p < .05$)

Table B-2. Normalized EMG (%MVIC) for pre-landing by sex with SQ:BW as a covariate.

Muscle	Drop Height (cm)	Male (n = 13)				Female (n = 15)			
		Unadjusted		Adjusted		Unadjusted		Adjusted	
		Mean	SD	Mean	SE	Mean	SD	Mean	SE
Vastus lateralis[a]	28	7.62	3.72	9.53	1.95	12.56	5.73	10.91	1.78
	44	10.70	6.31	12.61	1.95	17.16	8.59	15.51	1.78
Vastus medialis[a]	28	10.96	4.46	13.77	2.22	17.24	6.89	14.82	2.02
	44	14.97	6.99	17.78	2.22	22.18	9.47	19.77	2.02
Rectus femoris	28	7.83	4.21	8.11	2.30	13.42	7.61	13.19	2.01
	44	11.52	6.67	11.81	2.30	16.35	8.29	16.12	2.01
Biceps femoris	28	8.31	4.85	7.36	1.14	4.98	1.77	5.87	1.09
	44	8.58	4.62	7.64	1.14	6.11	3.12	6.99	1.09
Semimembranosus	28	8.58	6.20	9.85	2.35	7.30	2.85	6.12	1.38
	44	8.16	5.47	9.43	2.35	8.65	4.07	7.47	1.38
Gluteus maximus	28	10.32	4.87	12.33	1.77	15.11	5.92	13.37	1.62
	44	11.65	5.55	13.67	1.77	17.95	6.92	16.70	1.62
Gluteus medius	28	13.25	5.95	12.81	2.29	12.95	7.41	13.32	2.10
	44	15.63	8.04	15.20	2.29	16.32	7.38	16.78	2.10
Tibialis anterior[a]	28	8.77	4.32	9.82	1.56	10.47	4.32	9.58	1.42
	44	11.10	5.36	12.15	1.56	13.64	6.13	12.74	1.42

[a] Significant main effect for height ($p < .05$)

Table B-3. Normalized EMG (%MVIC) for post-landing by sex with SQ:BW as a covariate.

Muscle	Drop Height (cm)	Male (n = 13)				Female (n = 15)			
		Unadjusted		Adjusted		Unadjusted		Adjusted	
		Mean	SD	Mean	SE	Mean	SD	Mean	SE
Vastus lateralis[a]	28	30.33	11.22	33.56	4.50	42.04	14.92	38.22	4.13
	44	35.13	12.77	38.36	4.50	52.85	19.21	50.06	4.13
Vastus medialis	28	38.25	12.02	42.44	4.99	48.28	16.16	44.69	4.55
	44	43.72	11.22	47.91	4.99	59.39	20.55	55.78	4.55
Rectus femoris[a,b]	28	14.02	5.45	13.63	3.29	22.98	7.64	23.30	2.88
	44	18.26	7.15	17.87	3.29	34.69	15.00	35.01	2.88
Biceps femoris[b]	28	12.31	6.33	13.06	1.78	7.37	2.97	6.68	1.70
	44	12.80	8.66	13.54	1.78	8.66	4.62	7.97	1.70
Semimembranosus	28	22.69	8.47	22.72	2.46	17.88	5.34	17.85	2.35
	44	24.45	10.86	24.84	2.46	21.90	5.79	21.87	2.35
Gluteus maximus[b]	28	19.61	9.63	18.73	4.04	32.06	14.99	32.81	3.71
	44	24.04	11.70	23.17	4.04	36.29	13.69	37.05	3.71
Gluteus medius	28	21.54	7.08	22.17	3.87	21.65	14.00	21.11	3.55
	44	25.51	10.07	26.35	3.87	25.51	15.16	26.35	3.55
Tibialis anterior	28	35.80	13.45	35.97	3.60	38.06	10.96	37.91	3.28
	44	36.77	9.56	36.94	3.60	40.86	9.71	40.81	3.28

[a] Significant main effect for height ($p < .05$)
[b] Significant main effect for sex ($p < .05$)

Table B-4. Normalized EMG for pre and post-landing by strength groups (Low vs High).

Muscle	Height (cm)	Pre-landing Low (n = 14) Mean ± SD	Pre-landing High (n = 14) Mean ± SD	Post-landing Low (n = 14) Mean ± SD	Post-landing High (n = 14) Mean ± SD
Vastus lateralis[a,b,c,d]	28	13.06 ± 5.95	7.48 ± 3.00	41.21 ± 14.21	30.90 ± 10.01
	44	18.34 ± 8.88	9.98 ± 4.71	53.19 ± 20.33	36.06 ± 12.02
Vastus medialis[a,b,d]	28	18.10 ± 7.17	10.59 ± 2.96	48.39 ± 17.68	39.90 ± 10.42
	44	23.67 ± 9.89	14.04 ± 4.80	59.71 ± 22.40	44.59 ± 8.90
Rectus femoris[b,c,d]	28	13.07 ± 8.10	8.63 ± 4.36	22.44 ± 8.75	15.30 ± 5.33
	44	17.25 ± 9.10	10.92 ± 4.65	32.22 ± 3.50	22.19 ± 12.49
Biceps femoris	28	5.29 ± 1.72	7.78 ± 4.96	8.37 ± 3.51	11.03 ± 6.60
	44	6.75 ± 3.06	7.81 ± 4.84	9.99 ± 3.61	11.27 ± 8.74
Semimembranosus	28	7.14 ± 2.97	8.63 ± 5.93	18.15 ± 4.67	22.09 ± 8.86
	44	8.47 ± 4.10	8.36 ± 5.37	21.71 ± 6.07	24.45 ± 10.38
Gluteus maximus[b]	28	15.72 ± 5.93	10.05 ± 4.43	30.79 ± 15.71	21.75 ± 10.94
	44	18.61 ± 6.86	11.44 ± 5.15	32.40 ± 13.05	28.81 ± 15.20
Gluteus medius	28	14.56 ± 6.97	11.62 ± 6.21	23.42 ± 13.79	19.77 ± 7.73
	44	17.83 ± 6.57	14.17 ± 8.26	28.64 ± 14.84	23.85 ± 10.49
Tibialis anterior[a,b]	28	10.89 ± 4.57	8.59 ± 2.26	40.23 ± 13.90	33.79 ± 9.13
	44	15.39 ± 6.77	9.56 ± 2.52	40.80 ± 10.14	37.25 ± 9.26

