Investigation of female lower limb muscle reaction to multidirectional perturbation

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Abstract

Investigation of female lower limb muscle reaction to multidirectional perturbation

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Anterior cruciate ligament (ACL) injuries are more prevalent in female athletes compared to male athletes. Researchers have explored the mechanism of an ACL injury in both males and females using mathematical modeling, interview, in-vivo arthroscopy, clinical evaluation, cadaver studies, motion analysis, and electromyography. However, an unexpected perturbation that mimics an ACL injury mechanism has not yet been used. Therefore, this study explored lower extremity muscle activity following an unexpected perturbation that mimics the mechanism of an ACL injury as well as the contribution of the initial stance of the athlete to an injury.

Female Concordia varsity athletes were recruited in Montreal, QC. Data was collected using the VICON motion capture system, Noraxon DTS EMG, and a goniometer. Participants were asked to maintain balance on their non-dominant leg during unexpected perturbations in the lateral, posterior, and rotational motions as well as a combination motion that mimics an ACL injury mechanism.

The mean EMG values were greatest during the post-perturbation phase for all muscles compared to the pre-perturbation and perturbation phases for both knee conditions. The time of occurrence of the maximum EMG values revealed that the muscles reached the maximum EMG value later following the onset of perturbation in the rotation direction in order to stabilize the knee joint and/or maintain balance during the lateral, posterior, and combination perturbations.

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List of Figures and Tables

Abbreviations

ACL: Anterior Cruciate Ligament

ANOVA: repeated measures analysis of variance

ASIS: Anterior superior iliac spine

COP: Center of pressure

DTS: Direct Transmission System

EMG: Electromyography

MANOVA: repeated measures multivariate analysis of variance

MS: milliseconds

PSIS: Posterior superior iliac spine

TNMT: Targeted neuromuscular training

uV: Microvolt

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1.0 Theoretical Context

1.1 The Burden of ACL Injuries in Sport

Basketball and soccer are sports in which athletes are exposed to stresses and strains that increase the risk of injury in the lower extremity (Weltin et al., 2016)(Malinzak et al., 2001). Due to its popularity, researchers have been focusing on finding methods to prevent these injuries through training. Although the injury reports are similar between males and females, female athletes frequently report hip, lower leg and shoulder injuries and male athletes frequently report thigh injuries (Sallis et al., 2001). The reported injuries occur more often during competition than a practice session (Newman and Newberg, 2010) (Ireland, 1999). The most common injuries in basketball are lower extremity injuries, with lateral ankle sprains composing 9.4% of all reported injuries in the NBA over a 10 year study from 1988-1989 to 1997-1998 (Agel et al., 2007). Federation Internationale de Football Association (FIFA) has also reported that 17% of overall injuries are lower extremity injuries of which 12% is reported as knee injuries, and 18% is reported as ankle injuries (FIFA, 2014). Through jumps, sprints, and repeated stops and starts involving deceleration and acceleration as seen in basketball and soccer, the knees are susceptible to acute and overuse injuries (Omi et al., 2018)(Steffen et al., 2016)(Agel et al., 2007) (Silvers et al., 2005)(McLean et al., 2005)(Silvers & Mandelbaum, 2007) (Malinzak et al., 2001). Landing knee joint kinematics, cutting, pivoting, and skeletal alignment are factors that contribute to knee joint injuries (Wang et al., 2015). A 6-year study conducted by the Australian Institute of Sport demonstrated that knee injuries compose 18.8% of reported injures while 16.6% are ankle injuries. Although there is a high percentage of reported knee injuries overall, the ankle sprain is the most commonly reported injury (Hickey et al., 1997). Overall, 66% of injuries related to sports are lower extremity injuries (Padua et al, 2018). Of the reported knee injuries, there has been a rise in anterior cruciate ligament (ACL) injuries as well as patellofemoral joint injuries since mid-1970s, which cannot be explained solely by the increase in the number of female athletes (Baker, 1998).

Female athletes are more prone to ACL injuries in comparison to male athletes (Padua et al, 2018)(Agel et al., 2007)(Ireland, 1999) (Slauterback et al., 2002). In basketball, the female to male ratio for ACL injuries was reported as 3.5:1 (Prodromos et al., 2007). In soccer, a recent study reported an ACL injury rate of 2.55 per 10 000 athletes (Thompson et al., 2017). Furthermore, studies involving female basketball athletes demonstrated that ACL injuries were reported 2 to 5 times more by female athletes compared to male athletes (Burnham et al., 2017)(Thompson et al., 2017)(Steffen et al., 2016)(Trojian and Ragle, 2008)(Ireland, 1999). A 10 year cohort study also revealed that female basketball athletes were 2.89 times more susceptible to ACL injuries compared to male basketball players and female soccer players were 2.29 times more susceptible to ACL injuries compared to male soccer players (Ireland, 1999). Studies have also demonstrated an incidence rate as high as 8:1 when comparing female athletes to male athletes (Malinzak et al., 2001)(Lindenfeld et al., 1994)(Wojtys et al., 2003). It has also been reported that 70-78% of ACL injuries are due to a non-contact injury mechanism (Padua et al., 2018)(Golden et al., 2009)(Silvers & Mandelbaum, 2007)(McLean et al., 1999).

ACL tears are considered one of the most severe injuries as they result in a significant loss of time on the court or field and require surgical repair followed by extensive rehabilitation (Hickey et al., 1997). Female participation in sport activities and subsequent ACL injuries have increased since the establishment of Title IX of the United States Education Amendments Act of 1972, which stated that, an activity or education program financed by the federal government cannot prohibit participation based on sex (Hewett et al., 2009)(Silvers & Mandelbaum, 2007)(Huston & Wojtys, 1996)(Myer et al., 2005). In 1985, approximately 50 000 knee surgeries were performed in the United States and 65% of the injuries occurred during sports (Ireland, 1999). It is now estimated that approximately 100 000 - 250 000 ACL reconstruction surgeries are performed each year in the United States (Sugimoto et al., 2012) (Hewett et al., 2009) (Silvers & Mandelbaum, 2007). The estimated cost associated with each ACL injury is US $17 000 to $38 000, which includes diagnostic tests, surgery, and rehabilitation (Padua et al, 2018) (Sugimoto et al., 2012) (Hewett et al., 2010). The overall annual cost of ACL reconstruction in the United States is estimated to be US $1.7-3 billion (Padua et al., 2018)(Sugimoto et al., 2012) (Hewett et al., 2009) (Silvers & Mandelbaum, 2007). Of this total, US $650 million is allotted to female high school and collegiate varsity athletes (Hewett et al., 2009). Following an ACL injury, an athlete loses 6 months or more of sports participation, and is at a higher risk of sustaining a second ACL injury (Sugimoto et al., 2012). During this time, the athlete may also lose scholarship funding, perform poorly academically, and sustain long-term disability (Hewett et al., 2010). Although 82% of athletes continue participating in sports following ACL reconstructive surgery, only 63% of athletes are able to return to the same level of engagement in sport activities prior to their injury and only 44% of athletes are able to return the same level of competition prior to injury (Padua et al., 2018). Burnham et al. (2017) also suggests an individualized approach to reconstruction and neuromuscular training may help recovery rates. ACL injuries also put the athlete at risk for osteoarthritis 10-15 years after injury occurrence (Omi et al., 2018)(Padua et al., 2018)(Fox et al., 2017)(Steffen et al., 2016)(Quatman et al., 2009)(McLean et al., 2005). A study in Sweden revealed that 34% of the population of females who were previously soccer athletes with ACL injuries had radiographic evidence of osteoarthritis (Silvers et al., 2005). A decreased quality of life due to limited knee motion and an increase in cost of healthcare result from these consequences (Sugimoto et al., 2012). As a result of these factors, female non-contact ACL injury research has been conducted focusing on associated risk factors, the mechanism of the injury explained through biomechanical and neuromuscular influences, the role of leg dominance, and methods of injury prevention.

1.2 Risk Factors Affecting Female ACL Injuries

As a result of the evidence indicating that women are at a higher risk of a non-contact ACL injury, there have been several studies that aim to determine the differences between males and females to explain the increased incidence of ACL injuries in female athletes. There have been differences found between males and females through the comparison of anatomical, hormonal, biomechanical and neuromuscular factors, but it was not possible to prove that these factors are contributors to the risk of an ACL injury (Steffen et al., 2016)(Quatman et al., 2009)(Silvers & Mandelbaum, 2007).

Risk factors reported by the International Olympic Committee that are associated with the increased number of overall reported injuries by female athletes are preovulatory phase of the menstrual cycle, decreased intercondylar notch width, and a predisposition to increased knee abduction during landing as the tibia moves away from the femur medially (Renstrom et al., 2008) (Carson & Ford, 2011) (Vescovi, 2011). An increase in hormones, specifically oestrogen and relaxin, has been correlated with a decrease in collagen production, which affects the recovery of tendons and ligaments (Silvers et al., 2005)(Silvers & Mandelbaum, 2007) (Slauterback et al., 2002). However, this change in hormone levels cannot be used as evidence to explain ACL injuries during the menstrual cycle (Silvers et al., 2005). During increased knee abduction, there is also a valgus collapse at the knee joint, which may be a result of a greater posterolateral tibial plateau slope in females with ACL injuries, exposing the athletes to increased lateral rotations in the transverse plane (Quatman et al., 2009). A review of the injuries and risk factors by Alentorn et al. (2009) demonstrates other associated risk factors for lower extremity injuries, which include anatomical risk factors such as BMI, knee hyperextension, joint laxity, as well as genetic predisposition and prior history of injuries. Other developmental and hormonal risk factors include pubertal and post pubertal maturation, and ACL tensile strength. Biomechanical risk factors include knee abduction, anterior tibial shear, lateral trunk motion, tibial rotation, dynamic foot pronation, fatigue, and ground reaction forces. Neuromuscular risk factors include recruitment of hamstring fibers, hip abduction strength, and trunk proprioception (Alentorn et al., 2009). When compared to males, the cross-sectional area and strength of the lower extremity muscles are less in females. The knee joint ligaments of female athletes of the National Collegiate Athletic Association (NCAA) had less muscular protection due to decreased torsional stiffness of the muscles during external loading compared to male athletes of similar size and sport (Wojtys et al., 2003). Among these risk factors, extensive research has been conducted over several decades to determine the extent of the influence of biomechanical and neuromuscular factors on female non-contact ACL injuries.

1.3 ACL Injury Mechanism

1.3.1. History of ACL Injury Mechanism and Diagnosis

Although the diagnosis of an ACL injury has changed over time as a result of research and practice over several decades, the proposed mechanism of an ACL injury remains similar. In 1976, Feagin et al. reported that the occurrence of most non-contact ACL injuries is during deceleration and change in direction of motion. The mechanism was described as a valgus stress at the knee joint due to external rotation of the lower leg (Feagin et al., 1976). During the same year, Torg et al. (1976) reported that the ACL is not the sole factor controlling knee stability in the anteroposterior direction and that ACL tears were discovered during 79% of surgeries to repair torn medial menisci. During the 1970s, the anterior drawer test and Lachman's test were used as methods for ACL tear diagnosis. However, Lachman's test was reported as the most reliable to detect ACL instability (Torg et al, 1976). During the pivot shift test, those with ACL injuries are able to function confidently when movements are in the sagittal plane but describe instability when movements are rotational (Quatman & Hewett, 2009). Proper diagnosis of an ACL injury was said to use various clinical tests to be able to take into account or rule out injury of the medial meniscus (Torg et al., 1976). Repairing the ACL by using a figure 8 suture was deemed unsatisfactory (Feagin et al., 1976). Although the exploration of prevention techniques was not yet mentioned, the importance of a proper ACL tear diagnosis was being explored (Feagin et al., 1976) (Torg et al., 1976) (Buckley et al., 1989). In 1989, Noyes et al. determined that the ACL must be stretched 50% more than its resting length for failure. ACL injury research also focused on its debilitating effect and the occurrence of a partial to complete tear (Noyes et al., 1989) (Donald et al., 1985). Rehabilitation post ACL surgery included hamstring strengthening whereas quadriceps strengthening was delayed, demonstrating that the basic understanding of the ACL injury mechanism and rehabilitation was similar (Buckley et al., 1989).

1.3.2 Influence of Biomechanical Factors

From an epidemiological view, the exact mechanism of an ACL injury is still inconclusive (Kobayashi et al., 2010). The planes of the knee motion as well as the loading and mechanism of an ACL injury have been studied through mathematical modeling, interview, in-vivo arthroscopy, clinical evaluation, video analysis, motion analysis, and electromyography

(EMG) analysis. These methods of analysis have led to inconclusive results and contradictions (Quatman & Hewett, 2009). At 20-30 degrees of knee flexion, the ACL is expected to provide 85% of the total restraint to anterior translation of the tibia at the knee joint. The notion that the angles of the knees at full extension in the sagittal plane and strong forces from the quadriceps muscles are the main contributors to ACL injury is common (Quatman & Hewett, 2009). An epidemiological study by Kobayashi et al. (2010) revealed that the dynamic alignment of the lower extremity that was most common for ACL injury was knee valgus and foot abduction. A study conducted by Numata et al. (2017) also confirmed that dynamic knee valgus is a risk factor for ACL injury. Knee valgus may be due to the distal tibia's abduction motion relative to the femur or internal/external rotational motion at the knee joint in the transverse plane between the tibia and femur. Other studies suggest that as the angle at knee flexion increases, the internal rotation of the tibia also increases up to 21 degrees of rotation with knee flexion at 90 degrees, therefore increasing the strain placed on the ACL. In addition to this, in-vivo biomechanical analyses and video analyses have shown evidence of movement in the coronal plane as well with an increase in valgus load at the knee joint during injury occurrence (Myer et al., 2009)(Quatman & Hewett, 2009). Another study indicated that a change in the initial stance by bending the knees to attain a crouched position allowed for better balance during anterior and posterior perturbations (LeVangie, 2013). Therefore, this information reveals that non-contact ACL injuries are due to the load that the ligaments of the knee joint must share as a result of an increase in load or motion in the sagittal, coronal, and transverse planes or multiple planes (Quatman & Hewett, 2009).

There is also evidence that the mechanism of an ACL injury is different between males and females. Studies that combine both biomechanical and epidemiological standpoints suggest that knee movement in the coronal plane and torques are predictors of non-contact ACL injuries in female athletes (Quatman & Hewett, 2009)(Myer et al., 2009). The mechanism of non-contact ACL injuries in women during basketball is mostly through valgus collapse in the coronal plane (Quatman & Hewett, 2009) (McLean et al., 2005). As seen in Figure 1, the knee is also between 0 degrees and 30 degrees, near full extension, and external tibial rotation is present during a deceleration motion while the foot is planted compared to male athletes (Quatman & Jewett, 2009) (Silvers et al., 2005). Within the athletic population, the knee valgus motion and torque are higher in females than males (Quatman & Hewett, 2009). Knee abduction angle is also larger in female athletes compared to male athletes, measuring more than 8 degrees compared to uninjured athletes (Hewett et al., 2009) (Boden et al., 2009). Peak articular pressures are present at the posterior and lateral aspect of the tibia and the lateral condyle of the femur when there is a 5° abduction angle at the knee joint. There is also increased ACL strain during a combined motion involving abduction and anterior translation of the tibia when there is a 5° abduction angle at the knee joint. Mathematical modeling has demonstrated that a perturbation during a side-step maneuver may cause external valgus (Quatman & Hewett, 2009). Therefore, a valgus collapse at the knee joint through these motions would result in an ACL injury. By decreasing these knee motions (abduction, anterior translation, internal and external rotation of the tibia), the risk of female ACL injuries can be reduced (Quatman et al., 2011) (Ireland, 1999).

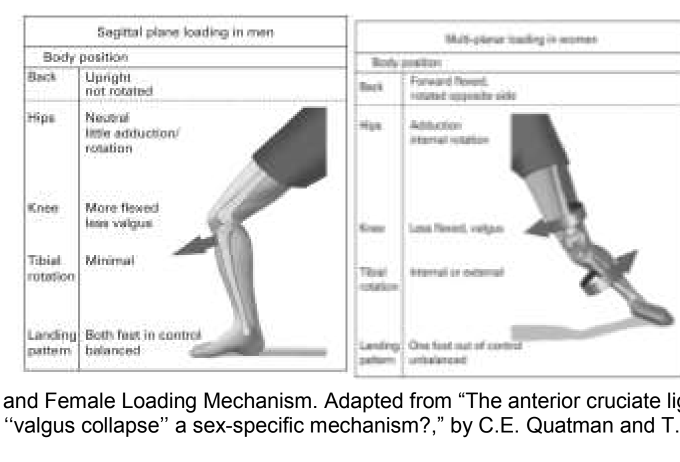


Figure 1. Male and Female Loading Mechanism. Adapted from “The anterior cruciate ligament injury controversy: is ‘‘valgus collapse’’ a sex-specific mechanism?,” by C.E. Quatman and T.E. Hewett, 2009.

