QUADRICEPS AVOIDANCE CHARACTERISTICS OF PERSONS WITH A RECONSTRUCTED ANTERIOR CRUCIATE LIGAMENT DURING A FORWARD LUNGE

by

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Abstract

Anterior cruciate ligament (ACL) tears are injuries that often require surgery and physical therapy. Previous research have shown that patients after ACL reconstruction develop a compensatory mechanism called quadriceps avoidance where the use of the quadriceps is avoided and greater knee flexion is demonstrated during gait. Quadriceps avoidance is considered to be an abnormal movement pattern that can have negative effects after ACL reconstruction especially when it is adopted for a long time. While quadriceps avoidance has been well documented in gait, it has not been researched much in more strenuous functional movements such as the forward lunge that often comprise physical activity.

The knowledge about the quadriceps avoidance characteristics that an ACL reconstruction brings about during functional movement is limited; thus not much is known regarding the long-term functional outcomes of ACL reconstruction. Thus, the main purpose of this investigation was to quantitatively examine the quadriceps avoidance characteristics of an ACLR group during four phases of a forward lunge by comparing them to the same characteristics of a healthy control group and the uninvolved group.

Nineteen participants (13 healthy control, 6 ACLR) were recruited for this study. Reflective motion capture markers were attached to participants who completed 10 repetitions of the forward lunge onto a force platform with each leg alternating leading legs with their arms across their chest. Using marker and force platform data, the moments about the knee in three dimensions were computed. There were no differences between control and ACLR participants in any of the knee moment outcome measures in any of the four phases along the sagittal, frontal, and transverse anatomical planes that were investigated (p > 0.05). No differences in knee moments indicate that ACLR limbs exhibited a level of quadriceps avoidance that was not different than the level exhibited by healthy control or uninvolved limbs when lunging forward. These findings suggest that current treatment methods are able to restore normal quadriceps
avoidance characteristics and the injury risk posed by these characteristics to ACLR individuals are no greater than the risk posed to healthy individuals when participating in full physical activity after surgery.
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<tr>
<td>ACL</td>
<td>Anterior Cruciate Ligament</td>
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<tr>
<td>ACLR</td>
<td>Anterior Cruciate Ligament Reconstructed</td>
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<td>ANOVA</td>
<td>Analysis of Variance</td>
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<td>cm</td>
<td>Centimetre</td>
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<td>EMG</td>
<td>Electromyography</td>
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<td>FPT</td>
<td>Functional Performance Test</td>
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<td>Hz</td>
<td>Hertz</td>
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<tr>
<td>kg</td>
<td>Kilogram</td>
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<tr>
<td>m/s</td>
<td>Metres per Second</td>
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<tr>
<td>NCAA</td>
<td>National Collegiate Athletic Association</td>
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<tr>
<td>Nm</td>
<td>Newton Metres</td>
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<tr>
<td>TKR</td>
<td>Total Knee Replacement</td>
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<tr>
<td>USD</td>
<td>United States Dollar</td>
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<td>V</td>
<td>Volts</td>
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Chapter 1

Introduction

The anterior cruciate ligament (ACL) acts as a mechanical restraint to stabilize the knee (Fink, Vassilev, Kleipool, Fu, & Lephart, 2000; Huston & Wojtys, 2000; Whiting & Zernicke, 2008). However, when the ACL is torn, typically during physical activity, the mechanical restraint weakens thereby decreasing knee stability (Herrington, Wrapson, Matthews, & Matthews, 2005; Myklebust & Bahr, 2005). If left unrepaired, individuals with a torn ACL are likely to have difficulty participating in physical activity due to a combination of pain, reduced proprioception, subsequent damage to surrounding structures, and episodes of the knee giving-way (Daniel et al., 1994; Finsterbush, Frankl, Matan, & Mann, 1990; Ingersoll, Grindstaff, Pietrosimone, & Hart, 2008; Kannus & Järvinen, 1989; Kowalk, Duncan, McCue, & Vaughan, 1997; Lam et al., 2009). Furthermore, the estimated annual cost associated with ACL tears is approximately $500 million USD (Griffin et al., 2000). To prevent the aforementioned consequences of an unrepaired ACL, reconstructive surgery to repair a torn ACL increases knee stability and decreases the risk of further injury (Jennings, Rasquinha, & Dowd, 2003; Siegel, Vandenakker-Albanese, & Siegel, 2012).