[a,b] Significant main effect for height and group respectively for pre-landing ($p < .05$)

[c,d] Significant main effect for height and group respectively for post-landing ($p < .05$)

APPENDIX C - Correlation graphs

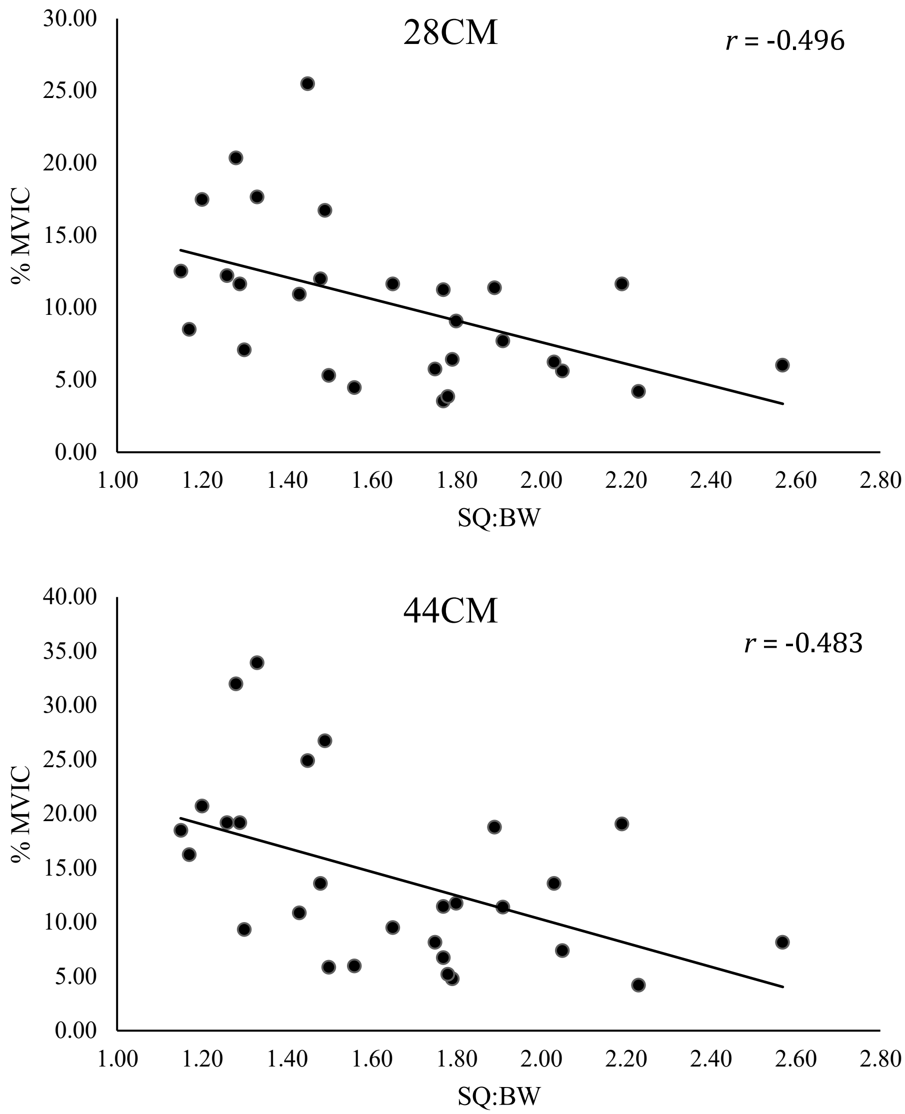
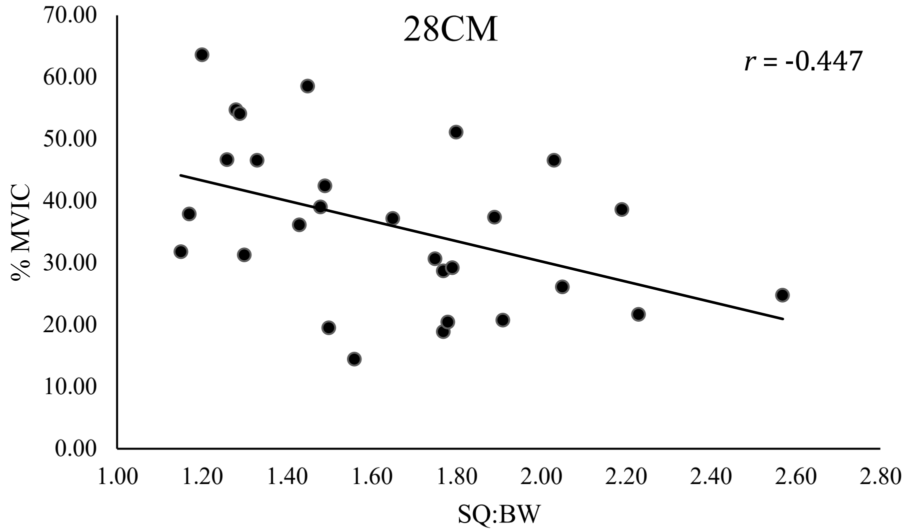


Figure C-1. Correlation of SQ:BW and VL activity in the drop landings for all participants (pre-landing).