Imaging and diagnostics of bone bruising also reveal that a valgus collapse is the likely occurrence during an ACL injury. As indicated in Figure 2, magnetic resonance images indicate bruising present for 80% of the studies on the lateral femoral condyle and the posterior and lateral sections of the tibial plateau following an ACL injury (Quantman & Hewett, 2009)(Quatman et al., 2011). In addition to this, the images reveal through bruising on the lateral aspect of the tibia and femur that there is lateral compression that occurs when there is unloading at the medial aspect of the knee joint (Quantman & Hewett, 2009). The maneuvers that may be responsible for bruising on the posterior tibial plateau are internal rotation, abduction, or anterior translation of the tibia, as well as external rotation of the femur (Quantman & Hewett, 2009). Female bone bruising was mostly present posterior and lateral on the tibia following an ACL injury. Male bone bruising mostly revealed medial meniscal injuries as well as lateral collateral and posterior cruciate ligament injuries. Therefore, this evidence indicates that ACL injuries in females are due to a valgus motion whereas ACL injuries in males are due to motions in the sagittal place at the knee joint (Quantman & Hewett, 2009). Similar to this, McLean et al. (1999) reported that male athletes spent more time on stabilizing the knee joint in the sagittal plane during the stance phase of the cutting maneuver compared to female athletes, which corresponds to a longer period of eccentric quadriceps contraction.

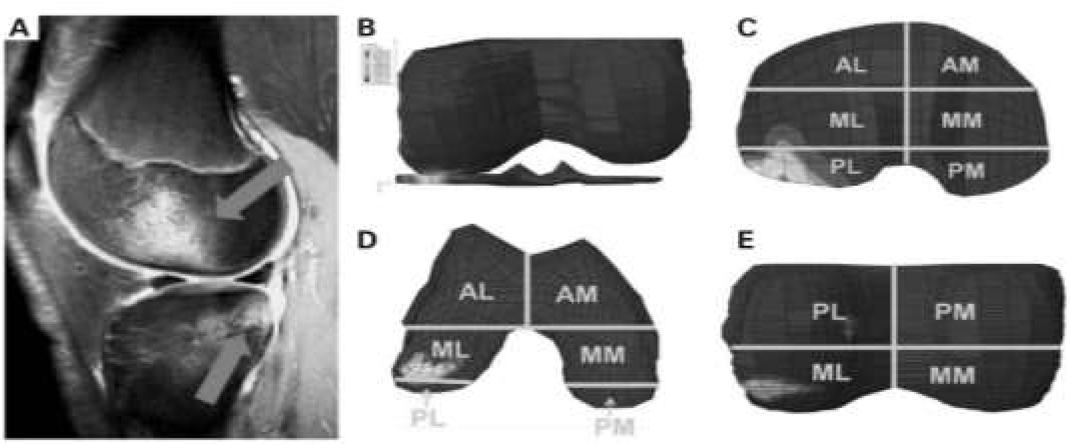


Figure 2. Magnetic Resonance Imaging of ACL Injury Loading Mechanism . Adapted from "The anterior cruciate ligament injury controversy: is ''valgus collapse'' a sex-specific mechanism?," by C.E. Quatman and T.E. Hewett, 2009.

1.3.3 Influence of Neuromuscular Factors

The active contraction of the muscles that cause stiffness at the knee joint is an important factor when evaluating stability of the knee joint, since the strength and recruitment pattern of muscles are crucial for knee stability. The ligaments and muscles of the knee joint endure external loads. A shear load is shared between the ligaments and the muscles that cross the knee joint and is usually equal to the stiffness that is generated at the joint (Wojtys et al., 2003). If there is less stiffness in the muscles of the joint, then mostly the ligaments and other structures that are present must support the load, which in turn may lead to a rupture of the ligament as a result of increased stiffness. The co-contraction of muscles decreases the anteroposterior and rotational displacement motions of the knee joint (Steffen et al., 2016)(Wojtys et al., 2003). When performing a landing task, females land with less flexion at the knee joint compared to males, leading to a neuromuscular imbalance. In this instance, the quadriceps muscle group dominates in the extended position to stabilize the knee joint (Hewett et al., 2010). The quadriceps muscle group encourages the occurrence of an ACL injury since its attachment on the tibia may cause an anterior shear force. Contrary to this, the hamstring muscle group protects the ACL by preventing excessive anterior tibial translation. If the hamstring muscle group contraction is delayed compared to the quadriceps, the ACL may be at risk of rupture (Thompson et al., 2017)(Ueno et al., 2017)(Steffen et al., 2016)(Silvers & Mandelbaum, 2007)(Malinzak et al., 2001)(Bennett et al, 2008). Early contraction of the quadriceps muscles in unplanned situations during a landing task may also cause ACL injuries as a result of anterior tibial force (Ueno et al., 2017). In addition to this, a study conducted by Ruan et al. (2017) suggests that static stretching of the hamstring reduces co-contraction of the hamstring and quadriceps, but did not increase the risk of an ACL injury due to cutting tasks. Cadaver studies also demonstrated that ACL injuries were more likely due to an increase in quadriceps force and anterior tibial force during valgus loads. (Quatman & Hewett, 2009). Another cadaveric study applied anterior shear motion and internal tibial rotation to the knee joint and the results confirmed previous findings (Bates et al., 2017). A study comparing recreational athletes demonstrated through EMG data that female athletes have increased quadriceps muscle contraction and decreased hamstring muscle contraction as well as decreased knee flexion during cross-cutting and side-cutting tasks. A 50ms delay in hamstring contraction was observed between female and male athletes (Malinzak et al., 2001). At a flexed knee position with angle of 0-30 degrees, the tibia is forced to move forward as a result of quadriceps contraction, which may in turn force the knee into a valgus position through increased lateral muscle contraction or decreased medial muscle contraction (Myer et al., 2009). Females also generate lower isometric, concentric, and eccentric contractions of the quadriceps and hamstring muscle groups compared to males (Benett et al., 2008). Female athletes with a noncontact ACL injury demonstrated lower quadriceps strength compared to healthy female athletes, but demonstrated similar quadriceps strength and decreased hamstring strength compared to healthy male athletes (Myer et al., 2009)(Huston & Wojtys, 1996). Furthermore, increased recruitment of the vastus lateralis muscle in female athletes may also contribute to anterior shear force at the knee joint (Myers et al., 2009). If the ground reaction forces are not absorbed properly by the muscle groups, the ligaments must absorb the force during an abrupt movement, giving rise to a possible rupture of the ACL. An important muscle group for control of the lower extremity is the posterior chain comprised of the gluteals, hamstrings, and the calf muscles. If this posterior chain of muscles is properly recruited to absorb the ground reaction forces, there is less strain on the ligaments and joint capsule of the knee (Hewett et al., 2010)(Myers et al., 2009). A valgus collapse at the knee joint may result in a subsequent ACL rupture due to inadequate neuromuscular control in female athletes while performing high-risk maneuvers (Myers et al., 2005). Therefore, the combination of factors such as decreased hip control in the lateral direction, decreased hamstring involvement, decrease in the timing of contractions, decreased peak flexion angle during a jump and land task, decreased core stability are known to contribute to the incidence of an ACL injury in female athletes (Brophy et al., 2010).

1.4 Role of Leg Dominance in Non-contact ACL Injuries

Leg dominance can result in imbalance that may cause ACL injuries. Balance is a motor skill acquired with practice as a result of muscle synergies. A decreased ability to balance is linked to a higher risk of ligament injuries as well as an asymmetry in balance, which may be indicative of a difference between both lower extremities. These asymmetries include muscle strength, activation, and thickness (Gstottner et al., 2009). A study by Gstottner et al. (2009) revealed that a statistical significant difference is not present regarding balance when comparing the dominant and non-dominant legs. However, it was observed that the non-dominant leg was used more for improved balance.

Through the combined information from the vestibular, visual and somatosensory system, which are coordinated by the central nervous system, an individual is able to stand straight and upright with correct posture (Matsuda et al., 2008) (Gstottner et al., 2009). The displacement of the center of pressure (COP) of the athlete is minimized with greater balance and is controlled by the central nervous system (Barone et al., 2011). There are two types of balance stability. Static stability is the capability of the individual to retain balance while in a static position, whereas dynamic stability is the capability of the individual to balance during a movement and repositioning themselves to correct posture. Stability during single leg stance versus double leg stance is not consistent between sports and is dependent upon the level of the athlete as well as their position on the team (Matsuda et al., 2008). Athletes generally have a preferred leg to kick with and have the opposite leg planted. In soccer, the dominant leg is used to kick the ball, while the non-dominant leg used to support the weight of the athlete (Matsuda et al., 2008) (Matsuda & Demura, 2010) (Barone et al., 2011) (Hewett et al., 2010). More female athletes have a preferred leg as the dominant leg compared to male athletes, therefore shifting their weight onto one leg and tearing the ACL. This may be due to the greater difference in muscle strength and recruitment patterns as well as flexibility when comparing both limbs in female athletes (Hewett et al., 2010). Most non-contact ACL injuries of female soccer athletes occur in the non-dominant, supporting, leg. In contrast, male non-contact ACL injuries occur in the dominant, kicking, leg. This evidence suggests that gender does play a role in non-contact ACL injuries. However, some studies have reported no significant correlation between gender and leg dominance in relation to non-contact ACL injuries, whereas other studies have reported that that female soccer athletes injure the dominant leg more compared to the non-dominant leg during contact ACL injuries (Brophy et al., 2010).

When comparing center of pressure displacement between athletes from different sports, specifically soccer, basketball, and swimming, with non-athletic individuals, a significant difference was not found between the dominant leg and non-dominant leg stance (Mokhtarzadeh, et al., 2017)(Matsuda et al., 2008) However, the soccer athletes exhibited less sway in the vertical and horizontal directions compared to athletes on basketball and swim teams and non-athletic individuals, indicating that the soccer athletes are more stable during single leg stance compared to the other groups. This may be the result of training since soccer athletes support their body weight on one leg while kicking the ball (Matsuda et al., 2008) (Matsuda et al., 2011)

(Barone et al., 2011). When comparing female NCAA basketball and soccer athletes, the basketball athletes displayed lower dynamic stability, which may be due to soccer athletes performing single leg reaching tasks away from their base of support during passing, receiving, and shooting motions (Bressel et al., 2007).

1.5 ACL Injury Research Involving Perturbation Platforms

Several studies have explored the effects of perturbation on muscle co-contraction and knee kinematics. A study by Yom et al. (2014) explored in-flight perturbation by having the female recreational athletes perform a drop landing with an unexpected lateral perturbation. Following the lateral perturbation, the participants landed with extended ankle, knee, and hip joint positions, greater knee abduction, and greater hip adduction (Yom et al, 2014). A study by Stearns et al. (2012) focused on the effects of a training program that targets hip muscle performance found that following the training program, there was decreased loading at the knee joint in the frontal place as well as greater use of the hip muscles and greater hip flexion angles, which may help reduce the incidence of ACL injuries. Furthermore, a study by Weltin et al. (2016) used a moving platform for sliding and counteracting movements while the participant performed a lateral reactive jump onto the platform. Following the implementation of a plyometric and perturbation training program, the results reveal decreased knee extension moments and knee internal rotational moments, which may decrease ACL injury risk (Weltin et al., 2016). In addition to this, a study conducted by Hurd et al. (2006) also demonstrated that neuromuscular training improved quadriceps-hamstring balance and active stiffness at the knee joint when comparing male and female athletes. The participants walked on a platform moving in the lateral direction at heel contract before and after neuromuscular training. Prior to training, female participants demonstrated quadriceps dominance and decreased active knee stiffness compared to male participants. Female participants also had greater co-contraction indices between medial gastrocnemius and vastus lateralis muscles during both preparatory and weight acceptance phases of gait compared to the male participants (Hurd et al., 2006).

Another study by Chmielewski et al (2005) explored the differences between participants who are able to compensate and participants who were not able to compensate as well with the absence of an ACL post-injury by having these participants walk across a stationary or moving (lateral or posterior) platform before and after 10 sessions of perturbation training. The study determined that the participants who are better able to compensate before the training has a higher co-contraction index and low peak knee flexion angles compared to participants with an intact ACL. However, following perturbation training, the movement patterns of the participants who are able to able compensate without an ACL were closer to the participants who had an intact ACL. There were lower co-contraction indexes and higher peak flexion angles reported during stance in participants who were able to compensate. More specifically, the quadriceps femoris to hamstring muscle and quadriceps femoris to gastrocnemius muscle co-contraction ratios were lower. The movement pattern of participants who were not able to compensate as well with the absence of an ACL had a joint stiffness pattern with reduced knee motions, slower muscle activation, and general co-contraction of muscles that cross the knee joint as a method to protect the joint and limit degrees of freedom, therefore limiting muscle activation required for dynamic stability at the knee joint (Chmielewski et al., 2005).

A recent study by Malfait et al. (2015) explored dynamic knee stability, composed of the interaction of the visual, vestibular, and somatosensory systems, through single planar perturbations and multi-planar perturbations. As a result of unexpected events challenging neuromuscular control and studies demonstrating that dynamic valgus ACL injury mechanism includes hip adduction, knee internal rotation, knee abduction, and foot pronation, this study explored multi-planar perturbations with different amplitudes, velocities, and accelerations, which mimic the suspected ACL injury mechanism. The multi-planar perturbation combined posterior and lateral translations to cause knee abduction, rotation around a vertical axis to cause external rotation, and rotation around an anterior-posterior axis to cause foot pronation. Although there was significantly greater muscle activity with more challenging conditions, there were no significant differences in muscle activity reported when comparing the multi-planar and single planar perturbations with the same amplitudes.

1.6 Future of Non-contact ACL Injury Research

With the knowledge gained from research regarding non-contact ACL injury mechanism, neuromuscular warm-up strategies are being integrated into practices by coaches as a measure to prevent lower extremity injuries (Silvers et al., 2005). A randomized controlled study demonstrated that the injury prevention program decreased the risk of severe injuries and overuse injuries (Soligard et al., 2008). Another study by Soligard et al. (2010) revealed that athletes with high compliance to the injury prevention program reported lower rates of lower extremity injuries compared to athletes with an intermediate compliance. A randomized control study including the Center for Disease Control and Prevention (CDC), FIFA, and NCAA reported a decrease in overall ligament injury at the knee joint and a decrease in ACL injuries during competitions as well as no ACL injuries during practices following an injury prevention program (Silvers et al., 2005). Through setting goals, the ability to differentiate sensory information by completing various exercises may be gained (Gstottner et al., 2009).

A limitation affecting the success of neuromuscular training programs is the limited information about the joints and the muscular responses during high-risk maneuvers. Severe knee joint injuries may result from movements that are uncommon and therefore, the position of the joint during initial contact and the valgus loading that occurs should be further investigated. With this information, the intervention may target the cause of the injury and will be an effective method of non-contact ACL injury prevention. Current research proposes that valgus loading at the knee joint can be reduced through alterations in hip flexion, hip extension, internal and external rotation of the hip, as well as knee varus and knee valgus movements before the foot has contact with the ground. Further investigation suggests that landing with decreased hip flexion, hip internal rotation, and knee valgus can aid injury prevention (Omi et al., 2018)(Hewett et al., 2017)(Nguyen et al., 2017)(Steffen et al., 2016)(McLean et al., 2005). Another study found that landing with less hip flexion is associated with increased risk of ACL injury (Leppänen et al., 2017). A study by Hewett et al.(2017) involving 624 female basketball, volleyball, and soccer athletes concluded that targeted neuromuscular training (TNMT) increased hip external rotation, increased hip abduction strength, decreased peak trunk extension, and increased peak trunk flexion to reduce the risk of ACL injuries. By acknowledging the factors that contribute to an ACL injury within a female population, which include and are not limited to training the muscle involved in hip abduction, external rotation, extension, as well as core stability and decreased proprioception, these injury prevention intervention programs are becoming a success (Omi et al., 2018). Studies have shown that in soccer, handball, and floorball, neuromuscular training is effective in reducing the incidence of ACL injuries in female athletes (Omi et al., 2018). The focus of research has been on the improvement of jump-landing technique through a decrease in deceleration during landing in the sagittal plane. This alteration would decrease anterior shear force, increase knee flexion, and increase hip flexion through usage of lateral hip muscles to prevent dynamic knee valgus motions (Brophy et al., 2010). However, research regarding a decrease in deceleration during landing in the sagittal place neglects important information regarding frontal and transverse plane motions, which also are factors in ACL injury mechanism (Quatman & Hewett, 2009).

Of these programs, FIFA has implemented an intervention called the 11+ consisting of 3 parts that involve 15 exercises in total. The first part is composed of running exercises at a slower speed as well as active stretching. The second part is composed of 6 sets of exercises with levels of difficulty that are performed to increase core strength, leg strength, balance and plyometrics. The third part is composed of moderate to high speed running exercises along with planting and cutting movement exercises. Therefore, the three parts are composed of core training, neuromuscular control and balance, and plyometrics and agility. While completing the warm-up exercises, it is important for the athletes to pay close attention to posture and body control, as well as leg alignment and knee-over-toe positions so that they will obtain the full benefits upon completion the prevention program (F-Marc, FIFA 2008). A study by Herman et al. demonstrates that the 11+ program is successful in reducing overuse injuries and overall injuries of the lower extremity reported by female amateur athletes (Herman et al., 2012). Although injury prevention programs have been successful, the ACL injury rates remain similar to rates prior to the implementation of injury prevention programs (Fox et al., 2017).