After reconstructive surgery, physical rehabilitation attempts to restore the range of motion, strength, neuromuscular control, dynamic stability, and function of the involved knee and its surrounding structures (Pezzullo & Fadale, 2010; Wilk, Macrina, Cain, Dugas, & Andrews, 2012). The clinician assesses recovery and determines if the patient is ready to return to full physical activity by conducting tests that indicate the health status of the involved knee. These test might include, anterior-posterior knee stability, tested with an arthrometer or Lachman’s test, muscle strength, and function (Lam et al., 2009; Zhang, Huang, Yao, & Ma, 2015). Although extensive examination methods exist, the decision to return a patient to physical activity
following ACL reconstruction is not based solely on objective criteria and includes the clinician’s subjective opinion.

Once a clinician determines that a patient has sufficiently recovered, the patient is allowed to return to full physical activity without restriction. If patients were to be cleared without fully regaining neuromuscular control, future debilitating complications of and around the knee such as a re-tear of the reconstructed ACL may occur (Bell, Smith, Pennuto, Stiffler, & Olson, 2014; Marcacci, Grassi, Muccioli, Nitri, & Zaffagnini, 2014). The most prominent neuromuscular compensatory mechanism in the ACL-injured population is quadriceps avoidance whereby the quadriceps muscle group tends not to be used in an effort to reduce tibial translation in the anterior direction relative to the femur (Andriacchi, Hurwitz, Bush-Joseph, & Bach, 2000; Berchuk, Andriacchi, Bach, & Reider, 1990; Fink et al., 2000; Georgoulis, Papadonikolakis, Papageorgiou, Mitsou, & Stergiou, 2003; Georgoulis et al., 2005; Hart, Pietrosimone, Hertel, & Ingersoll, 2010; Knoll, Kiss, & Kocsis, 2004; Limbird, Shiavi, Frazer, & Borra, 1988).

Individuals who have undergone an ACL reconstruction also demonstrate some degree of quadriceps avoidance (Knoll et al., 2004; Limbird et al., 1988). Quadriceps avoidance can be considered to be an abnormality that can have negative effects such as degenerative changes, pain, and inefficient movement if left uncorrected; these effects can become more pronounced by participating in full physical activity with such an abnormality (Berchuk et al., 1990; Georgoulis et al., 2005; Hart et al., 2010; Pfeifer & Banzer, 1999).

With the goal of having the patient safely return to physical activity, clinicians should focus on dynamic, functional movements that typify the target physical activity during physical therapy and evaluation. Functional movements are of interest because they primarily comprise physical activity. The forward lunge is a functional movement that is recommended to ACLR patients during physical therapy (Flanagan, Wang, Greendale, Azen & Salem, 2004; Fowler Kennedy Sports Medicine Clinic, 2009; Hall et al., 2015; Noyes Knee Institute, 2011; Salil,
Bibek, Dhillon, & Ashish, 2015). The rehabilitation benefits of the forward lunge are that it increases muscle strength and neuromuscular control of the involved limb enabling improved function (Hall et al., 2015; Salil et al., 2015). The forward lunge plays a direct role in improving function since the forward lunge itself and the muscle contraction pattern that occurs during a forward lunge are often observed in everyday activities and in more strenuous physical activity (Flanagan et al., 2004; Hall et al., 2015). Because of how frequently the forward lunge is carried out in daily life, it is an integral part of daily life and can reflect the physical functional ability of individuals (Flanagan et al., 2004; Hall et al., 2015).

Aside from gait, there is limited research regarding the functional outcomes of ACL reconstructed (ACLR) patients. The knowledge regarding functional characteristics—specifically, whether ACLR patients are safely partaking in physical activity without exhibiting abnormal compensatory mechanisms—of ACLR patients who are observed during functional movements such as the forward lunge after they have returned to full physical activity is unclear. Because of this limited knowledge, it is unknown if ACLR patients are participating in physical activity without threatening abnormalities and in a safe manner that does not increase their risk of injury. It would be beneficial to know if a movement that is often carried out during physical activity is posing a risk for injury to the already vulnerable ACLR population (Kuenze et al., 2015).