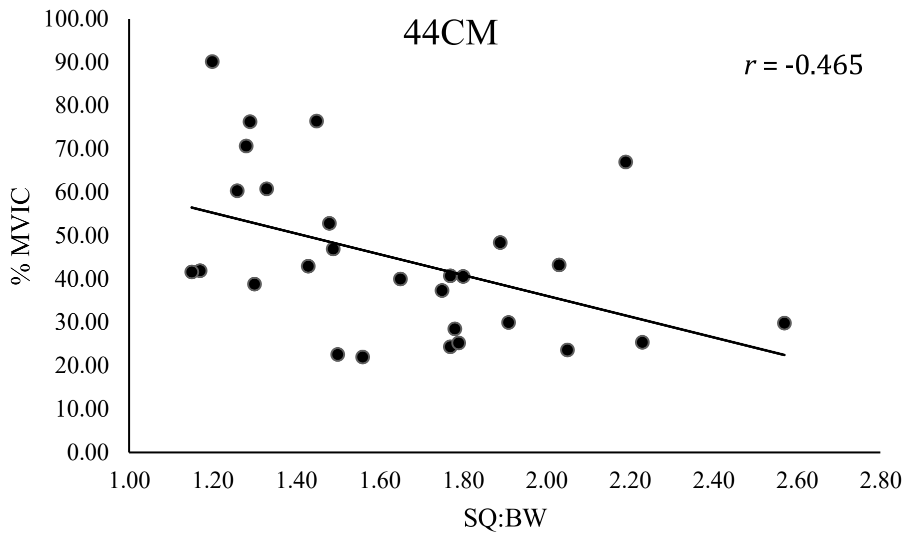
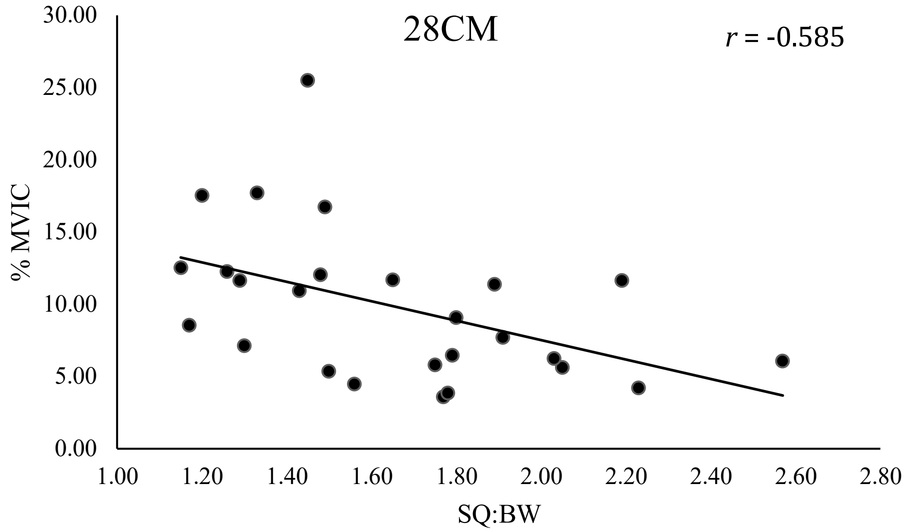


Figure C-2. Correlation of SQ:BW and VL activity in the drop landings for all participants (post-landing).