2.0 Rationale and Research Objectives

An important area of research is to explore lower limb muscle activity and muscle recruitment of the non-dominant leg of athletes during a manoeuvre that imitates an ACL injury mechanism. Although there is ongoing research exploring the mechanism of an ACL injury, there are very few studies that measure muscle activity and explore the timing of muscle activity during an unexpected perturbation that mimics an ACL injury mechanism. Specifically, it is important to determine the muscle activity and the order of lower limb muscle recruitment to be able target deficiencies in the injury prevention programs implemented by strength and conditioning coaches around the world. Also, the contribution of the initial stance to the ACL injury mechanism has not yet been explored.

The purpose of the study was to explore and determine the reaction of lower extremity muscles based on initial stance (flexed and straight knee), specifically at the knee joint, during multiple directions of perturbation (lateral, posterior, rotational, combination). The combination direction combines the lateral, posterior, and rotational directions that together imitate an ACL injury mechanism as demonstrated in the study by Malfait et al. (2015) to induce knee abduction, hip adduction, and external knee rotation. The dependent variables were mean EMG values, maximum EMG values, and the time of occurrence of the maximum EMG values. These dependent variables were explored by subdividing the duration of the perturbation into three different phases (pre-perturbation, perturbation, and post-perturbation phases). The neuromuscular responses were assessed during 3 phases; 150 ms before the initiation of the perturbations (pre-perturbation), 500 ms during the perturbations, and 250 ms after the perturbations (post-perturbation). Therefore, the objectives were the following based on 8 conditions (flexed and straight at the knee joint during four directions of perturbation) being investigated:

1) To understand lower extremity muscle activity of female athletes by comparing mean EMG values within different phases of an ACL injury mechanism.

2) To understand lower extremity muscle activity of female athletes by exploring mean EMG values between the pre-perturbation phase, perturbation phase, and post-perturbation phase across different components of a perturbation that mimics an ACL injury mechanism as well as the maximum EMG values and the time at which the maximum EMG values occur following the onset of a perturbation in each direction.

2.1 Hypotheses

1) The mean EMG values of the lower extremity muscles will be greatest during perturbations in the combination direction and straight knee condition.

2) The mean EMG values will be greatest during post-perturbations in the combination direction and straight knee condition.

3) The mean EMG values of the lower extremity muscles will be greatest during the post-perturbation phase compared to the pre-perturbations and perturbation phases in the combination direction and straight knee condition.

4) The maximum EMG value will be greatest and the time of occurrence of maximum EMG value will be earlier during the combination direction in the straight knee condition.

3.0 Methodology

3.1 Subjects

Thirteen female participants from varsity teams were recruited from various universities in Montreal, Quebec. Inclusion criteria: 1) age 18 to 24 years; 2) active member of a varsity team; 3) physically active at least 5 days a week; Exclusion criteria: 1) Recent or prior history of major lower extremity injuries such as ACL and/or meniscus injury; 2) Everyday use of knee and/or ankle braces or taping for stability during physical activity; 3) previous enrolment in an injury prevention exercise intervention program. The eligibility criteria were to ensure that confounding factors were minimized as well as ensuring patient safety.

3.2 Material and Apparatus

The equipment included motion analysis using the VICON system (Vicon Motion Systems Ltd. West Way, Oxford, UK) and 8 infrared cameras that were capturing at a sampling frequency of 100 Hz. The cameras detected passive reflective markers that were placed on the participant. Muscle activity data was collected using 9-channels of the DTS EMG system with a sampling frequency of 1500 Hz (Noraxon U.S.A. INC, Scottsdale, AZ, USA). The interelectrode distance was 2cm. During posterior and lateral perturbations of the platform, the acceleration was 3500 mm/s^2, the speed was 200mm/s, and the perturbation was 50mm. The angular velocity during rotational perturbation was 20 °/s and the average angular acceleration was 400 $°/s^2$. During rotational motion, the angle that the platform moved was 5 degrees. The combination motion combined the lateral, posterior, and rotational motions. A hand held plastic goniometer was used to measure the angle at the knee joint for the flexed knee condition.

3.3 Procedure

The research study was a counterbalanced research design where the testing order was determined at random. The experiment was a single-blind experiment. The participants who accepted to take part in the study after receiving information in person or via email and meet the eligibility criteria were tested to obtain measurements during a two-hour session. All data collection was completed at the PERFORM Center (Montreal, QC) where the necessary equipment was available.

Two experimenters were present during each session. One experimenter was responsible for the computer and the other was responsible for all measurements and manual muscle testing, as well as measuring the knee angle for specific trials. Prior to each session, the VICON system and cameras were calibrated. The project was approved by the Concordia Research Ethics Committee. At the start of each the session, the subjects understood and completed the informed consent before beginning the experiment. Measurements of the leg length, knee width and ankle width were obtained, as well as information such as age, sport, activity level, weight, and height. The participant was explained the overview of the data collection process and the preparatory tasks that were completed: manual muscle testing to place EMG electrodes (Appendix B), and the perturbation platform. The non-dominant leg, also known as the balance leg, was used for EMG data collection and was determined by asking the participants which leg they would use to kick a ball and testing the opposite leg (Gstottner et al., 2009). EMG data was collected from the following muscles: lateral gastrocnemius (LG), medial gastrocnemius (MG), biceps femoris (BF), semitendinosus (ST), gluteus medius (GM), vastus lateralis (VL), vastus medialis (VMO), fibularis longus (FL), tibialis anterior (TA). The muscles were located using manual muscle testing (Kendall et al., 2005) for the placement of the electrode at the middle of the muscle belly according to the Noraxon guide, as illustrated in Appendix B. To decrease skin impedance and to ensure proper electrode contact and adhesion, the skin was abraded and cleaned using gauze and alcohol before placing the electrodes. During manual muscle testing to locate each muscle, the participants were instructed to meet the resistance applied by the tester and to hold for approximately 5 seconds, until they were instructed to relax. A total of 4 reflective markers were placed on the perturbation platform at each corner to track its movement. Prior to stepping onto the perturbation platform, the participant was fitted with an upper body harness adjusted to an extent that did not impede their balance response.

After completing the set-up, the participants were asked to stand on the perturbation plate with both feet to familiarize them with the four perturbations (posterior, lateral, rotational, combination). The combination perturbation is a combination of the posterior, lateral, and rotational perturbations to mimic the mechanism of an ACL injury. Following the familiarization period, the subjects were asked to maintain balance while standing on the non-dominant leg, or balance leg, as the perturbation platform moves. It was indicated to them that if they lose their balance and bring down the dominant leg to touch the platform, they may keep both legs on the platform. If they were able to remain on the balance leg for the entire perturbation, they may place the dominant leg on the platform once the platform begins to reposition itself to the center. The knee conditions were straight, without hyperextension at the knee, and flexed at 30 degrees, which was measured by the researcher prior to each perturbation. A total of 32 trials (four in each condition and direction of perturbation) were completed by each participant. The knee conditions (straight and bent) were alternated between each trial. The participants were blind to the order of the perturbation throughout the experiment.

Once the data collection was complete, the participant was unhooked from the harness and all equipment will be removed. The skin was checked for blemishes and was cleaned using rubbing alcohol and gauze. The participant was debriefed about the purpose of the project and all questions were answered.

4.0 Data Analysis

4.1 Statistical Analysis

Each perturbation was separated into three phases for the mean EMG value: pre-perturbation, perturbation, post-perturbation. The onset of the perturbation was when the speed reached 5mm/s. The four reflective markers on the platform were used to calculate the speed. The neuromuscular responses were assessed during 3 phases; 150 ms before the initiation of the perturbations (pre-perturbation), 500 ms during the perturbations, and 250 ms after the perturbations (post-perturbation). The EMG of the lower extremity muscles were recorded using a wireless system (Noraxon TeleMyo DTS, Scottsdale, Arizona, USA) and transferred to NEXUS Software (Vicon^{TM} system, Vicon, Los Angeles, USA) for further processing. To verify the synchronization of those systems, the onset of the muscular activities were contrasted to the motion of the 4 reflective markers that were put at the corners of the perturbation platform to determine the initiation of the perturbations. We found a delay in the EMG signal due to its passage through the NEXUS Software. For all the trials, that phase lag was taken into account to determine the onset of the perturbations, and accordingly, pre-perturbation, perturbation and post-perturbation windows. The EMG values from each phase were compared for each direction of perturbation (posterior, lateral, rotational, combination) using single factor repeated measures analysis of variance (ANOVA) for each participant. Differences among perturbations within each phase were compared using repeated measures multivariate analysis of variance (MANOVA) for each direction of perturbation (posterior, lateral, rotational, combination). The mean EMG, the maximum EMG, and the time of occurrence of the maximum EMG were computed on filtered signals. A Butterworth filter was used with a high pass frequency of 20 Hz and low pass frequency of 500 Hz. Similar to other studies, the mean and maximum EMG signals were analyzed in millivolts (mV) (Martelli et al., 2015) (Thain et al., 2016). The time of occurrence of the maximum EMG value is reported as a percentage of the duration of a phase. These statistical analyses were performed at a 5% level of significance in SPSS for Windows Version 20 (SPSS Inc., Chicago, IL, USA). A Bonferroni post hoc test was performed if a statistical main effect for conditions was observed (α=0.05). The files used by MATLAB (Mathworks, Natick, MA, USA) were C3D files exported from VICON. MATLAB codes provided by biomechZoo (Montreal, QC, CAN) were used to process raw C3D files to extract the mean and maximum EMG values, and the time of occurrence of the maximum EMG values.

5.0 Results

5.1 Comparison of Mean EMG Values

Please refer to Table 1 for all information related to the mean EMG values. Figure 3, Figure 4, Figure 5, and Figure 6 can be found in this section. All other graphs can be found in Appendix A.

5.1.1 Comparison of Mean EMG Values During Lateral Direction

The mean EMG values of the lateral and medial heads of the gastrocnemius muscle are similar for the both knee conditions. However, the value is slightly higher in the straight knee condition during the post-perturbation phase for both muscles.

The peroneus longus and tibialis anterior muscles have similar mean EMG values during the pre-perturbation and perturbation phases. However, the mean EMG value of the peroneus longus muscle during the post-perturbation phase is greater during the straight knee condition compared to the flexed knee condition. The mean EMG value of the tibialis anterior muscle during the post-perturbation phase in the flexed knee condition is greater compared to the straight knee condition.

The vastus medialis and vastus lateralis muscles have higher values in the flexed knee condition compared to the straight knee condition, as shown in Figure 3 and Figure 4. However, the differences are similar in value when comparing the pre-perturbation and perturbation phases and slightly higher when comparing the pre-perturbation and perturbation phases to the post-perturbation phase.

The mean EMG values of the biceps femoris muscle, as seen in Figure 5, in the flexed knee condition during the post-perturbation phase are greater compared to the straight knee condition. The mean EMG values of the semitendinosis muscle, as seen in Figure 6, in both knee conditions during the post-perturbation phase are similar. The mean EMG values of the vastus medialis and vastus lateralis muscles during the post-perturbation phase are similar to the values of the biceps femoris and semitendinosis muscles. The mean EMG value of the biceps femoris muscle during the post-perturbation phase in the flexed knee position is slightly greater than the value in the straight knee condition.

The mean EMG values of the gluteus medius muscle during the post-perturbation phase are similar in both knee conditions. However, the difference between the perturbation phase and post-perturbation phase values is great in the straight knee condition compared to the flexed knee condition.

5.1.2 Comparison of Mean EMG Values During Posterior Direction

The mean EMG values of the medial head of the gastrocnemius muscle during the post-perturbation phase are greater than the values of the lateral head of the gastrocnemius muscle. However, the trend for the pre-perturbation and perturbation phases during both knee conditions is similar for the medial and lateral heads of the gastrocnemius muscle.

The mean EMG values of the tibialis anterior muscle are also greater during the flexed knee condition compared to the straight knee condition. However, during the flexed knee condition, the mean EMG values of the tibialis anterior muscle and the medial head of the gastrocnemius muscle are similar in value and greater for the medial head of the gastrocnemius muscle during the straight knee condition.

The mean EMG values of the vastus medialis and vastus lateralis muscles, as seen in Figure 3 and Figure 4, have similar values during all three phases during the flexed knee condition. The biceps femoris muscle and semitendinosus muscle, as seen in Figure 5 and Figure 6, have similar values when comparing the flexed knee condition to the straight knee condition within each respective muscle. However, the mean EMG values during the post-perturbation phase of the semitendinosus muscle for both knee conditions are greater compared to the biceps femoris muscle. The mean EMG values of the gluteus medius muscle are greater in the flexed knee condition compared to the straight knee condition.

5.1.3 Comparison of Mean EMG Values During Rotational Direction

The mean EMG values of the lateral and medial heads of the gastrocnemius muscles are greater for the straight knee condition compared to the flexed knee condition across all phases of perturbation. The mean EMG values of the medial head of the gastrocnemius muscle are greater than values of the lateral head of the gastrocnemius muscle.

The tibialis anterior muscle and peroneus longus muscle have similar values when comparing the flexed knee condition to the straight knee condition within each respective muscle across all phases of perturbation. The pre-perturbation and perturbation phase values are similar for both muscles. However, the difference between the pre-perturbation and perturbation phases is lesser compared to the difference between the pre-perturbation and post-perturbation phase as well as the perturbation phase and post-perturbation phase for the peroneus longus muscle.

The vastus medialis and vastus lateralis muscles, as seen in Figure 3 and Figure 4, have similar values when comparing the flexed knee condition to the straight knee condition within each respective muscle. However, the values in the flexed knee condition are greater than the straight knee condition. In the straight knee condition, there is a slight increase in the mean EMG value for the when comparing the pre-perturbation and perturbation phases to the post-perturbation phase. The mean EMG values of the biceps femoris and semitendinosus muscles, as seen in Figure 5 and Figure 6, are similar when comparing both knee conditions within each muscle respectively. The mean EMG values of the gluteus medius are slightly greater in the flexed knee condition.

5.1.4 Comparison of Mean EMG Values During Combination Direction

Higher values in the flexed knee position for the vastus lateralis and vastus medialis, as seen in Figure 3 and Figure 4, compared to the straight knee condition suggest greater muscle activity. The semitendinosus and biceps femoris muscles, as seen in Figure 5 and Figure 6, have higher values during the post-perturbation phase of the combination perturbation compared to the vastus lateralis and vastus medialis for both conditions. The mean EMG values of medial and lateral gastrocnemius muscles are higher than the vastus medialis and vastus lateralis muscles as well as the biceps femoris and semitendinosus muscles during the post-perturbation phase in the flexed condition. The mean EMG values of the lateral and medial heads of the gastrocnemius muscle are greater during the post-perturbation phase in the straight knee condition compared to the flexed knee condition. During the straight knee condition in the post-perturbation phase, the mean EMG value is highest for the semitendinosus muscle. The mean EMG value of the gluteus medius muscle is greatest in the flexed knee condition during the post-perturbation phase. The peroneus longus muscle achieved the highest mean EMG value during the post-perturbation phase for both knee conditions.

Table 1 – Mean (SD) of the muscles' EMG values (mV) at 30° of knee flexion and straight knee during posterior, lateral, rotational, and combination perturbations in pre-perturbations (150 ms before the initiation of the perturbations), perturbations, and post-perturbations (250 ms after the perturbations) phases.