The presence of abnormal compensatory mechanisms during functional movements can be detected, analyzed, and used to determine if there are issues with ACLR patients who participate in full physical activity that need to be addressed. Particularly, kinetic characteristics of ACLR limbs while lunging can be examined and compared to the characteristics of healthy control and contralateral uninvolved limbs to determine if quadriceps avoidance existed since symptoms of quadriceps avoidance include knee moments along anatomical planes that differ from healthy limbs. This topic has the potential to identify if ACLR individuals are indeed safely partaking in physical activity from a quadriceps avoidance perspective and are at a risk for knee
injuries that result due to compensatory mechanisms that is no greater than individuals who havenever experienced an ACL tear as determined by functional assessments. This topic may alsoillustrate the need for current surgical reconstruction techniques and physical therapy methods toimprove to be able to correct abnormal compensatory mechanisms and for current assessmentmethodsto be more stringent and sensitive in order to prevent ACLR patients from returning tophysical activity when they have an increased risk of developing complications in and around theknee due to the aforementioned maladaptations.
Chapter 2

Literature Review

2.1 ACL Anatomy

The ACL is a ligament that stabilizes the knee. It connects the femur and the tibia as it runs anteriorly from the lateral femoral condyle to the anterior aspect of the midtibial plateau (Whiting & Zernicke, 2008). The ACL serves primarily as a passive, mechanical restraint to anterior translation of the tibia with respect to the femur and secondarily to prevent excessive tibial rotation (Fink et al., 2000; Georgoulis et al., 2005; Huston & Wojtys, 2000; Whiting & Zernicke, 2008). The ACL has two bundles: an anteromedial bundle and a posterolateral bundle. During flexion the anteromedial bundle is tight and the posterolateral bundle is lax whereas in extension the anteromedial bundle is lax and the posterolateral bundle is tight (Whiting & Zernicke, 2008).
2.2 Mechanism of Injury

The mechanisms of ACL injury can be classified using the guidelines set by the American Orthopaedic Society of Sports Medicine into 3 categories: direct contact, indirect, or non-contact (Marshall, Padua, & McGrath, 2007). In a direct contact injury an external force is applied to the knee resulting in injury of said knee. In an indirect injury an external force applied to an individual but not directly to the knee. In a non-contact injury the forces applied to the knee are from an individual’s own movement with no contact with another individual or object.

The majority of documented ACL injuries by the National Collegiate Athletic Association (NCAA) from 1990 to 2002 were non-contact injuries (Boden, Dean, Feagin, & Garrett, 2000). In the general population approximately 70% of ACL injuries occur due to non-contact mechanisms of injury (Bershadsky, Arendt, & Agel, 2005), a rate similar to the aforementioned NCAA
findings. A non-contact injury is likely to be sustained if 1) the knee was in valgus, 2) the knee flexion angle was less than 30°, 3) the foot was externally rotated relative to the knee, and 4) the centre of gravity of the body was behind the knee upon landing or decelerating to a stop after running (Hughes, 2014; Marshall et al., 2007). These conditions are analogous with the finding that abruptly decelerating and changing direction of motion (i.e. cutting) and landing after jumping with the knee near full extension are the most common movements leading to ACL injuries in athletic populations (Boden et al., 2000; Bottoni, 2005).

2.3 Consequences of Injury and Repair

The main consequence of an ACL tear is knee instability. The mechanical restraint is lost and the tibia is allowed to translate in the anterior direction relative to the femur (Whiting & Zernicke, 2008). This translation is the reason patients experience episodes of the knee giving-way (Siegel et al., 2012). With this increased knee instability, patients experience pain and refrain from vigorous physical activity (Lam et al., 2009). Muscle strength around the knee is lost due to disuse and functional ability is compromised out of prudence and a desire not to further injure and inflict pain and discomfort on oneself (Hiemstra, Webber, MacDonald, & Kriellaars, 2000). Additionally, an ACL tear, if left untreated, can lead to mensical tears and articular condylar cartilage damage (Finsterbush et al., 1990; Marcacci et al., 2014). Degenerative arthritis of the knee, discomforting symptoms, and an inability to return to sport have been documented as long-term consequences to an ACL tear (Andriacchi et al., 2000; Carey, Huffman, Parekh, & Sennett, 2006; Daniel et al., 1994; Shah, Andrews, Fleisig, McMichael, & Lemak, 2010).