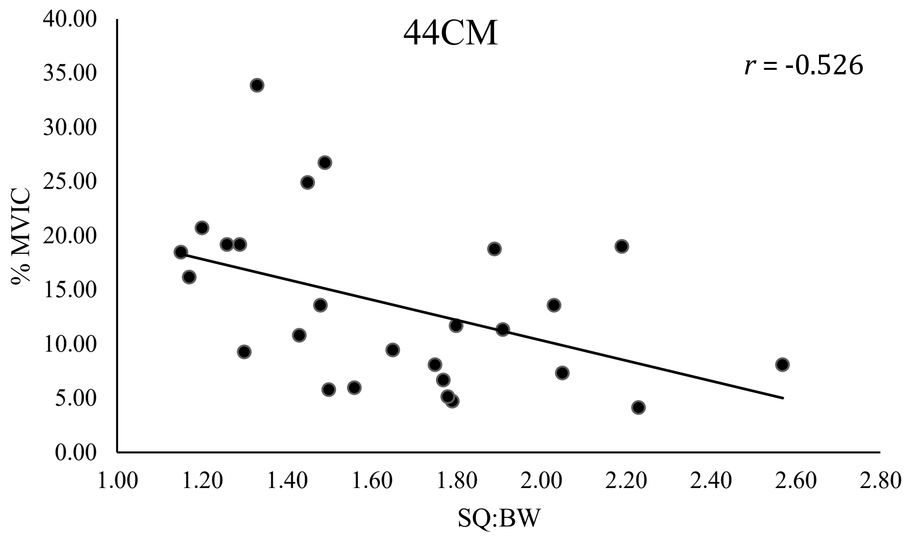
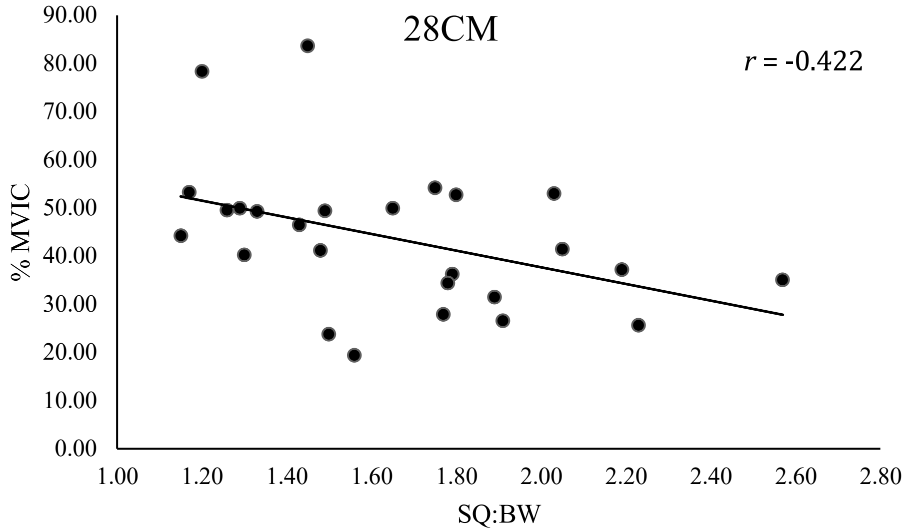


Figure C-3. Correlation of SQ:BW and VMO activity in the drop landings for all participants (pre-landing).



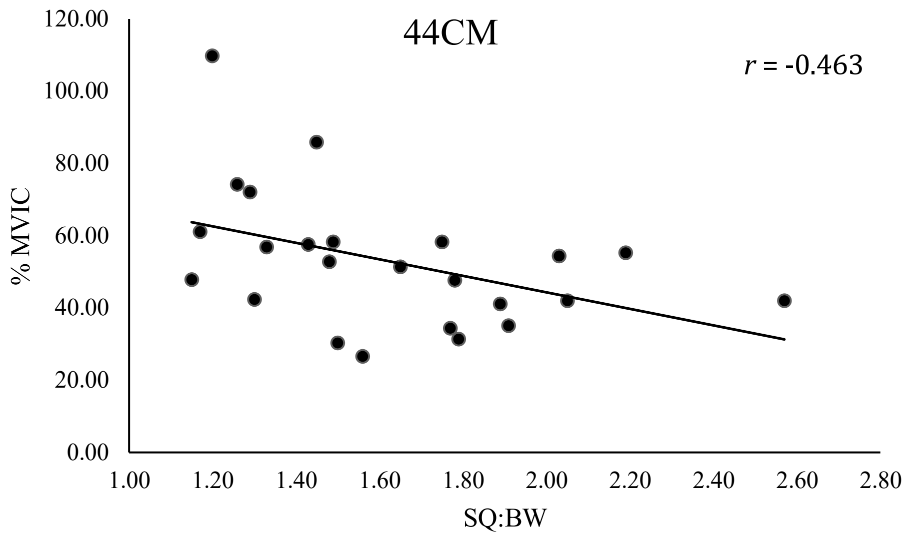


Figure C-4. Correlation of SQ:BW and VMO activity in the drop landings for all participants (post-landing).