Muscle	Knee position	Perturbation direction	Pre-perturbation (mV)	Perturbation (mV)	Post-perturbation (mV)
Lateral gastrocnemius (LG)	Flexed	Lateral	1.27 (0.61)	1.29 (0.52)	3.09 (1.38) [1,2]
		Posterior	1.32 (0.58)	1.51 (0.55) [1]	3.86 (1.69) [1,2]
		Rotational	1.13 (0.52)	1.17 (0.43)	2.81 (1.14) [1,2]
		Combination	1.09 (0.54)	1.56 (0.58)[1]	4.42 (2.01)[c 1,2]
	Straight	Lateral	1.76 (1.00)[a,b,c,d]	1.78 (0.72)[a,c]	3.67 (1.53) [1,2]
		Posterior	1.34 (0.57)	1.76 (0.77)[a,c 1]	4.43 (2.20)[c 1,2]
		Rotational	1.46 (0.59)	1.45 (0.62)	4.03 (2.47) [1,2]
		Combination	1.52 (0.68)[d]	2.17 (0.64)[a,b,c,d,e,f,g 1]	6.22 (2.69)[a,b,c,d,e,f,g 1,2]
Medial gastrocnemius (MG)	Flexed	Lateral	1.45 (0.93)	1.57 (1.03)	2.31 (1.23) [1,2]
		Posterior	1.67 (0.97)	2.04 (0.87) [1]	6.45 (3.02) [a 1,2]
		Rotational	1.54 (0.99)	1.24 (0.60)	5.54 (2.36) [a 1,2]
		Combination	1.12 (0.67)	1.99 (0.77) [1]	5.53 (2.06) [a 1,2]
	Straight	Lateral	2.68 (1.41)[a,b,c,d]	2.96 (1.59)[a,b,c,d]	3.09 (1.69) [b,c,d 1]
		Posterior	3.13 (1.61)[a,b,c,d]	4.13 (1.59)[a,b,c,d,e 1]	8.10 (3.49) [a,c,d,e 1,2]
		Rotational	2.89 (1.40)[a,b,c,d]	2.99 (1.58)[a,b,c,d,f]	6.53 (2.65) [a,e 1,2]
		Combination	2.75 (1.41)[a,b,c,d]	3.96 (1.66)[a,b,c,d,e,g 1]	9.24 (3.07) [a,b,c,d,e,g 1,2]
Tibialis anterior (TA)	Flexed	Lateral	2.69 (2.13)	3.80 (2.78) [1]	6.49 (2.62) [1,2]
		Posterior	4.07 (2.47)[a]	3.46 (2.07)	6.16 (3.73) [1,2]
		Rotational	3.02 (2.14)	3.30 (2.01)	3.98 (2.10) [a,b 1,2]
		Combination	2.05 (1.29)[b]	2.64 (1.55) [1]	4.09 (1.79) [a,b 1,2]
	Straight	Lateral	2.70 (1.98)[b]	2.55 (1.54)[a]	5.02 (2.39) [1,2]
		Posterior	2.68 (2.09)[b]	2.30 (1.53)[a]	5.07 (3.37) [1,2]
		Rotational	3.27 (1.85)	3.30 (1.82)	4.05 (2.14) [a,b 1,2]
		Combination	2.86 (1.80)	2.65 (1.48)	4.52 (1.99) [a,b 1,2]

Peroneus longus (PL)	Flexed	Lateral	2.53 (1.27)	3.44 (2.37) [1]	10.93 (4.53) [1,2]
		Posterior	2.77 (1.39)	2.95 (1.21)	6.61 (2.94) [a][1,2]
		Rotational	2.14 (0.83)	2.13 (0.74)[a]	4.88 (2.19) [a][1,2]
		Combination	2.43 (1.30)	3.89 (1.44)[c][1]	13.25 (5.58) [b,c][1,2]
	Straight	Lateral	3.15 (2.25)[c]	3.52 (1.60)[c]	13.51 (6.08) [b,c][1,2]
		Posterior	2.63 (1.23)	2.84 (1.49)	6.65 (2.60) [a,d,e][1,2]
		Rotational	2.78 (1.78)	2.64 (1.46)[d]	5.66 (3.22) [a,d,e][1,2]
		Combination	2.65 (1.49)	4.07 (2.56)[b,c,f,g][1]	11.11 (4.11) [b,c,f,g][1,2]
Vastus lateralis (VL)	Flexed	Lateral	1.62 (0.60)	1.63 (0.50)	2.20 (0.80) [1,2]
		Posterior	1.59 (0.48)	1.61 (0.47)	1.92 (0.56) [1,2]
		Rotational	1.57 (0.54)	1.51 (0.41)	2.05 (0.67) [1,2]
		Combination	1.42 (0.39)	1.46 (0.37)	2.00 (0.59) [1,2]
	Straight	Lateral	0.69 (0.33)[a,b,c,d]	0.74 (0.35)[a,b,c,d]	1.25 (0.50) [a,b,c,d][1,2]
		Posterior	0.64 (0.27)[a,b,c,d]	0.71 (0.31)[a,b,c,d]	1.04 (0.48) [a,b,c,d][1,2]
		Rotational	0.82 (0.39)[a,b,c,d]	0.78 (0.33)[a,b,c,d]	1.29 (0.56) [a,b,c,d][1,2]
		Combination	0.59 (0.28)[a,b,c,d]	0.67 (0.29)[a,b,c,d][1]	1.91 (1.06) [e,f,g][1,2]
Vastus medialis (VM)	Flexed	Lateral	1.55 (0.54)	1.71 (0.68)	1.98 (0.48) [1,2]
		Posterior	1.63 (0.59)	1.70 (0.55)	1.72 (0.44)
		Rotational	1.63 (0.51)	1.65 (0.64)	1.82 (0.62)
		Combination	1.39 (0.49)	1.42 (0.39)	1.66 (0.51) [1,2]
	Straight	Lateral	0.65 (0.37)[a,b,c,d]	0.65 (0.34)[a,b,c,d]	1.11 (0.48) [a,b,c,d][1,2]
		Posterior	0.46 (0.23)[a,b,c,d]	0.48 (0.23)[a,b,c,d][1]	0.96 (0.53) [a,b,c,d][1,2]
		Rotational	0.65 (0.34)[a,b,c,d]	0.72 (0.44)[a,b,c,d]	0.94 (0.39) [a,b,c,d][1,2]
		Combination	0.56 (0.26)[a,b,c,d]	0.62 (0.29)[a,b,c,d]	1.39 (0.69) [a,b,c,f,g][1,2]
Biceps femoris (BF)	Flexed	Lateral	0.80 (0.51)	0.79 (0.46)	1.98 (1.29) [1,2]
		Posterior	0.71 (0.37)	0.81 (0.41)	1.86 (0.75) [1,2]
		Rotational	0.76 (0.51)	0.71 (0.44)	1.48 (0.83) [1,2]
		Combination	0.53 (0.34)[a]	0.71 (0.49)	3.53 (2.48) [a,b,c][1,2]
	Straight	Lateral	0.51 (0.41)[a]	0.55 (0.41)[b]	1.35 (0.94) [d][1,2]
		Posterior	0.45 (0.31)[a,c]	0.48 (0.35)[a,b]	1.37 (0.72) [d][1,2]
		Rotational	0.44 (0.33)[a,b,c]	0.46 (0.37)[a,b]	1.17 (0.78) [d][1,2]
		Combination	0.47 (0.39)[a,c]	0.54 (0.44)[b]	2.93 (1.78) [a,b,c,e,f,g][1,2]
Semitendinosus (ST)	Flexed	Lateral	0.92 (0.60)	0.85 (0.56)	2.24 (1.23) [1,2]
		Posterior	0.91 (0.57)	0.83 (0.47)	2.48 (1.11) [1,2]
		Rotational	0.80 (0.54)	0.85 (0.54)	1.47 (0.73) [b][1,2]
		Combination	0.61 (0.48)	0.75 (0.53) [1]	3.04 (1.43) [c][1,2]
	Straight	Lateral	0.80 (0.69)	0.91 (0.81)	2.19 (1.38) [1,2]
		Posterior	0.61 (0.53)	0.72 (0.65)	2.36 (1.43) [1,2]
		Rotational	0.78 (0.72)	0.67 (0.59)	1.61 (1.04) [b,d][1,2]
		Combination	0.69 (0.60)	0.81 (0.55)	3.33 (1.60) [a,b,c,e,f,g][1,2]

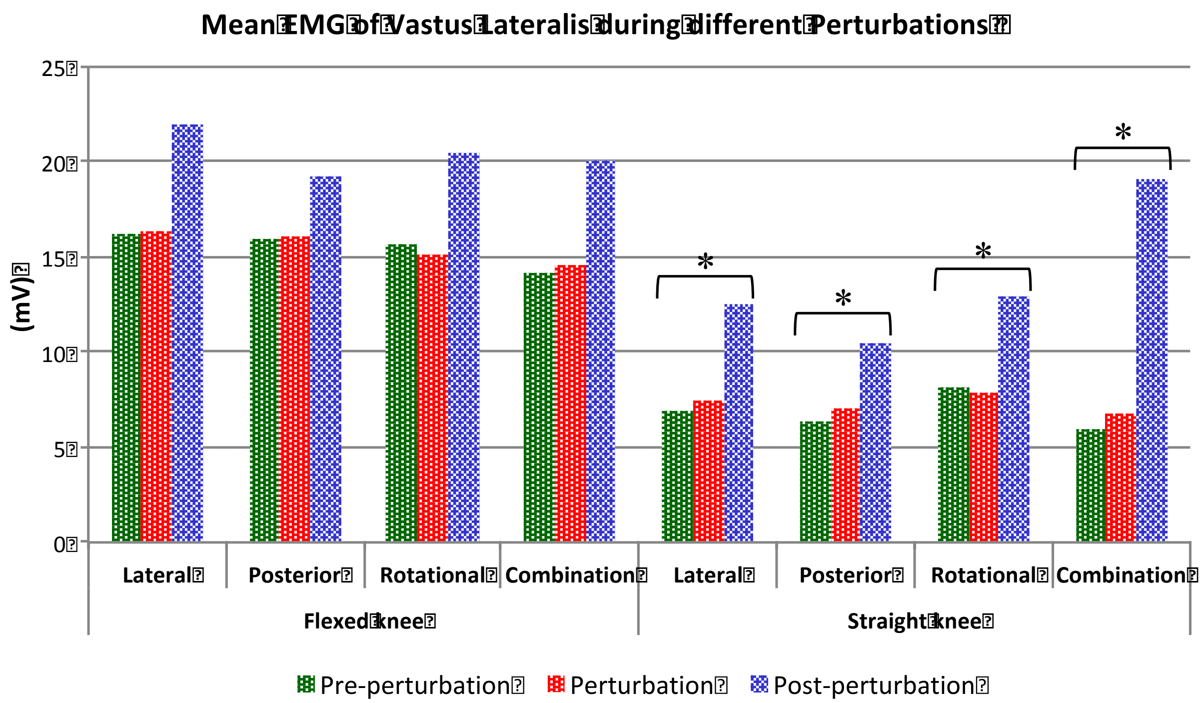
Gluteus medius (GM)	Flexed	Lateral	1.31 (0.70)	1.27 (0.64)	2.41 (1.09) [1,2]
		Posterior	1.28 (0.71)	1.31 (0.70)	1.79 (0.86) [a] [1,2]
		Rotational	1.15 (0.63)	1.39 (0.84)	1.63 (0.86) [a] [1,2]
		Combination	1.36 (0.88)	1.33 (0.78)	2.51 (1.08) [b,c] [1,2]
	Straight	Lateral	0.77 (0.31)[a,b,d]	0.75 (0.34)[a,b,c,d]	1.93 (0.82) [1,2]
		Posterior	0.70 (0.36)[a,b,c,d]	0.73 (0.39)[a,b,c,d]	1.30 (0.63) [a,d,e] [1,2]
		Rotational	0.99 (0.54)	0.89 (0.43)[a,b,c,d]	1.29 (0.53) [a,b,d,e] [1,2]
		Combination	0.90 (0.42)[a,b,d]	0.95 (0.44)[b,c]	2.26 (1.01) [c,f,g] [1,2]

Superscript letters indicate "Within phase differences"
Superscript numbers indicate "Between phase differences"

[a] Flexed knee, lateral perturbation vs. other conditions ($p<0.05$).
[b] Flexed knee, posterior perturbation vs. other conditions ($p<0.05$).
[c] Flexed knee, rotational perturbation vs. other conditions ($p<0.05$).
[d] Flexed knee, combination perturbation vs. other conditions ($p<0.05$).
[e] Straight knee, lateral perturbations vs. other conditions ($p<0.05$).
[f] Straight knee, posterior perturbation vs. other conditions ($p<0.05$).
[g] Straight knee, rotational perturbation vs. other conditions ($p<0.05$).

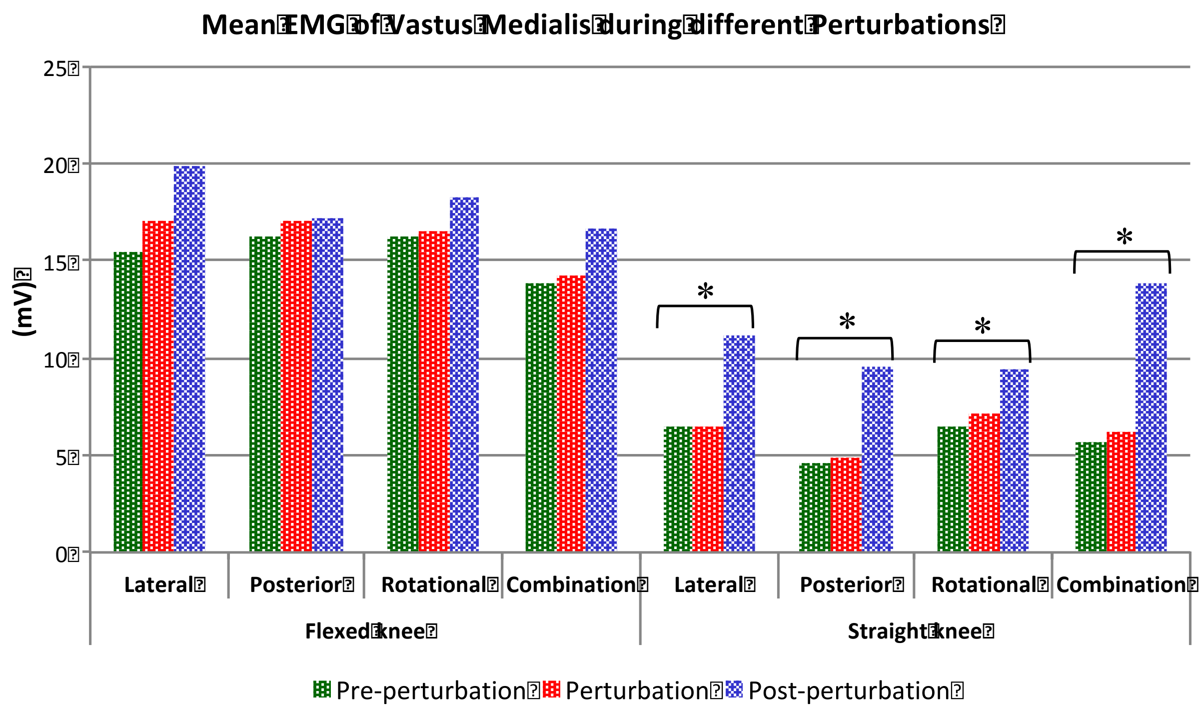
[1] pre-perturbation vs the other phases ($p<0.05$).
[2] perturbations vs post-perturbation phase ($p<0.05$).

Figure 3 – Mean EMG Values of Vastus Lateralis Muscle During Different Perturbations



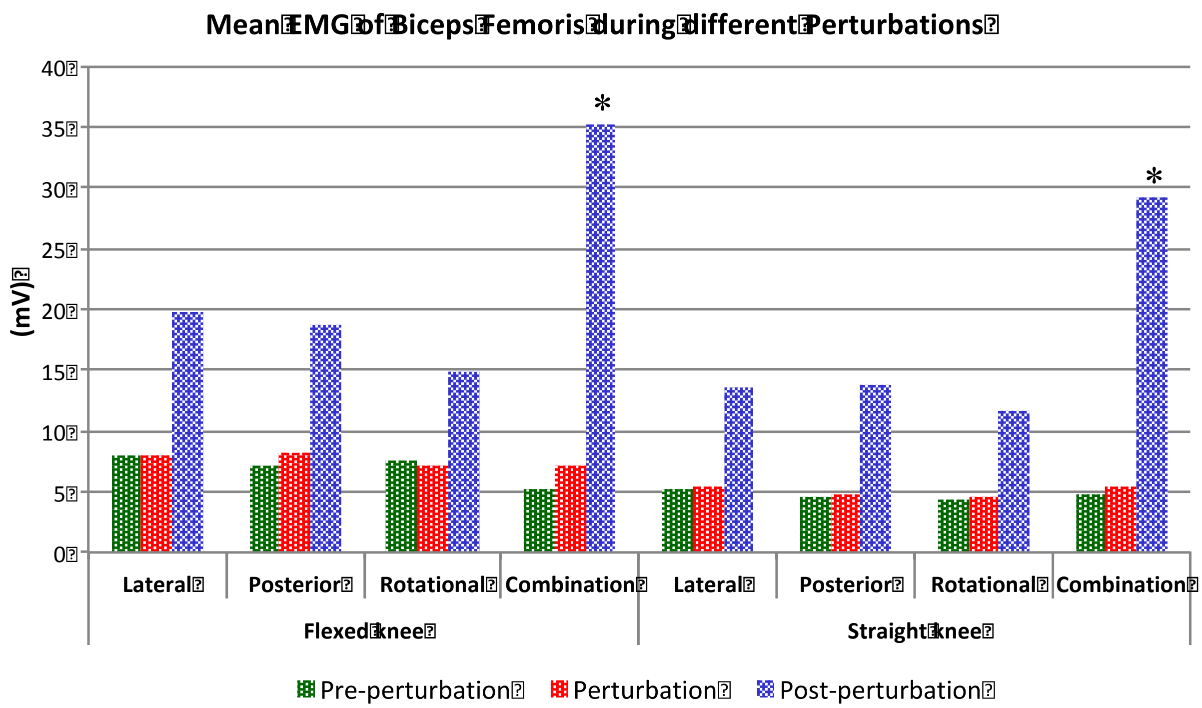
*significant difference within phases
Post-perturbations significantly greater than the two other phases

Figure 4 – Mean EMG Values of Vastus Medialis Muscle During Different Perturbations