For those who are physically active, surgical reconstruction is the best recourse to treat an ACL tear (Andriacchi et al., 2000; Siegel et al., 2012). The goal of surgical reconstruction is to replace the damaged ACL with a tissue graft that can serve as the new ACL. The goal of the
surgery is to restore stability to the knee which decreases episodes of giving-way, incurring a subsequent knee injury, and developing pathologies.

2.4 Recovery Timeline

Advancements in surgery have made ACL reconstruction less invasive which makes a full recovery and return to physical activity by patients more likely (Siegel et al., 2012). This allows patients to engage in range of motion and weight-bearing exercises sooner as well as progressing to more physically demanding functional movements, movements specific to the goals of the patient, sooner (Kvist, 2004). Patients are now returning to their desired physical activity within four to six months rather than in the nine to twelve months which previously was considered the typical duration of recovery (Kvist, 2004). The decision made by the clinician to allow the patient to return to full physical activity is based on the degree of stability of the involved knee, time since surgery, and subjective opinions (Myer, Paterno, Ford, Quatman, & Hewett, 2006). Subjective opinions of clinicians are relied on as currently, there is no valid, objective, ACL-specific scientific evidence a clinician can use to clear a post-reconstruction patient to return to physical activity (Barber-Westin & Noyes, 2011; Pezzullo & Fadale, 2010).

2.5 Current Assessment Guidelines

A wide variety of tests have been suggested in literature in attempts to establish objective return to activity rules for patients with a reconstructed ACL. The incidence of ACL injuries has led to research of over 5,000 published articles (Whiting & Zernicke, 2008). Recent research suggests using functional performance tests (FPTs) to objectively evaluate knee function to determine if ACL reconstructed patients are ready to return to activity typical of their daily
activity (Flanagan et al., 2004). However, objective criteria in practice to assess a patient’s readiness to safely return to their desired physical activity level are limited (Lam et al., 2009).

Currently, the most objective criterion suggested in literature to assess ability, rehabilitation progress, and readiness of a patient to return to activity involves having patients perform a FPT, primarily the single-leg hop for distance test—where participants jump on one leg to attain maximum horizontal distance—and then calculate a within-patient bilateral symmetry index by dividing the score achieved by the involved leg by the score achieved by the uninvolved leg and multiplying by 100% (Alkjaer, Simonsen, Magnusson, Aagaard, & Dyhre-Poulsen, 2002; Noyes, Barber, & Mangine, 1991). However, there are limitations with this approach. The single-leg hop for distance FPT has been suggested to be an unsafe and stressful clinical test for patients due to the risk of the patient experiencing symptoms that are consequences of their ACL injury and the risk of the patient falling and incurring further injury during the test (Alkjaer et al., 2002). The limitation of the bilateral symmetry index is the possibility of yielding an invalid patient assessment. If the bilateral symmetry index is greater than 85%, the patient is cleared to return to full activity (Barber, Noyes, Mangine, McCloskey, & Hartman, 1990; Mattacola, Jacobs, Rund, & Johnson, 2004; Noyes et al., 1991). While the 85% symmetry index is an objective criterion, its reliability, sensitivity, and specificity has been called into question as patients have been misclassified based on the criterion (Barber et al., 1990; Noyes et al., 1991). A patient with acceptable symmetry may still not be ready to return to activity. Their two legs may perform similarly but their strength, stability or symmetry may be poor relative to healthy individuals because the contralateral uninvolved leg can lose functional ability as a result of the ACL tear via neuromuscular alterations that influence both legs (Button, van Deursen, & Price, 2005; Schroeder, Krishnan, & Dhaher, 2015). Therefore, it may be prudent to compare patients to healthy individuals to accurately assess their readiness to return to activity. An acceptable bilateral symmetry index can mask inadequate function as indicated by raw functional test scores.
Poor raw scores can suggest that the patient is not ready to return to activity and if cleared to return the patient may be at a greater risk for injury and may compromise their performance. The limitations of the described objective bilateral symmetry index elucidates the need for improved objective decision rules when determining if an individual with a reconstructed ACL can be cleared to return to physical activity.

When assessing patients after an ACL reconstruction, the focus of a clinician should not be limited to the anatomical integrity of the knee joint, the ACL itself, muscles surrounding the knee, and scores from functional performance tests such as the single-leg hop test (Marshall et al., 2015). Clinician focus should include functional deficiencies stemming from neuromuscular mechanisms used during dynamic movements due to the increased risk of ACL re-injury or injury to the contralateral limb that occurs when partaking in physical activity with abnormal neuromuscular mechanisms (Marshall et al., 2015; Myer et al., 2006).