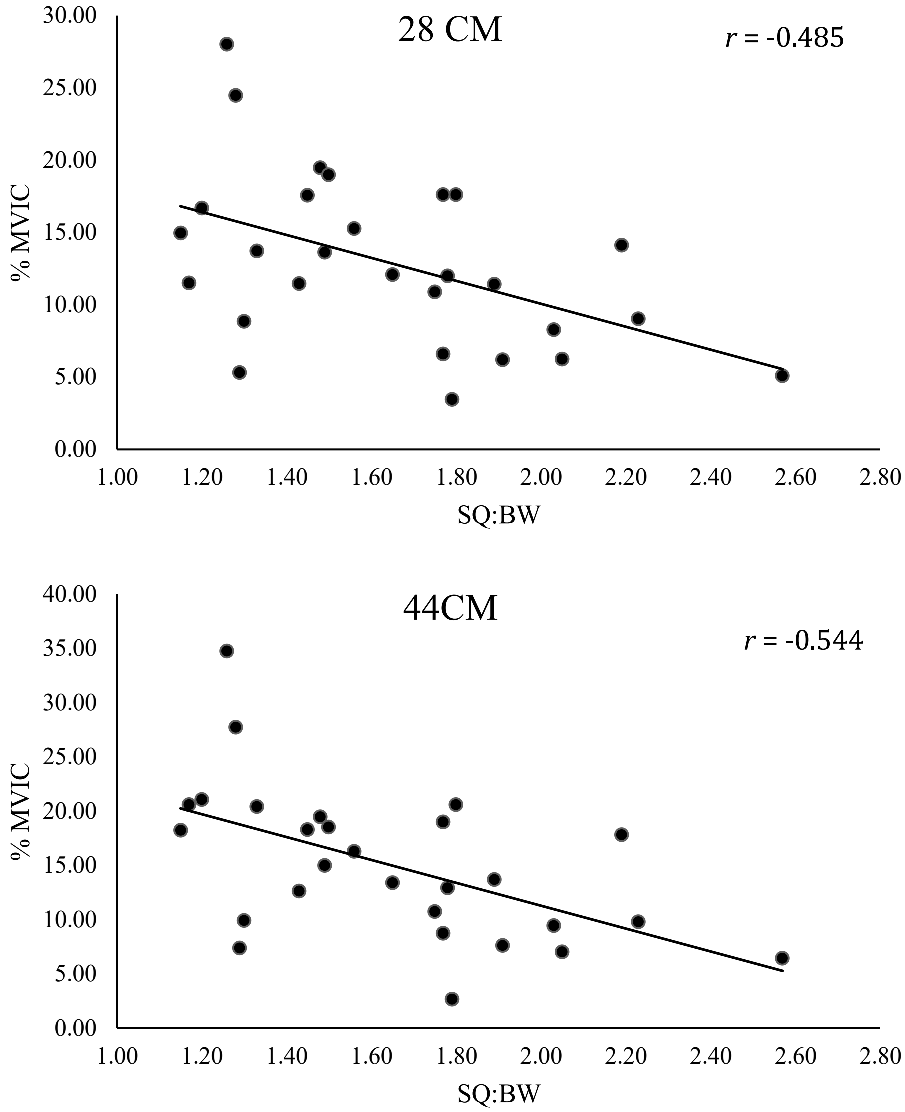


Figure C-5. Correlation of SQ:BW and GMAX activity in the drop landings for all participants (pre-landing).

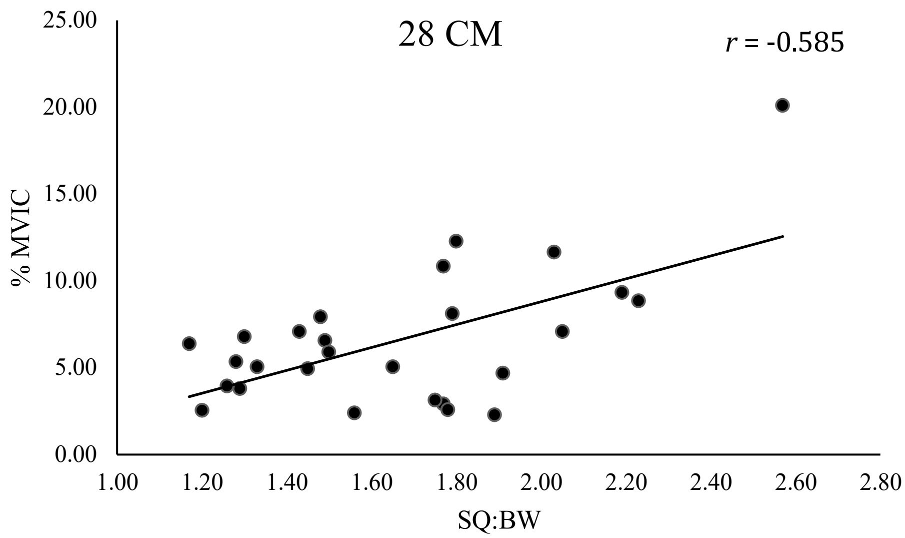


Figure C-6. Correlation of SQ:BW and BF activity in the drop landing at 28cm for all participants (pre-landing).

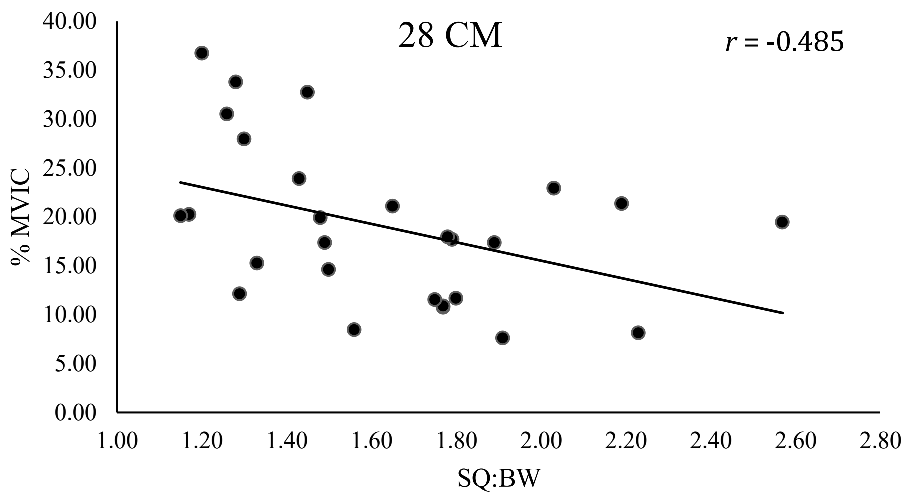


Figure C-7. Correlation of SQ:BW and RF activity in the drop landing at 28cm for all participants (pre-landing).