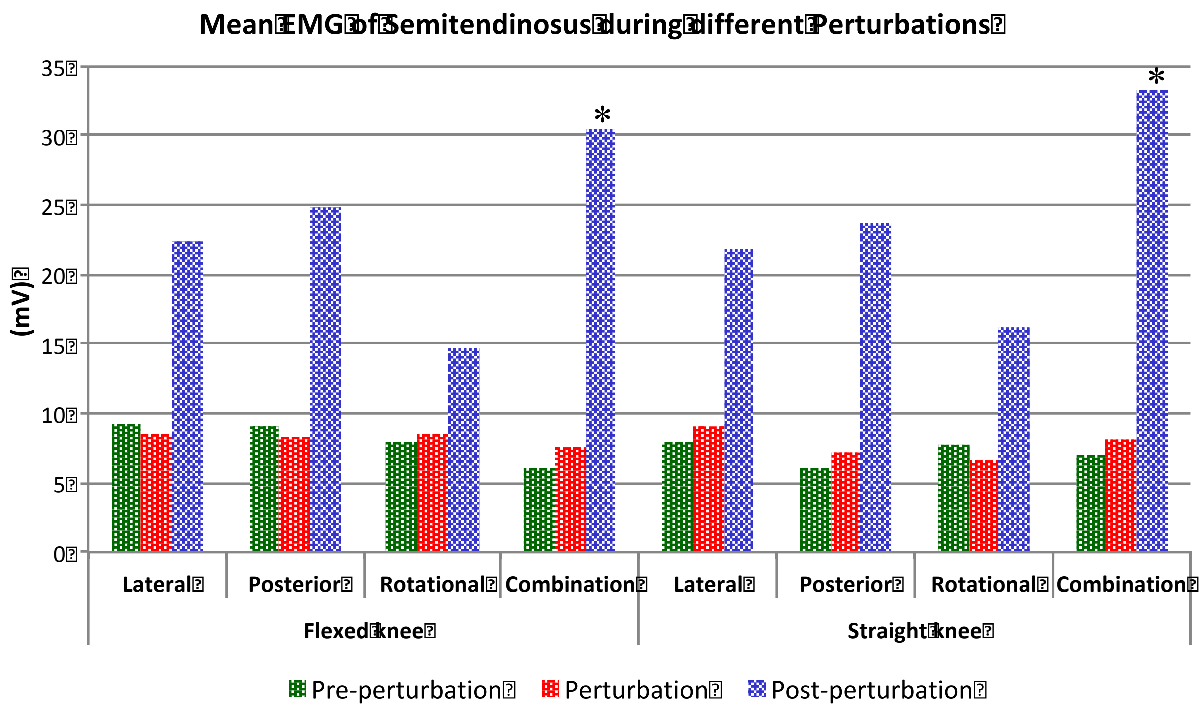
*significant difference within phases
Post-perturbations significantly greater than the two other phases

Figure 5 – Mean EMG Values of Biceps Femoris Muscle During Different Perturbations



*significant difference within phases
Post-perturbations significantly greater than the two other phases

Figure 6 – Mean EMG Values of Semitendinosus Muscle During Different Perturbations



*significant difference within phases
Post-perturbations significantly greater than the two other phases

5.2 Comparison of Maximum EMG Values Following Onset of Perturbation

Please refer to Table 2 for all information related to the maximum EMG values.

The maximum EMG values of lateral and medial heads of the gastrocnemius muscle are slightly greater during the straight knee condition for all directions of perturbation. The lowest values following the onset of the perturbation for the gastrocnemius muscle are during the lateral perturbation in both knee conditions. The highest maximum EMG value achieved in the flexed knee condition for the lateral and medial heads of the gastrocnemius muscle are during the rotational direction. The highest maximum EMG values achieved for the lateral and medial heads of the gastrocnemius in the straight knee condition are during the combination direction.

For the tibialis anterior muscle, the maximum EMG values are greater in the flexed knee condition compared to the straight knee condition for the lateral, posterior, and rotation directions. Contrary to this, the maximum EMG value of the tibialis anterior muscle is greater in the straight knee condition compared to the flexed knee condition for the combination direction. The lowest maximum EMG values of the tibialis anterior muscle recorded following the onset of perturbation are during the combination direction in both knee conditions.

The maximum EMG values for the peroneus longus muscle are greater in the straight knee condition compared to the flexed knee condition for the lateral, posterior, and rotation direction. However, in the combination direction, the maximum EMG value of the peroneus longus is greater in the flexed knee condition compared to the straight knee condition.

The maximum EMG values of the vastus medialis and vastus lateralis muscles are greater in the flexed knee condition compared to the straight knee condition. The lowest maximum EMG value for the vastus medialis muscle was achieved during the posterior direction. The highest maximum EMG value achieved by the vastus lateralis and vastus medialis muscles in the straight knee condition is during the combination direction.

The maximum EMG values for the biceps femoris muscle are greater in the flexed knee condition during the lateral, posterior, and rotational perturbations. However, the maximum EMG value for the biceps femoris muscle during the combination direction is greater in the straight knee condition. The highest maximum EMG values achieved by the biceps femoris muscle are during the combination direction in both knee conditions.

The maximum EMG values of the semitendinosus muscle are greater in the straight knee condition compared to the flexed knee condition during the lateral, rotational, and combination perturbations. Contrary to this, the maximum EMG value of the semitendinosus muscle for the posterior direction is greater in the flexed knee condition compared to the straight knee condition. The highest maximum EMG values achieved by the semitendinosus are during the combination direction in both knee conditions.

The maximum EMG values of the gluteus medius muscle are greater in the flexed knee condition compared to the straight knee condition during all directions of the perturbation. The highest maximum EMG values achieved by the gluteus medius muscle are during the combination direction in both knee conditions.

Table 2 – Maximum (SD) of the muscles' EMG values (mV) at 30° of knee flexion and straight knee during posterior, lateral, rotational, and combination perturbations following onset of perturbations (750 ms total following onset of perturbation)

Muscle	Knee position	Perturbation Direction	Perturbation (mV)
Lateral gastrocnemius (LG)	Flexed	Lateral	5.64
		Posterior	7.68
		Rotational	8.08
		Combination	7.93
	Straight	Lateral	6.12
		Posterior	8.17
		Rotational	10.07
		Combination	11.88
Medial gastrocnemius (MG)	Flexed	Lateral	5.12
		Posterior	14.36
		Rotational	16.74
		Combination	14.82
	Straight	Lateral	7.38
		Posterior	17.02
		Rotational	18
		Combination	20.05
Tibialis anterior (TA)	Flexed	Lateral	13.14
		Posterior	11.97
		Rotational	11.62
		Combination	
	Straight	Lateral	8.31
		Posterior	9.85
		Rotational	10.77
		Combination	9.26

Peroneus longus (PL)	Flexed	Lateral	18.22
		Posterior	12.96
		Rotational	12.99
		Combination	21.46
	Straight	Lateral	20.75
		Posterior	14.63
		Rotational	14.01
		Combination	18.69
Vastus lateralis (VL)	Flexed	Lateral	4.29
		Posterior	3.41
		Rotational	4.41
		Combination	3.72
	Straight	Lateral	2.2
		Posterior	2.34
		Rotational	3.14
		Combination	3.41
Vastus medialis (VM)	Flexed	Lateral	3.62
		Posterior	
		Rotational	3.54
		Combination	3.53
	Straight	Lateral	1.94
		Posterior	1.54
		Rotational	2.16
		Combination	2.54
Biceps femoris (BF)	Flexed	Lateral	3.93
		Posterior	3.6
		Rotational	4.59
		Combination	7.19
	Straight	Lateral	2.89
		Posterior	2.95
		Rotational	4.04
		Combination	7.29

	Flexed	Lateral	4.49
		Posterior	6.09
		Rotational	5.82
		Combination	8.34
Semitendinosus (ST)			
	Straight	Lateral	4.65
		Posterior	5.4
		Rotational	6.89
		Combination	9.65
	Flexed	Lateral	5.83
		Posterior	3.41
		Rotational	3.11
		Combination	6.25
Gluteus medius (GM)			
	Straight	Lateral	4.39
		Posterior	2.34
		Rotational	2.75
		Combination	4.41

5.3 Comparison of Time of Occurrence of the Maximum EMG Values

Please refer to Table 3 for all information related to the time of occurrence of the maximum EMG values as well as Figure 5 and Figure 6. As seen in Figure 5, all muscles with the exception of tibialis anterior and vastus medialis muscle reach the maximum EMG values the latest following the onset of the rotation perturbation as well in the flexed knee condition. However, as seen in Figure 6, all muscles reach the maximum EMG values the latest following the onset of the rotation perturbation in the straight knee condition.

Lateral Gastrocnemius Muscle

The time of occurrence of the maximum EMG value in the flexed knee condition for the posterior direction is significantly smaller than the lateral, rotation, and combination directions in both knee conditions. The time of occurrence of the maximum EMG value in the flexed knee condition for the combination direction is significantly smaller the rotation direction in both knee conditions. The time of occurrence of the maximum EMG value in the straight knee condition for the posterior and combination directions are significantly smaller than the combination direction in the flexed knee condition as well as the lateral and rotation directions in both knee conditions.

Medial Gastrocnemius Muscle

The time of occurrence of the maximum EMG values for the lateral direction in both knee conditions are significantly smaller then the rotation direction in both knee conditions. The time of occurrence of the maximum EMG values for the posterior and combination directions in both knee conditions are significantly smaller than the lateral and rotation directions in both knee conditions.

Tibialis Anterior Muscle

The time of occurrence of the maximum EMG value for the lateral direction in both knee conditions, the posterior direction in the flexed knee condition, and the combination direction in the straight knee condition are significantly smaller than the rotation direction in both knee conditions. The time of occurrence of the maximum EMG value for the combination direction in the flexed knee condition is significantly greater than all other directions in both knee conditions. As seen in Figure 7, the tibialis anterior reaches the maximum value at the latest during the combination direction in the flexed knee condition.

Peroneus Longus Muscle

The time of occurrence of the maximum EMG value for the posterior direction in the flexed knee condition is significantly smaller than the combination direction in the straight knee condition. The time of occurrence of the maximum EMG value for the rotation direction in the flexed knee condition is significantly greater than all other directions in both knee conditions except the rotation direction in the straight knee condition. The time of occurrence of the maximum EMG value for the rotation direction in the straight knee condition is significantly greater than all other directions in both knee conditions except the rotation direction in the flexed knee condition.

Vastus Lateralis Muscle

The time of occurrence of the maximum EMG value for the rotation direction in the flexed knee condition is significantly greater than all other directions in both knee conditions, except the rotation direction in the straight knee condition. The time of occurrence of the maximum EMG value for the rotation direction in the straight knee condition is significantly greater than all other directions in both knee conditions, except the rotation direction in the flexed knee condition. The time of occurrence of the maximum EMG value for the combination direction in the flexed knee condition is significantly smaller than the lateral direction in the flexed knee condition.

Vastus Medialis Muscle

The time of occurrence of the maximum EMG values for the posterior direction in the flexed knee condition and the rotation direction in the straight knee condition are significantly greater than all other directions in both knee conditions. The time of occurrence of the maximum EMG value for the rotation direction in the flexed knee condition is significantly greater than the lateral direction in the flexed knee condition, the posterior direction in the straight knee condition, and the combination direction in both knee conditions. The time of occurrence of the maximum EMG is greatest during the posterior direction in the flexed knee condition, as seen in Figure 7.

Biceps Femoris Muscle

The time of occurrence of the maximum EMG value for the rotation direction in the flexed knee condition is significantly greater than all other directions in both knee conditions, except the rotation direction in the straight knee condition. The time of occurrence of the maximum EMG value for the rotation direction in the straight knee condition is significantly greater than all other directions in both knee conditions, except the rotation direction in the flexed knee condition. The time of occurrence of the maximum EMG value for the lateral direction in the flexed knee condition is significantly greater than the posterior direction in the flexed knee condition and the combination direction in both knee conditions.

Semitendinosus Muscle

The time of occurrence of the maximum EMG value for the rotation direction in the flexed knee condition is significantly greater than all other directions in both knee conditions, except the rotation direction in the straight knee condition. The time of occurrence of the maximum EMG value for the rotation direction in the straight knee condition is significantly greater than all other directions in both knee conditions, except the rotation direction in the flexed knee condition. The time of occurrence of the maximum EMG values for the lateral direction in both knee conditions is significantly greater than the posterior and combination directions in both knee conditions.

Gluteus Medius Muscle

The time of occurrence of the maximum EMG value for the rotation direction in both knee conditions is significantly greater than the combination direction in both knee conditions.

Table 3 – Time of occurrence of the maximum EMG values (% of time following onset of perturbation) at 30° of knee flexion and straight knee during posterior, lateral, rotational, and combination perturbations

Muscle	Knee position	Perturbation direction	Time of Occurrence (%) of 700ms
Lateral gastrocnemius (LG)	Flexed	Lateral	20.6%
		Posterior	8.9% [a,c,d,e,g,h]
		Rotational	25.6%
		Combination	19.4% [c,g]
	Straight	Lateral	21.4%
		Posterior	12.2% [a,c,d,e,g]
		Rotational	27.6%
		Combination	13.3% [a,c,d,e,g]
Medial gastrocnemius (MG)	Flexed	Lateral	20.7% [c,g]
		Posterior	7.1% [a,c,e,g]
		Rotational	27.4%
		Combination	10.7% [a,c,e,g]
	Straight	Lateral	19.4% [c,g]
		Posterior	8.2% [a,c,e,g]
		Rotational	26.7%
		Combination	9.0% [a,c,e,g]
Tibialis anterior (TA)	Flexed	Lateral	18.5% [c,g]
		Posterior	18.6% [c,g]
		Rotational	25.3%
		Combination	34.1% [a,b,c,e,f,g,h]
	Straight	Lateral	17.0% [c,g]
		Posterior	22.3%
		Rotational	25.8%
		Combination	15.1% [c,g]

Peroneus longus (PL)	Flexed	Lateral	15.2%
		Posterior	11.8% [h]
		Rotational	26.4% [a,b,d,e,f,h]
		Combination	15.7%
	Straight	Lateral	13.6%
		Posterior	13.9%
		Rotational	26.5% [a,b,d,e,f,h]
		Combination	16.7%
Vastus lateralis (VL)	Flexed	Lateral	18.9%
		Posterior	14.6%
		Rotational	27.5% [a,b,d,e,f,h]
		Combination	13.0% a
	Straight	Lateral	17.7%
		Posterior	14.6%
		Rotational	29.2% [a,b,d,e,f,h]
		Combination	16.1%
Vastus medialis (VM)	Flexed	Lateral	15.9%
		Posterior	37.3% [a,c,d,e,f,g,h]
		Rotational	25.6% [a,d,f,h]
		Combination	13.2%
	Straight	Lateral	18.6%
		Posterior	16.6%
		Rotational	29.0% [a,c,d,e,f,h]
		Combination	13.0%
Biceps femoris (BF)	Flexed	Lateral	19.4% [b,d,h]
		Posterior	12.9% [a,b,d,e,f,h]
		Rotational	27.6%
		Combination	13.0%
	Straight	Lateral	16.8%
		Posterior	16.2%
		Rotational	29.0% [a,b,d,e,f,h]
		Combination	14.2%

Semitendinosus (ST)	Flexed	Lateral	20.0% [b,d,f,h]
		Posterior	13.5%
		Rotational	27.9% [a,b,d,e,f,h]
		Combination	10.8%
	Straight	Lateral	18.6% [b,d,f,h]
		Posterior	13.7%
		Rotational	28.4% [a,b,d,e,f,h]
		Combination	12.6%
Gluteus medius (GM)	Flexed	Lateral	19.8%
		Posterior	18.5%
		Rotational	24.9% [d,h]
		Combination	16.5%
	Straight	Lateral	21.9%
		Posterior	22.2%
		Rotational	26.5% [d,h]
		Combination	16.9%

[a] Flexed knee, lateral perturbation vs. other conditions ($p<0.05$).
[b] Flexed knee, posterior perturbation vs. other conditions ($p<0.05$).
[c] Flexed knee, rotational perturbation vs. other conditions ($p<0.05$).
[d] Flexed knee, combination perturbation vs. other conditions ($p<0.05$).
[e] Straight knee, lateral perturbations vs. other conditions ($p<0.05$).
[f] Straight knee, posterior perturbation vs. other conditions ($p<0.05$).
[g] Straight knee, rotational perturbation vs. other conditions ($p<0.05$).
[h] Straight knee, combination perturbation vs. other conditions ($p<0.05$).

Figure 7 – Time of occurrence of the maximum EMG values at 30° of knee flexion during posterior, lateral, rotational, and combination perturbations

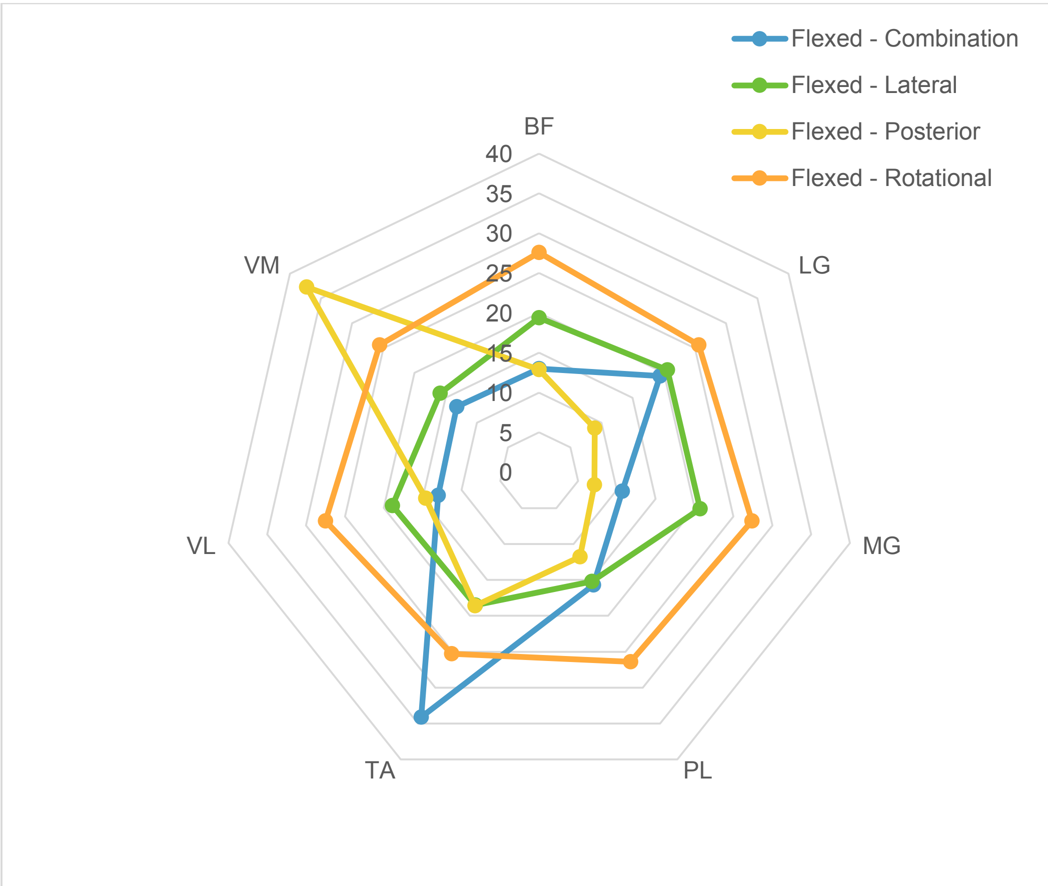
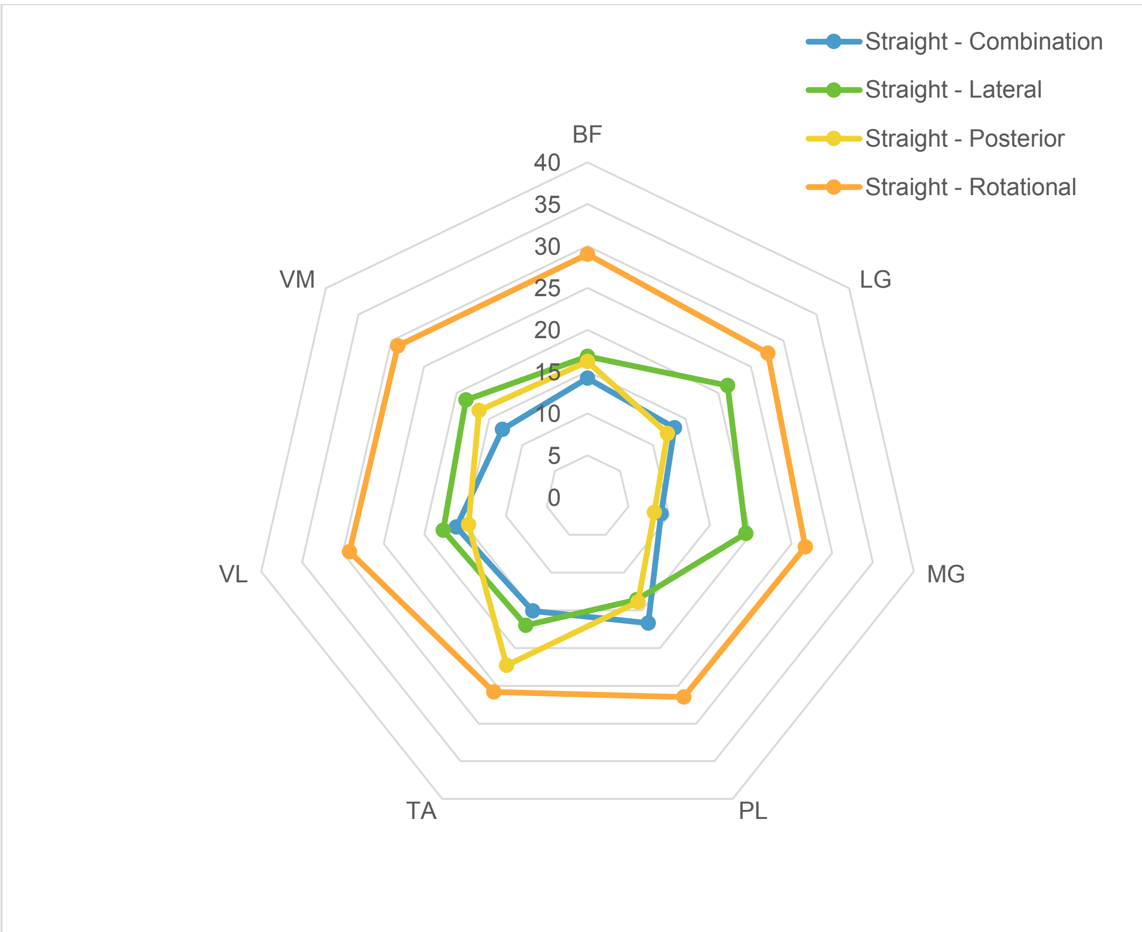


Figure 8 – Time of occurrence of the maximum EMG values at straight knee during posterior, lateral, rotational, and combination perturbations



6.0 Discussion

The purpose of the study was to explore lower limb muscle activity and the influence of knee conditions during a perturbation that mimics an ACL injury mechanism. This information may be used to help determine the reason behind the success of injury prevention programs that reduce the incidence of lower extremity injuries and could help improve these programs. Specifically, this may allow researchers to build on the existing knowledge of injury prevention programs that are being implemented by strength and conditioning coaches and help modify the programs based on muscle activity. To date, there is a lack of published studies regarding ACL injuries with an unexpected perturbation that mimics an ACL injury mechanism. By exploring muscle activation and recruitment and the effect of a posterior, lateral, and rotational motion in balance as well as the combination of these motions, which mimic the occurrence of an ACL injury, we can aid strength and conditioning coaches in improving exercise intervention programs that target injury prevention of the knee joint.

6.1 Understanding Mean and Maximum EMG Values - Lateral Direction

Contrary to what was reported by Malinzak et al. (2001) during side-cutting tasks, the mean EMG values of the lateral and medial heads of the gastrocnemius muscle are slightly higher in the straight knee condition during the post-perturbation phase, which may be explained by the muscle activity necessary to gain balance and may indicate that the athletes change to a more flexed position to balance. The lowest maximum EMG values for the gastrocnemius muscle are during the lateral perturbation in both knee conditions, which may be an indication that the contribution to balance by the gastrocnemius muscle is less during the lateral perturbation. This may also indicate that the lateral gastrocnemius muscle is working as well to gain balance through plantar flexion of the foot and/or flexion of the leg at the knee joint. In the flexed knee condition, the maximum EMG value of the lateral gastrocnemius muscle is greater than the maximum EMG value of the medial gastrocnemius muscle. It may be an indication that the knee is moving into a valgus position through increased lateral muscle contraction and decreased medial muscle contraction (Myer et al., 2009).

The mean EMG value of the peroneus longus muscle during the post-perturbation phase is greater in the straight knee condition, which indicates that the muscle aids in plantar flexion and eversion motion of the foot to regain balance during the lateral perturbation. The maximum EMG value is also greater in the straight knee condition. The mean EMG values of the tibialis anterior muscle during the post-perturbation phase in the flexed knee condition is greater, suggesting that the muscle is working to maintain balance through dorsiflexion and inversion of the foot. The maximum EMG value is also greater in the flexed knee condition.

The vastus medialis and vastus lateralis muscles have greater mean and maximum EMG values in the flexed knee condition since both muscles are contracted to maintain a flexed knee position. The mean EMG values of the vastus medialis and vastus lateralis muscles during the post-perturbation phase are similar to the values of the biceps femoris and semitendinosis muscles, which indicates that that both muscles are working simultaneously to maintain balance through co-contraction for joint integrity, which is supported by the findings of Fleischmann et al. (2011) during lateral landing and lateral jumping tasks. However, a study by Malinzak et al. (2011) revealed that increased quadriceps activation and decreased hamstring activation during side-cutting task. Contrary to the findings in a study by Oliveira et al. (2013) in trained individuals, the mean EMG value of the biceps femoris muscle during the post-perturbation phase in the flexed knee position is slightly greater, which may be an indication that the biceps femoris muscle is more engaged to prevent varus motion at the knee joint when flexed. In addition to this, the maximum EMG values of the semitendinosus muscle are similar in value for both knee conditions, whereas the maximum EMG values for the biceps femoris muscle are greatest in the flexed knee condition. This may indicate that the biceps femoris muscle is working to prevent varus knee position during the lateral perturbation. Contrary to this finding, medial hamstring preparatory activity was found to increase after the implementation of an injury prevention program, and reduced preparatory activity of the medial hamstring of the "landing limb" was thought to be a potential ACL injury risk factor (Fox et al., 2018).

The difference between the perturbation phase and post-perturbation phase mean EMG values of the gluteus medius muscle are greater in the straight knee condition, which may indicate that hip abduction and/or medial rotation aids with achieving balance, especially in the straight knee condition. However, the maximum EMG value of the gluteus medius muscle is greater during the flexed knee position, which may be due to the engagement of the gluteus medius muscle to assist the flexed knee position through abduction of the hip and internal rotation of the thigh. This is supported by the findings of Silvers et al. (2007), which states that a proper landing technique involves engaging knee and hip flexion during lateral cutting tasks.

6.2 Understanding Mean and Maximum EMG Values - Posterior Direction

The mean EMG values of the medial head of the gastrocnemius muscle during the post-perturbation phase are greater than the values of the lateral head of the gastrocnemius muscle. This may suggest that the muscle reactions to prevent valgus motion at the knee joint. In addition to this, the maximum EMG value of the medial head of the gastrocnemius muscle is greater in the straight knee condition, which indicates that medial gastrocnemius muscle is more engaged in order to maintain balance and prevent valgus motion at the knee joint. Contrary to this, Flaxman et al. (2013) reported that females had greater activation of the lateral gastrocnemius compared to males. A study by Landry et al. (2007) who also reported greater lateral gastrocnemius muscle activity compared to medial gastrocnemius muscle activity for straight-run task.

The mean and maximum EMG values of the tibialis anterior muscle are also greater during the flexed knee condition, which may be explained by the knee position. During the straight knee condition, the tibialis anterior muscle is contracted since the participant was told not to hyperextend at the knee joint. However, during the flexed knee condition, the tibialis anterior muscle is contracted in order to maintain balance through dorsiflexion of the foot. A study by Gstöttner et al. (2009) also found that the tibialis anterior muscle of the non-preferred leg reacted faster when the platform moved backwards whereas the tibalis anterior muscle of preferred leg reacted faster when the platform moved forward. During the post-perturbation phase, the tibialis anterior muscle in both knee conditions contracts to maintain the knee positions and regain balance.

The mean and maximum EMG values of the vastus medial and vastus lateralis muscles are greater in the flexed knee condition compared to the straight knee condition, which may be due to the muscle being engaged to maintain balance in the flexed knee position. The mean EMG values of the vastus medialis and vastus lateralis muscles have similar values during all three phases during the flexed knee condition as a result of co-contraction in order to maintain the flexed knee condition. Ruan et al. (2017) reported that reduced co-contraction of the quadriceps and hamstring is beneficial for athletes, but decreased hamstring strength also increases ACL injury risk. While comparing male and female athletes during running and cutting tasks, Malinzak et al. (2001) also reported increased quadriceps EMG values and decreased hamstrings EMG values. Palmieri-Smith et al. (2008) studied preparatory muscle activity and discovered that increased preparatory activity in the lateral quadriceps and lateral hamstring increased valgus knee angle and increased preparatory medial quadriceps activity decreased valgus knee angle. Since the participants were instructed not to hyperextend at the knee joint during the straight knee condition, the vastus medialis and vastus lateralis muscles are also slightly contracted since participants were slightly flexed at the knee joint when instructed against hyperextension. The mean and maximum EMG values of the gluteus medius muscle are greater in the flexed knee condition compared to the straight knee condition, which may result from the engagement of the muscle through hip abduction and/or internal rotation of the thigh in order to maintain balance in the flexed knee position.

6.3 Understanding Mean and Maximum EMG Values - Rotational Direction

Contrary to the results reported by Landry et al. (2007) stating that the lateral gastrocnemius muscle activity was greater than the medial gastrocnemius muscle activity during cross-cutting manoeuvre, the mean and maximum EMG values of the medial head of the gastrocnemius muscle are greater than values of the lateral head of the gastrocnemius muscle, which may suggest that the muscle reacts to prevent valgus motion at the knee joint. The maximum EMG value of the medial gastrocnemius muscle is greater in the straight knee condition compared to the flexed knee condition. The mean EMG values of the medial gastrocnemius muscle are also greater in the straight knee condition compared to the flexed knee condition during all phases for perturbation. Theses results suggest that these muscles are engaged during perturbation and post-perturbation phases to gain balance during the rotational perturbation. The mean EMG value difference between the perturbation phase and post-perturbation phase for the peroneus longus muscle is greatest, which may be an indication that the peroneus longus muscle helps gain balance though eversion of the foot during a rotational perturbation. Landry et al. (2007) also reported that the female participants had increased ankle eversion compared to male participants.

The mean and maximum EMG values for the vastus medial and vastus lateralis muscle are greater in the flexed knee condition, which may indicate that the muscles are contracted to maintain balance in a flexed knee position. In the straight knee condition, there is a slight increase in the mean EMG value for the when comparing the pre-perturbation and perturbation phases to the post-perturbation phase, which may suggest that the participants are transferring to a flexed knee position post-perturbation to regain balance. Myer et al. (2005) reported that contraction of the quadriceps muscle will pull the tibia forward and cause anterior shear at low knee flexion angles between 0° and 30° while mimicking an ACL injury risk manoeuvre. Increased firing of vastus lateralis or decreased firing of the vastus medialis could cause abducted positioning of the knee joint (Myer et al., 2005).

The mean EMG values of the biceps femoris and semitendinosus muscles are similar when comparing both knee conditions within each muscle respectively, suggesting that both muscles contribute to balance equally in both knee conditions. Contrary to this, a study by Kellis et al. (2004) exploring soccer kicks reported that the kicks cause significant changes in biceps femoris muscle activation strategies in the support leg. The biceps femoris muscle activation is increased at ground contact (Kellis et al., 2004). The mean EMG values of the gluteus medius are slightly greater in the flexed knee condition, which may be due to the engagement of the gluteus medius muscle during a flexed knee stance.

6.4 Understanding Mean and Maximum EMG Values - Combination Direction

Higher values in the flexed knee position for the vastus lateralis and vastus medialis compared to the straight knee condition suggest greater muscle activity. As a result of the insertion point of both muscles on the tibial tuberosity, there is an anterior shear force during the motion in the flexed knee position, similar to what was reported by Ruan et al. (2017). However, the semitendinosus and biceps femoris muscles have higher mean EMG values during the post-perturbation phase of the combination perturbation compared to the vastus lateralis and vastus medialis for both conditions, suggesting a greater posterior shear force compared to the anterior shear force. The mean and maximum EMG values of medial and lateral gastrocnemius muscles are higher than the vastus medialis and vastus lateralis muscles as well as the biceps femoris and semitendinosus muscles during the post-perturbation phase in the flexed condition, contributing to the greater posterior shear force of the femur. A study by Malfait et al. (2015) reported significantly greater vastus medialis, vastus lateralis, and medial hamstring activity during a multi-planar perturbation compared to a lateral single planar perturbation. No differences were reported in neuromuscular activity, peak knee flexion and peak knee abduction angles when comparing the single planar perturbations to the multi-planar perturbations (Malfait et al., 2015).

During the straight knee condition in the post-perturbation phase, the mean EMG value is highest for the semitendinosus muscle, suggesting that the muscle is activated to prevent valgus motion of the knee joint. Brown et al. (2013) indicated vastus lateralis pre-activity as a predictor of increased knee abduction moment. The mean value of the gluteus medius muscle is greatest for the flexed knee condition during the post-perturbation phase, suggesting an increase in the abduction and medial rotation of the thigh in a flexed knee stance. The peroneus longus muscle achieved the highest mean EMG values during the post-perturbation phase for both knee conditions, suggesting that plantar flexion and/or eversion of the foot may be a reaction to maintain balance during the combination perturbation. Studies performed Linford et al. (2006) and Thain et al. (2016) explore peroneus longus muscle activity related to ankle sprains, however studies have not explored its relationship to ACL injuries. These reactions may decrease the chance of ACL rupture as result of the strong posterior shear force of the femur, hip abduction, medial thigh rotation, as well as eversion and plantar flexion of the foot. However, since the population studied is a healthy, athletic population, there were no incidents reported during the course of the study.