APPENDIX D - Material and apparatus

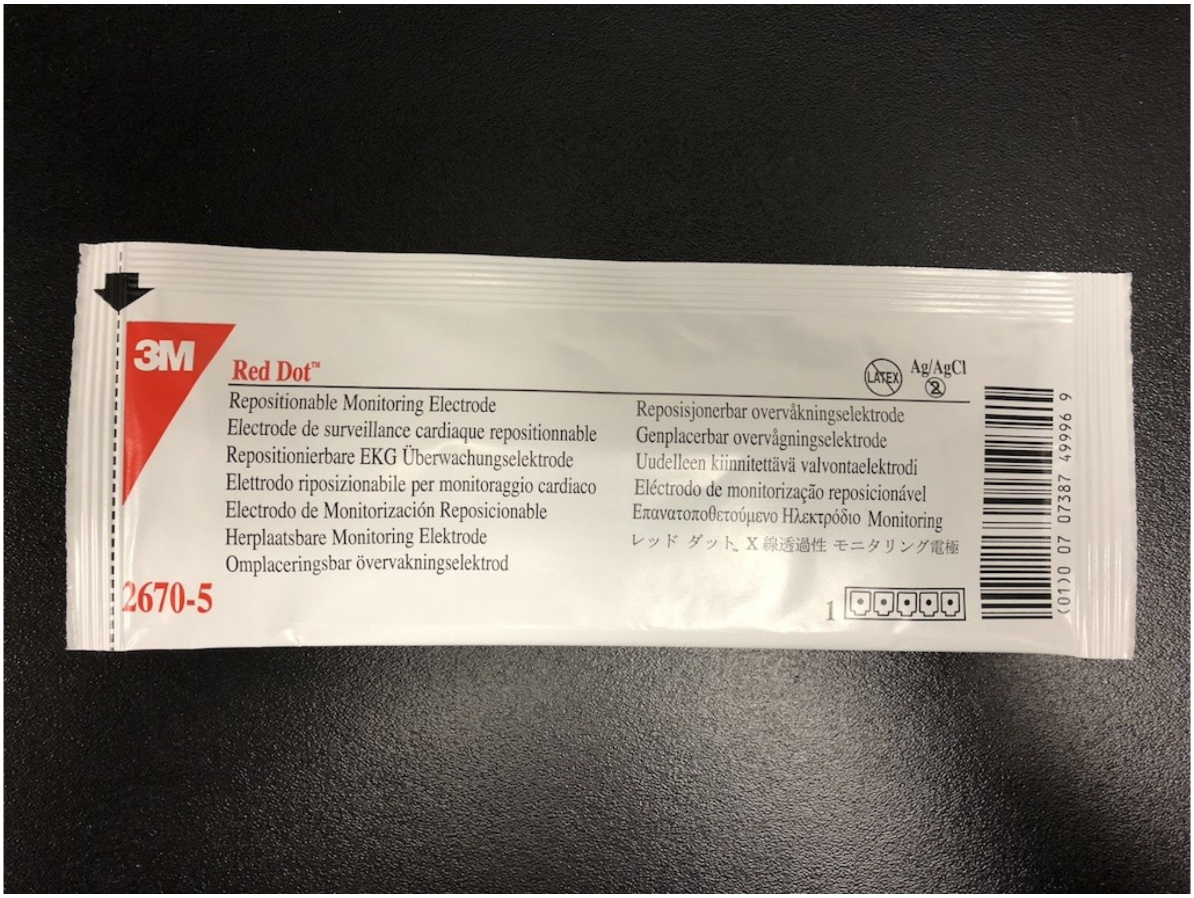


Figure D-1. Ag/AgCl surface electrodes used for EMG data collection (Red Dot™ 2670-5).

Figure D-2. Homemade footswitch to detect initial contact.

APPENDIX E - 1RM Back Squat and Drop Landing Set-up

Figure E-1. Weight room set-up to test the 1RM back squat. An elastic band is used to provide feedback when the appropriate squat depth is reached.