6.5 Understanding Time of Occurrence of Maximum EMG Values

Lateral and Medial Gastrocnemius Muscles

In both knee conditions, the lateral and medial gastrocnemius muscles reach the maximum EMG value earlier for the combination and posterior in both knee conditions. However, the maximum EMG value is reached earliest in the flexed knee condition during the posterior direction. A systemic review by Theisen et al. (2016) reported earlier onset of muscle activity in medial gastrocnemius in three studies. However, in our study, the patterns of activation are similar for the medial and lateral gastrocnemius muscles.

Tibialis Anterior Muscle

In the flexed knee condition, the tibialis anterior muscle responds significantly later during the combination direction following the onset of perturbation compared to all other directions in both knee conditions. However, during the combination direction in the straight knee condition the tibialis anterior muscle responds earlier to the onset of the perturbation. During the lateral and posterior directions in the flexed knee condition, the tibialis anterior responds earlier compared to the rotation direction in both knee conditions. This may indicate that this muscle is used for balance through inversion of the foot and may be important for balance in the lateral and posterior directions in the flexed knee condition and the combination direction in the straight knee condition.

Peroneus Longus Muscle

During the posterior direction in the flexed knee condition, the peroneus longus muscle responds the earliest following onset of the perturbation. In the rotational direction, the maximum EMG value is reached later in both knee conditions, which may be an indication that the peroneus longus muscle continues to react to maintain balance following the onset of perturbation in the rotational direction.

Vastus Medialis and Vastus Lateralis Muscles

In the rotational direction, the maximum EMG values of the vastus medialis and vastus lateralis muscles are reached near the end of the phase following the onset of perturbation. These muscles aid to stabilize the knee joint and therefore the muscles' reaction during the rotational phase suggests that the muscle continues to contract during the end of the phase to help maintain balance and aid joint stability. During the combination direction in the flexed knee condition, the maximum EMG value of the vastus lateralis muscle is reached earlier compared to all other perturbations. The vastus medialis muscle responds the slowest during the posterior direction in the flexed knee condition. Fox et al. (2017) reported that female athletes had increased activation of medial hamstrings prior to landing and increased activation of medial gastrocnemius at landing compared to a control group following an injury prevention program. A study by Palmieri-Smith et al. (2007) found that increased preparatory activity in the vastus lateralis was related to higher valgus knee angle whereas increased preparatory vastus medialis activity was related to lower valgus knee angles (Palmieri et al., 2007).

Biceps Femoris and Semitendinosus Muscles

The biceps femoris and semitendinosus muscles respond later following the onset of the perturbation during the rotational perturbation in both knee conditions. The biceps femoris muscle reaches the maximum EMG value later during the lateral direction in the flexed knee condition and the semitendinosus muscle reaches the maximum EMG value later during the lateral direction in both knee conditions. This may indicate that these muscles are working in both knee conditions to prevent hyperextension at the knee joint. Overall, these muscles react earlier during the combination perturbation and later during the rotational perturbation in order to stabilize the knee joint. A study by Palmieri-Smith et al. (2007) found that increased preparatory activity in the lateral hamstring was related to higher valgus knee angle. Malfait et al. (2015) stated that a greater difference was found when comparing the vastus lateralis muscle to the medial hamstring muscle during the preparatory phase of a side-cutting manoeuver, which may predict the risk of an ACL injury.

Gluteus Medius Muscle

When examining the rotational direction, the maximum EMG value is reached later in both knee conditions. However, the maximum EMG value is reached earliest during the combination direction in both knee conditions. The gluteus medius muscle aids balance through decreased adduction at the hip joint, which in turn may help the positioning of the knee joint during both perturbations and decrease valgus motion at the knee joint during these perturbations. However, a study by Palmieri-Smith et al. (2007) reported that pre-activation of the gluteus medius muscle did not change peak valgus knee angle.

6.6 Limitations

This research project faced many limitations and challenges during the recruitment phase. Although we had contacted several coaches and had done presentations in person for various teams, there was a lack of interest to participate from the athletes. Also, the inclusion criteria were very specific and therefore it was difficult to find athletes without chronic lower body injuries within a specific age group. This affected the quality of the findings since it was limited to the number of participants who were willing to participate over a span of 3 years.

The amount of data collected was immense and it was difficult to separate the data that was relevant to the research question and hypothesis. All participants were athletes at Concordia University and many of participants were from the same sports team. This may have affected the data collected since the participants may be following the same training program. Therefore, these results may be relevant for the female athletes from Concordia University, but may not be applicable for female athletes from other universities.

The maximum EMG response was calculated during the 750ms following the onset of the perturbation, unlike the division of mean EMG activity during the 500ms of perturbation and 250ms after the perturbation ended. Due to the start and end of the perturbation platform the body may be responding to the movement following the onset of the perturbation and our maximum may be a result of the second reaction at the cessation of the movement of the platform.

6.7 Conclusion

The mean EMG values for vastus medialis, vastus lateralis, and gluteus medius muscles were greatest during combination direction in the flexed knee condition, therefore rejecting the first and second hypotheses. The mean EMG values are greatest during the post-perturbation phase for all muscles compared to the pre-perturbation and perturbation phases for both knee conditions, which supports the third hypothesis. This may be explained by the increased muscle activity necessary to maintain balance since the participants maintain their stance during the pre-perturbation phase and react during the perturbation phase. In addition, the mean EMG values during the post-perturbation phase are greater than the other phases since the participant's reaction to the perturbation is to regain balance and therefore increasing muscle activity following the perturbation. The maximum EMG values and the time of occurrence of the maximum EMG values differed for each muscle, therefore rejecting the fourth hypothesis.

During the lateral, posterior, and rotational perturbations in the straight knee condition, the medial head of the gastrocnemius muscle, vastus lateralis muscle, vastus medialis muscle, and gluteus medius muscle have significant mean EMG values during all phases of perturbation. This is an indication that these muscles are engaged during the straight knee condition to maintain balance. The muscles on the medial aspect of the lower limb help to reduce valgus movement at the knee joint whereas the gluteus medius helps maintain knee position by reducing adduction, which may also help reduce valgus knee in a healthy population and in turn reduce the risk of an ACL injury. In addition to this, all muscles with the exception of the tibialis anterior muscle have significant EMG values during the post-perturbation phase of the combination direction in the straight knee condition, suggesting that all the muscles measured contribute to maintaining balance during a perturbation that mimics a high risk ACL injury mechanism. In the flexed knee condition, the mean EMG values of the peroneus longus, biceps femoris and semitendinosus muscles are significant during post-perturbation of the combination direction, which may also be an indication that these muscle engage to maintain balance in the flexed knee position. These muscles may contribute to ACL injury prevention by reducing hyperextension at the knee joint and internal tibial rotation. Therefore, these muscles may react post-perturbation to maintain stability at the knee joint in a healthy population.

The maximum EMG values of the medial head and lateral head of the gastrocnemius muscle, biceps femoris muscle, and semitendinosus muscle were greatest during the combination direction in the straight knee condition. This may be an indication that these muscles reach the maximum values to protect the knee joint and maintain balance in the flexed knee condition through decreased anterior shear force of the tibia or increased posterior shear force of the femur, which in turn may decrease the risk of an ACL injury. The maximum EMG values of tibialis anterior muscle and vastus medialis muscle are greatest for the lateral direction. During the combination direction, the maximum EMG values are greatest in the flexed knee condition for the peroneus longus muscle and gluteus medius muscle, suggesting that these muscles react to maintain balance through eversion of the foot and reduced adduction at the hip. This may also reduce the risk of an ACL injury.

The time of occurrence of the maximum EMG values of all the muscles tested, with the exception of the vastus medialis muscle, were reached the latest during the rotational direction. In the flexed knee condition, the time of occurrence of the maximum EMG values of the medial and lateral heads of the gastrocnemius muscle were reached the latest during the rotational direction. In the straight knee condition, the maximum EMG values of the tibialis anterior muscle, peroneus longus muscle, vastus lateralis muscle, biceps femoris muscle, semitendinosus muscle, and gluteus medius muscle are reached the latest following the onset of a perturbation during the rotational direction. These results suggest that the knee joint may not be well protected during the rotational perturbation since it is beneficial for the athlete if the muscles react earlier following the onset of perturbation. This may also increase the chance of an ACL injury.

The highest muscle activity, obtained by measuring mean EMG values, were from the lateral and medial heads of the gastrocnemius muscle and the peroneus longus muscle during the post-perturbation phase of the combination perturbation. These values were also significant in the straight knee condition, which suggests that the peroneus longus and gastrocnemius muscles contribute to maintaining balance, especially in the straight knee condition.

6.8 Future Research

Future researchers can conduct the same study to compare and contrast male and female EMG muscle activity. Statistically, female athletes suffer more ACL injuries than male athletes (Agel et al., 2007) (Ireland, 1999) (Slauterback et al., 2002). By comparing results from male and female athletes, the researcher may be able to determine the sex differences in muscle engagement between the two groups. This study can be replicated to investigate the difference between healthy athletes and athletes who have suffered ACL injury. This study can also be replicated by tracking the athletes over a period of time and retesting the athletes who have suffered an ACL injury in order to see determine how the values change post-injury

Joint kinematics can also be studied and compared with the EMG muscle activity. The data can also be compared between male and female athletes to investigate if there are similarities or differences that can explain the ACL injuries in female athletes. This study can also be replicated to investigate differences in muscle activity in young athletes.

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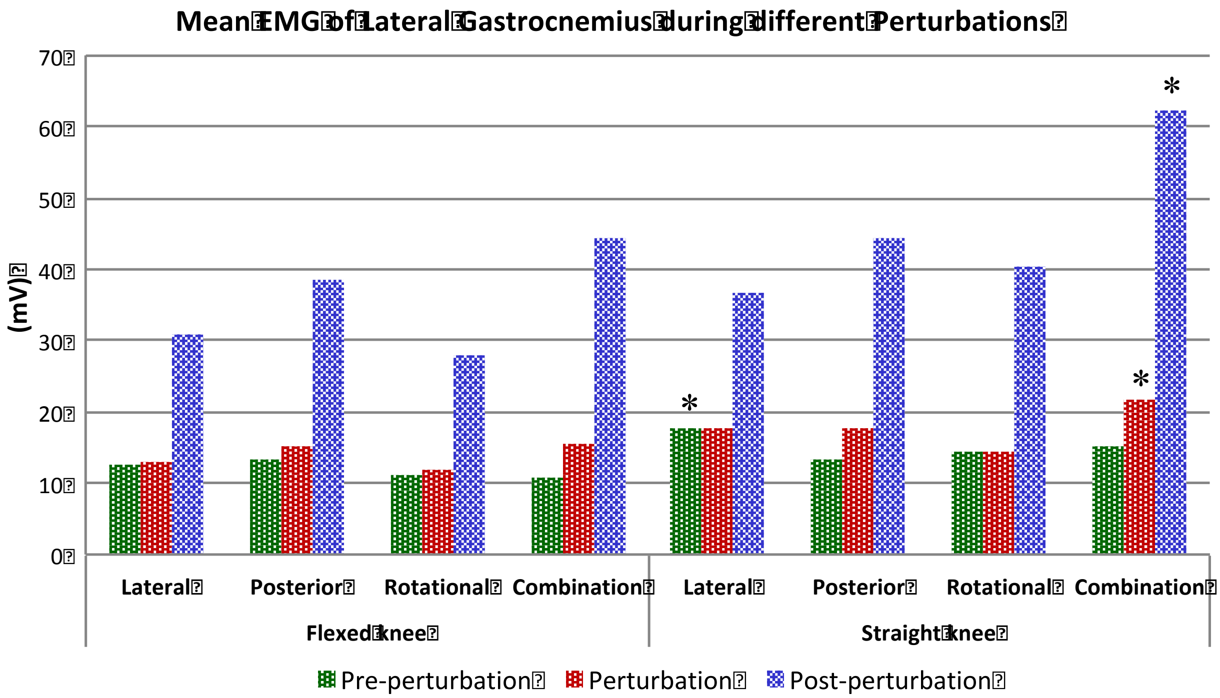
8.0 Appendices

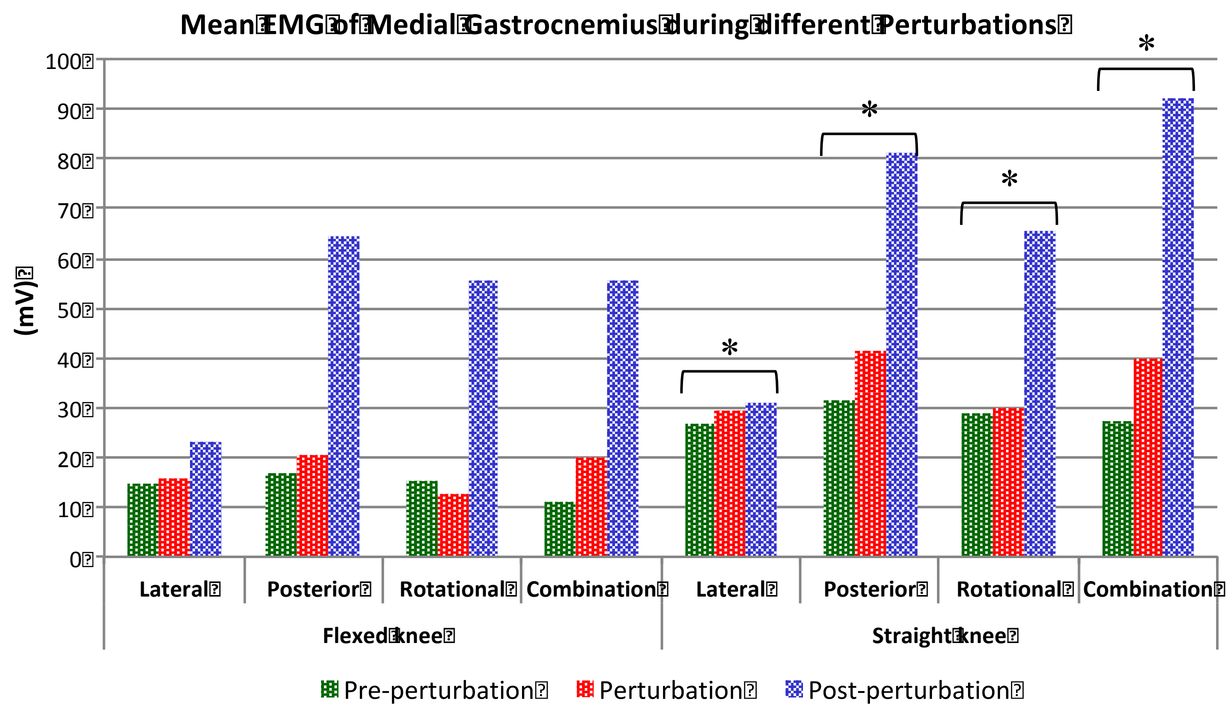
8.1 Appendix A

Graph 1 – Mean EMG Values of Lateral Gastrocnemius Muscle During Different Perturbations



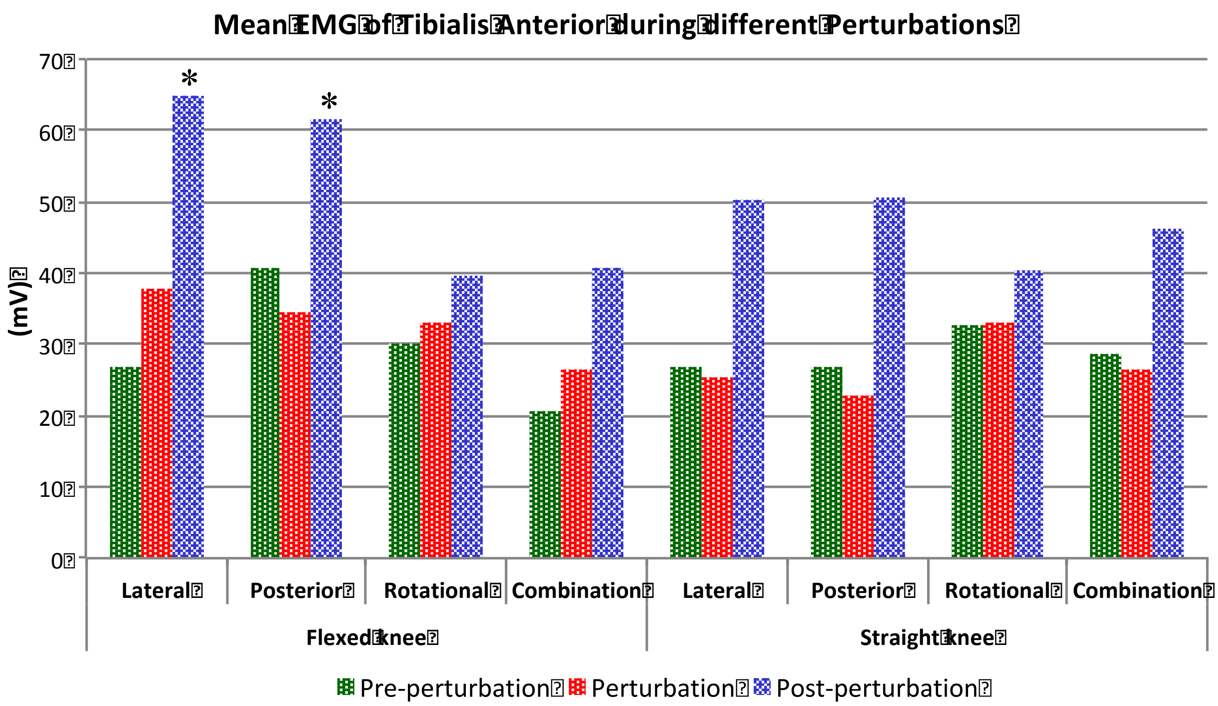
*significant difference within phases
Post-perturbations significantly greater than the two other phases

Graph 2 – Mean EMG Values of Medial Gastrocnemius Muscle During Different Perturbations



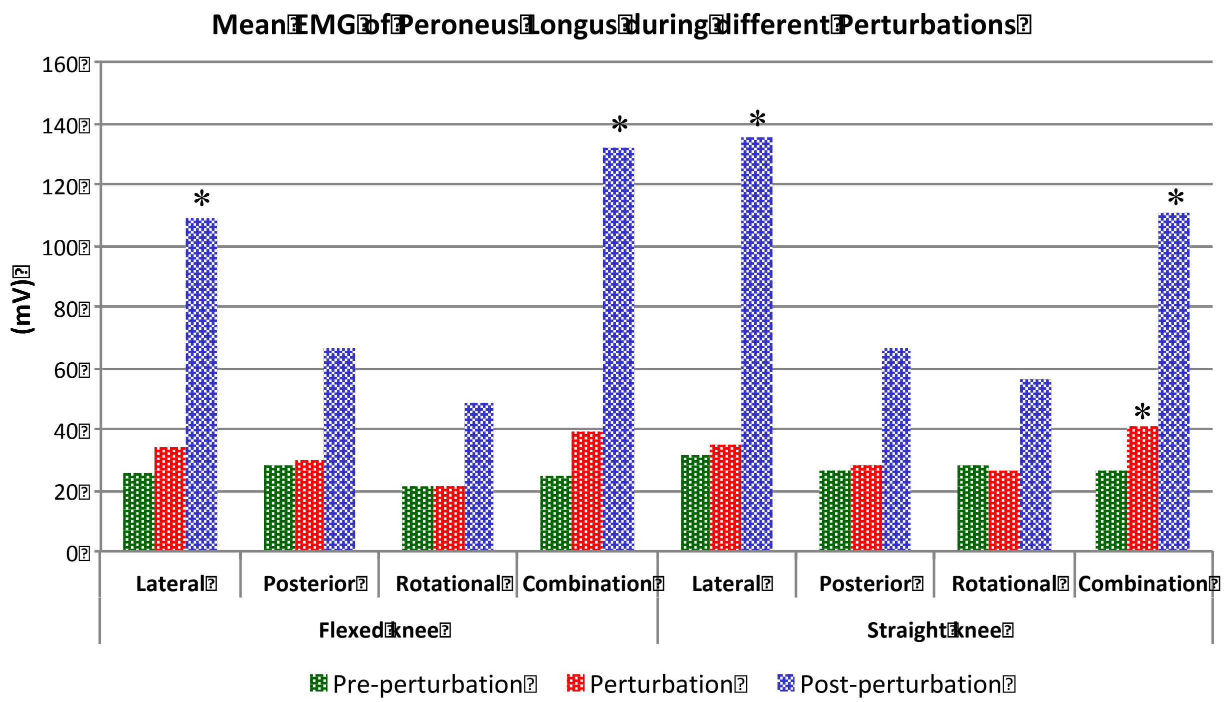
*significant difference within phases
Post-perturbations significantly greater than the two other phases

Graph 3 – Mean EMG Values of Tibialis Anterior Muscle During Different Perturbations



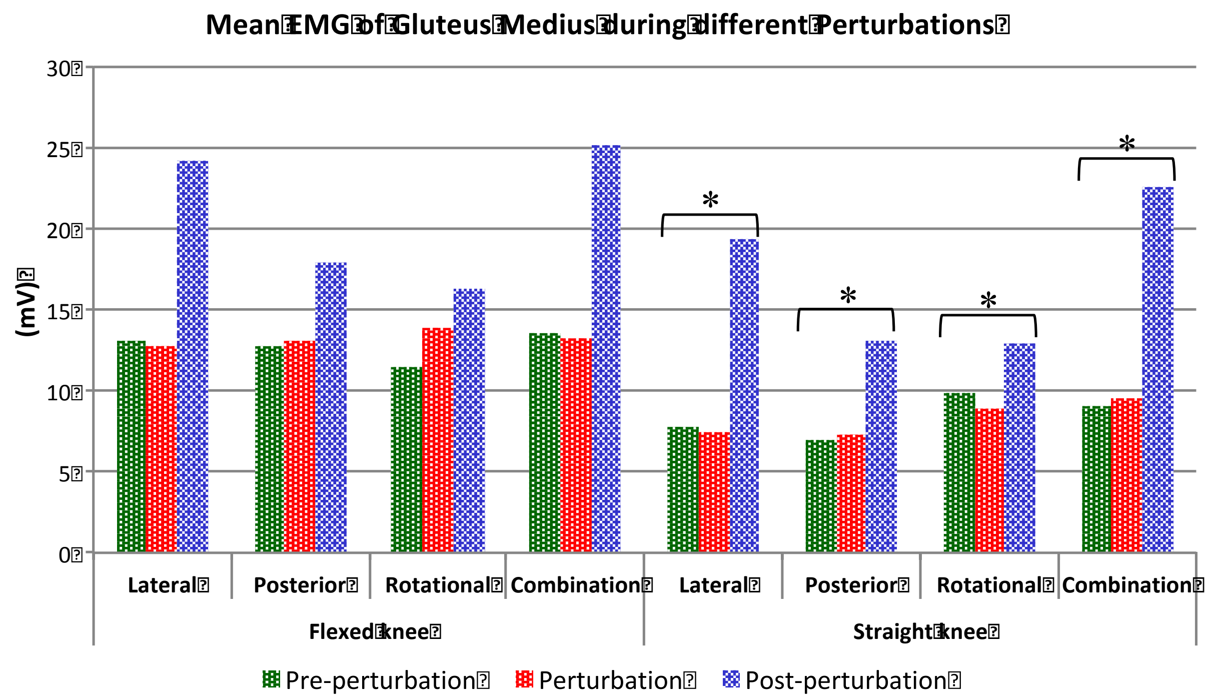
*significant difference within phases
Post-perturbations significantly greater than the two other phases

Graph 4 – Mean EMG Values of Peroneus Longus Muscle During Different Perturbations



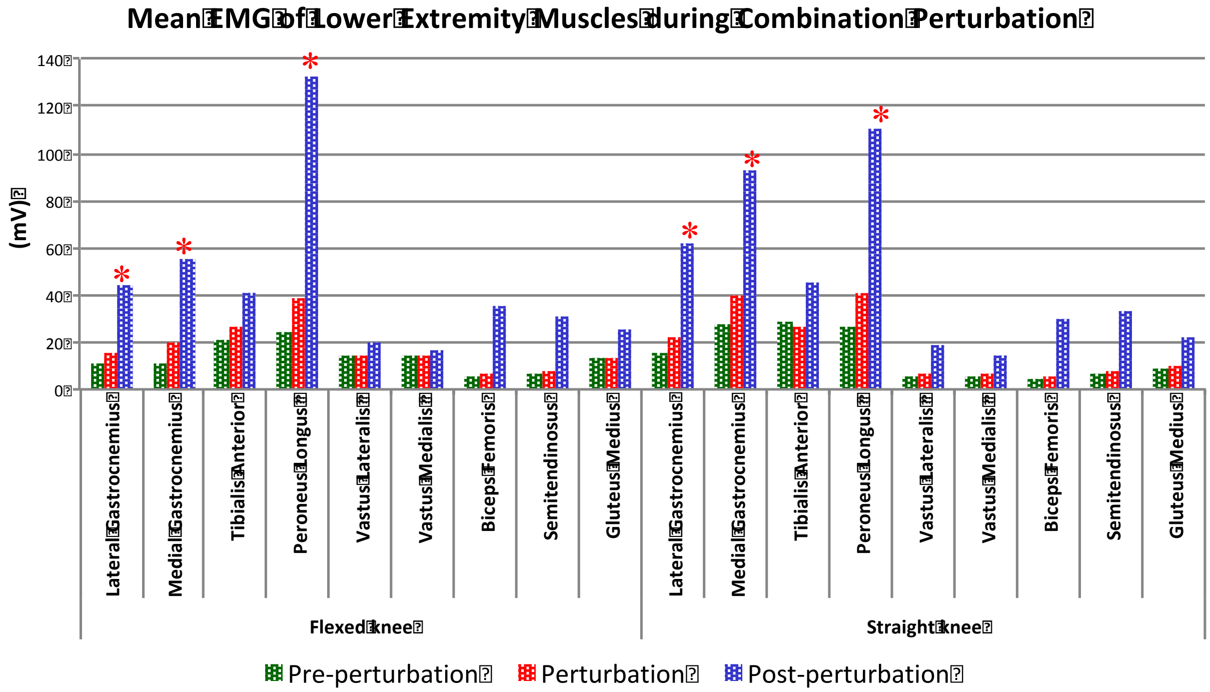
*significant difference within phases
Post-perturbations significantly greater than the two other phases

Graph 5 – Mean EMG Values of Gluteus Medius Muscle During Different Perturbations



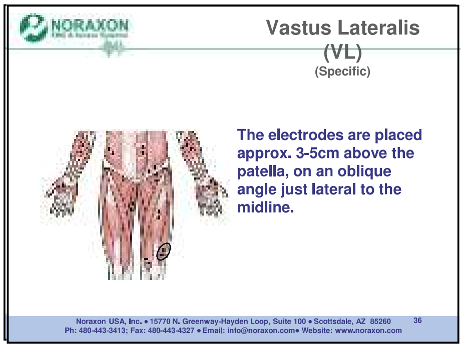
*significant difference within phases
Post-perturbations significantly greater than the two other phases

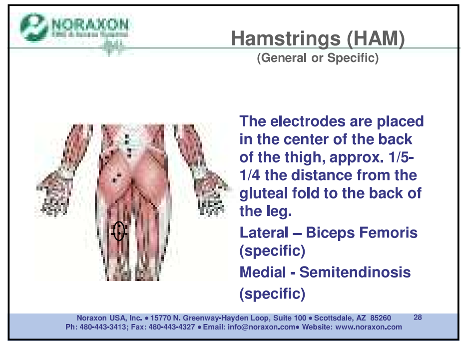
Graph 6 – Mean EMG Values of Lower Extremity Muscles During Different Combination Perturbation

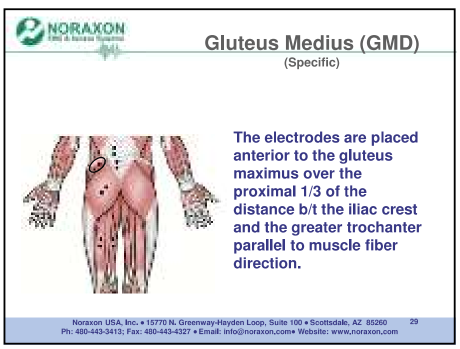


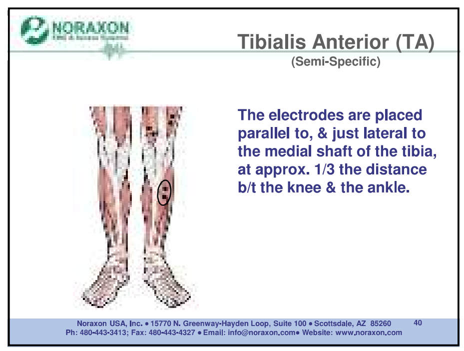
*Highest muscular activity

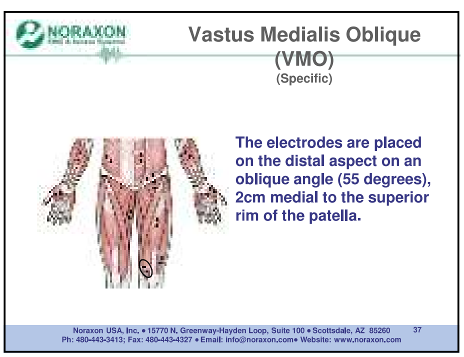
8.2 Appendix B

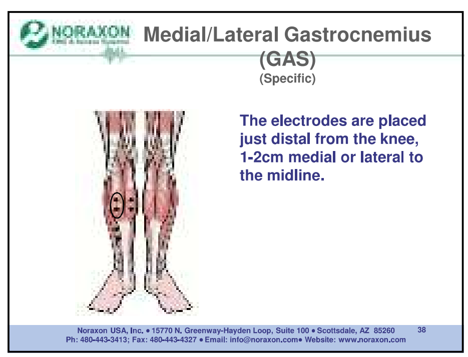




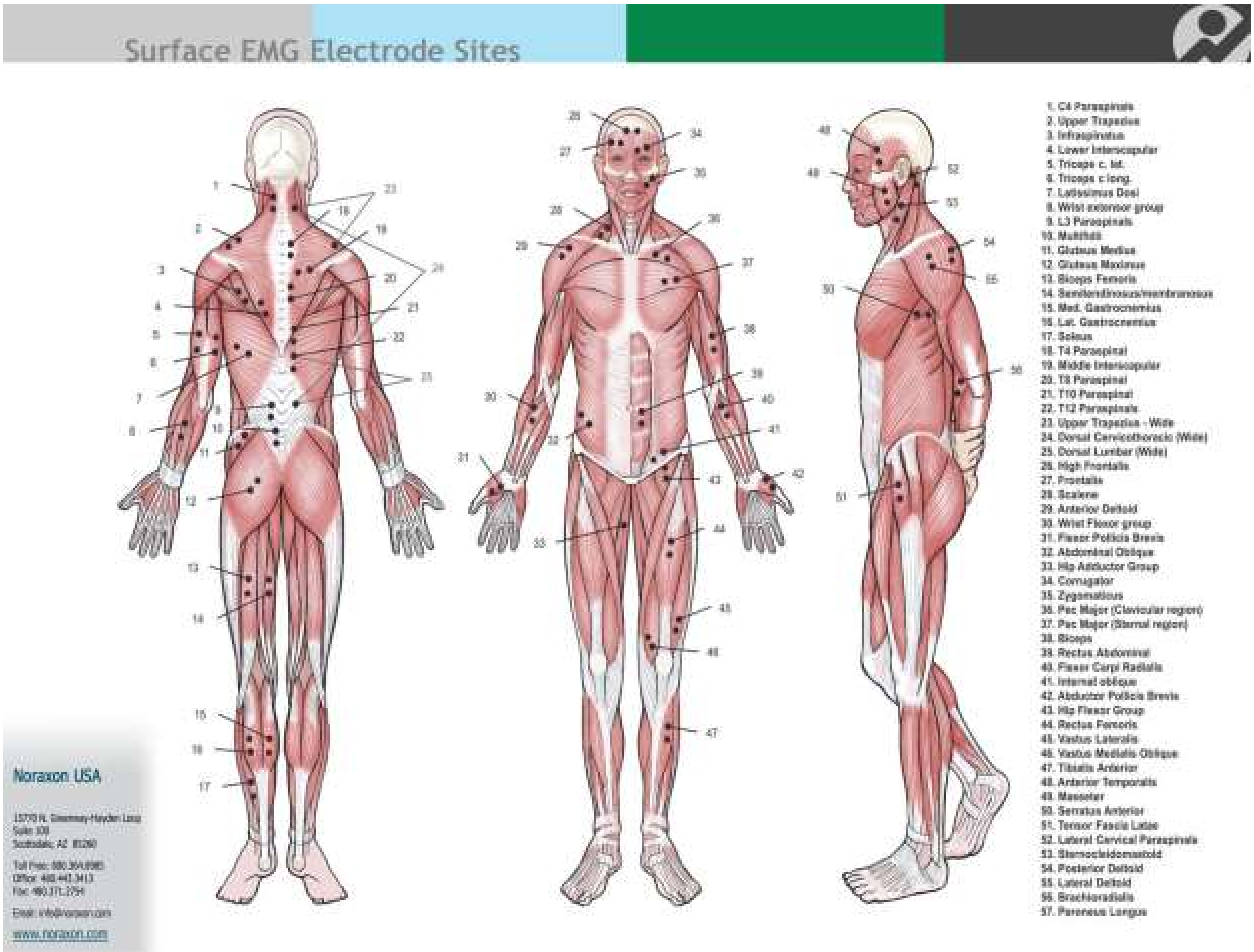








Reference: "Set-up and Application Guides." *Noraxon USA*, www.noraxon.com/support-learn/learn-and-share/set-application-guides/.



Reference: "Set-up and Application Guides." *Noraxon USA*, www.noraxon.com/support-learn/learn-and-share/set-application-guides/.