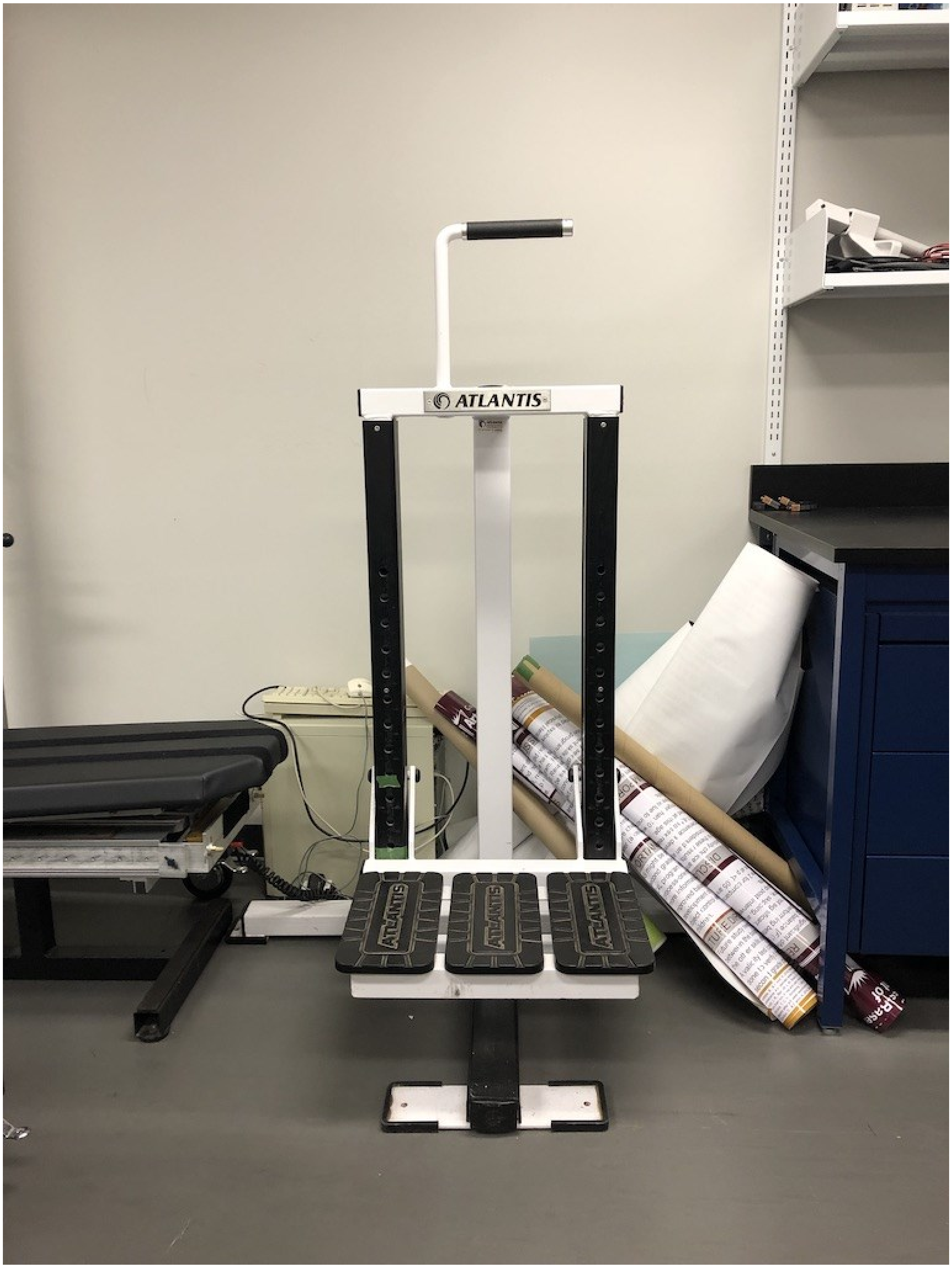


Figure E-2. Single-leg drop landing task set-up at a 28cm height.

Figure E-3 Single-leg drop landing task set-up at a 44cm height.

APPENDIX F - Warm-up procedure

Phase 1 (General)

- 5 minutes of low intensity on the stationary bike

Phase 2 (Specific)

- Standing quadriceps stretch to forward lunge (8x each side)
- Knee hug to side lunge (8x each side)
- World's greatest stretch with thoracic rotation (8x each side)
- Squat to stand with overhead reach (8x)

Each dynamic stretch was held for 2-3 seconds.

APPENDIX G - High vs Low strength groups

G.1 Results of High vs Low Strength groups

G.1.1 Mean EMG values during landing tasks

Participants were split into two groups (Low and High strength) based on their SQ:BW using the median split method. This method was used to investigate the effects of strength on neuromuscular activity instead of the sex differences. The cut-off value was 1.605 and each group was composed of 14 participants. The characteristics of each group can be found in Table .

Table G-1. Anthropometrics characteristics and strength measurements by strength groups (Low vs High).

	Low (n = 12 female, 2 males)	High (n = 3 females, 11 males)	*p* value
Age (years)	21.86 ± 1.75	23 ± 1.57	0.080
Height (cm)	168.83 ± 11.18	178.92 ± 7.82	0.010*
Body weight (kg)	69.70 ± 14.94	88.66 ± 17.71	0.005*
Squat 1RM (kg)	94.93 ± 28.63	171.39 ± 36.90	< .0005*
Squat to body weight ratio	1.34 ± 0.13	1.94 ± 0.25	< .0005*

* Statistical difference between groups ($p < 0.05$).

Mean EMG activities of each muscle were analyzed using a two-way (strength group x height) ANOVA. The descriptive statistics for the main effects of strength and drop height for the pre-landing and post-landing phases are shown in Table B-4. No interaction effects were found for any of the eight muscles analyzed. During the pre-landing phase, there was a significant main effect of strength group on muscle activity for the VL ($F_{1,52} = 18.682$, $p < .0005$), VMO ($F_{1,52} = 21.236$, $p < .0005$), RF ($F_{1,52} = 8.102$, $p = .006$), GMAX ($F_{1,52} = 17.953$, $p < .0005$) and TIBANT ($F_{1,52} = 11.255$, $p = .002$) muscles. The lower strength group had significantly more VL (low: *M*: 15.70%, *SD* = 7.89; high: *M*: 8.73%, *SD* = 4.08), VMO (low: *M*: 20.88%, *SD* = 8.90; high: *M*: 12.31%, *SD* = 4.28), RF (low: *M*: 15.16%, *SD* = 8.71; high: *M*: 9.77%, *SD* = 4.57), GMAX (low: *M*: 17.17%, *SD* = 6.46; high: *M*: 10.75%, *SD* = 4.77) and TIBANT (low: *M*: 13.14%, *SD* = 6.10; high: *M*: 9.02%, *SD* = 2.41) activity than higher group prior to landing (Figure 6).

During the post-landing phase, only the VL ($F_{1,52}$ = 12.260, p = .001; low: *M*: 47.20%, *SD* = 18.26; high: *M*: 33.48%, *SD* = 11.17), VMO ($F_{1,48}$ = 7.853, p = .007; low: *M*: 54.05%, *SD* = 20.60; high: *M*: 41.75%, *SD* = 9.93) and RF ($F_{1,50}$ = 7.820, p = .007; low: *M*: 27.33%, *SD* = 12.49; high: *M*: 18.74%, *SD* = 11.16) muscles had significantly more activity in the lower strength group compared to the higher strength group (Figure 7).

G.1.2 EMG mean time to peak after during single leg landings

A two-way (strength group x height) ANOVA revealed no significant interaction between strength group and drop height on the time to peak after initial contact for any of the eight muscles analyzed. Similarly, no main effects of strength group or drop height were observed.

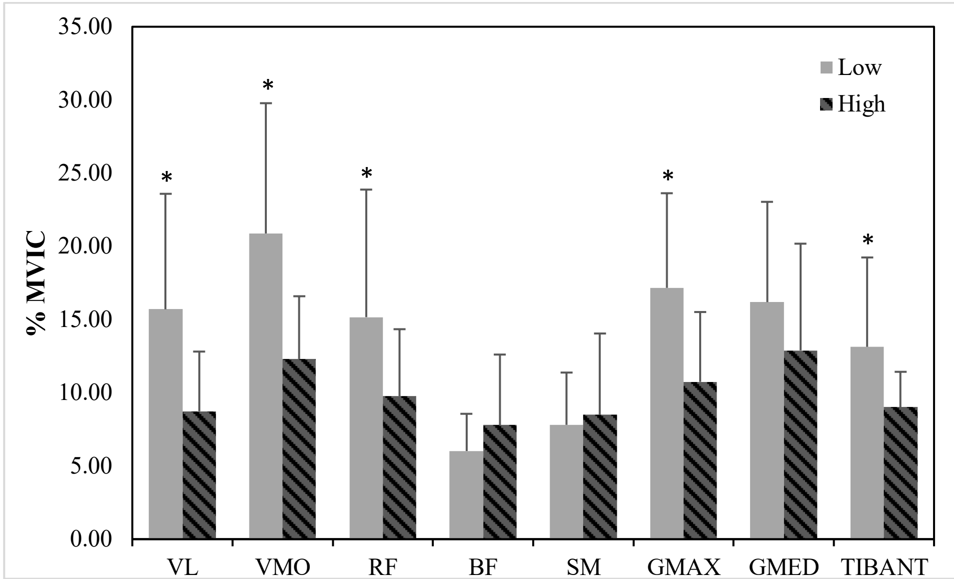


Figure G-1. Mean muscle EMG activity during the pre-landing phase.
Data are mean ± SD. * Significant differences between strength groups ($p < 0.05$)

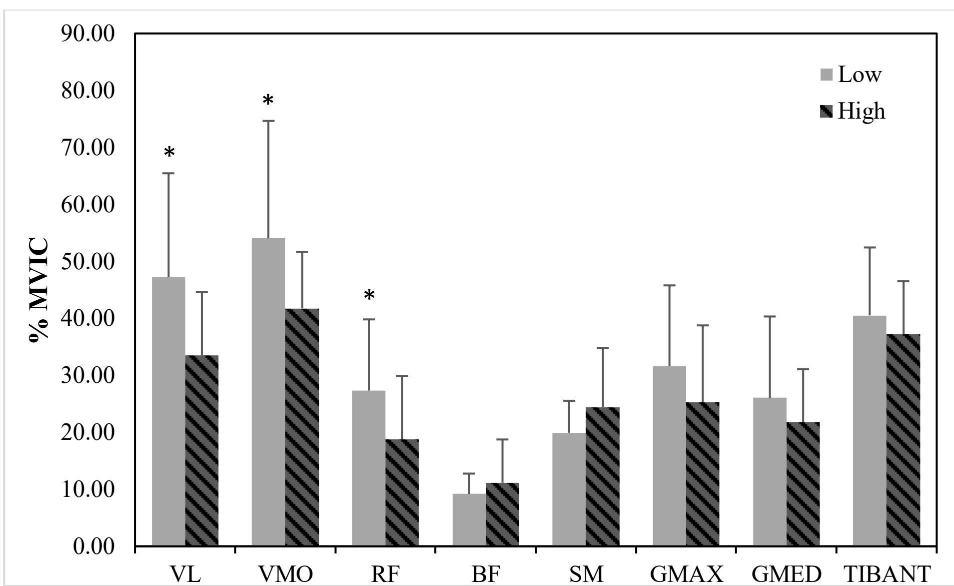


Figure G-2. Mean muscle EMG activity during the post-landing phase.
Data are mean ± SD. * Significant differences between strength groups ($p < 0.05$)

G.2 Discussion of High vs Low strength groups

G.2.1 Differences in muscle activity during landing

In an attempt to investigate the effect of strength on neuromuscular activity independently of sex, we divided the groups based on their SQ:BW using the median split method. Due to a small sample size and the distribution of the SQ:BW ratio among participants (females being mostly in the first tertile vs males in the third tertile) the median split method was preferred over tertiles. In the absence of a sex effect on muscle activity, the differences observed between sexes should be amplified by the greater gap in strength between the high and low groups if strength has an influence on muscle activity.

The low strength group demonstrated significantly more quadriceps (mean %MVIC) activity than the high strength group during both landing phases. Interestingly, no significant difference between the high and low groups in BF activity was observed even if the strength gap between the strength-based groups (*SQ:BW difference between groups* = 0.60) was bigger than the sex-based groups (*SQ:BW difference between groups* = 0.51). Similarly, no significant difference in GMAX activity was found between the low and high strength groups during the post-landing phase. The smaller differences observed between strength-based groups than sex-based groups for the BF and GMAX muscles suggest that sex may have a greater influence on muscle activity than strength. These findings support our previous observations on sex differences in BF and GMAX muscle activity during landing tasks.

G.1.2 EMG mean time to peak after during single leg landings

In our study, we did not observe any differences between the high and low strength groups in the time to peak muscle activity after initial contact. These finding suggest that the strength may not be an important factor when looking at differences in muscle activity time to peak after initial contact.