2.6 Return to Physical Activity

ACL tears are one of most commonly occurring injuries in physical activity (Andriacchi, Hurwitz, Bush-Joseph, & Bach, 2000) and were once considered a career-ending injury (Bak, Jorgensen, Ekstrand, & Scavenius, 2001). However, with advances in treatment, reconstructive surgery and rehabilitation, many individuals are able to make a full recovery (Ardern, Taylor, Feller, & Webster, 2012; Arder, Webster, Taylor, & Feller, 2011; Bak et al., 2001; Cooley, Deffner, & Rosenberg, 2001; Jennings et al., 2003; Kvist, Ek, Sporrsedt, & Good, 2005; Myklebust & Bahr, 2005; Namdari, Scott, Milby, Baldwin, & Lee, 2011; Siegel & Barber-Westin, 1998; Siegel et al., 2012). As proof, knees that undergo ACL reconstruction eventually demonstrate a gait pattern similar to that of uninjured knees (Georgoulis et al., 2003; Knoll et al., 2004; Timoney et al., 1993). Knee flexion-extension, valgus-varus, and internal-external rotation
patterns were not different between the two groups of knees but were different when compared to ACL-deficient knees suggesting that reconstruction restores normal knee kinematics during gait (Georgoulis et al., 2003). This finding parallels with the findings of Knoll et al. (2004) which suggest that pre-injury gait patterns can be re-established eight months after ACL reconstruction even though quadriceps avoidance is observed in gait initially after reconstruction.

With regards to sport, players are able to make a return to play after an ACL reconstruction. Bak et al. (2001) report that 36% of soccer players who underwent an ACL reconstruction returned to their preinjury performance level while 32% returned to play but at a lower performance level. Of those who did not return to soccer, 34% did not return as a result of complications in the reconstructed knee while 66% did not return due to issues unrelated to the involved knee. When basketball statistics reflecting the level of performance were compared between female professional basketball players who have never experienced an ACL injury and those who have, no within- or between-group differences were observed (Namdari et al., 2011). These results suggest that, similar to gait and soccer, preinjury physical activity performance can be regained after reconstruction (Bak et al., 2001).

Making a decision to allow a patient to return to their desired physical activity without restrictions should be made after considering potential consequences. It has been suggested that ACLR individuals are at a higher risk for injury and degenerative changes to the knee when partaking in full physical activity after completing an ACL rehabilitation regimen because of the possible presence of a lower extremity neuromuscular dysfunction that gives rise to abnormal functional adaptations (Kuenze et al., 2015). For instance, a return to physical activity in the presence of quadriceps dysfunction may predispose individuals with a reconstructed ACL to long-term knee degeneration (Kuenze et al., 2015). Quadriceps activation and strength deficits may be present during movement and result in altered mechanics that can negatively affect the knee (Kuenze et al., 2015). A persistent dysfunction may reduce the ability of ACLR individuals
to adapt to the demands of physical activity resulting in abnormal knee mechanics (Kuenze et al., 2015).

2.7 Forward Lunge

A forward lunge is a multijoint, closed kinetic chain and weight bearing exercise (Flanagan et al., 2004; Varadarajan, Gill, Freiberg, Rubash, & Li, 2009) performed in the sagittal plane and is a common rehabilitation exercise that is prescribed to patients who are rehabilitating after an ACL reconstruction (Flanagan et al., 2004; Fowler Kennedy Sports Medicine Clinic, 2009; Noyes Knee Institute, 2011; Salil et al., 2015). The purposes of a forward lunge in rehabilitation are to restore dynamic knee stability, musculature strength, and neuromuscular control around the knee (Dwyer, Boudreau, Mattacola, Uhl, & Lattermann, 2010; Hall et al., 2015). The lunge is considered to be functional because it couples concentric and eccentric contractions in a cycle (Hall et al., 2015); this cycle is prominent in physical activity and approximates the movement pattern of common activities in sport and daily life such as stepping and walking (Flanagan et al., 2004; Mattacola et al., 2004; Hall et al., 2015; Osternig, 2000). The benefits the forward lunge exercise bestows improves physical functional ability in individuals particularly those who are recovering from a knee injury (Flanagan et al., 2004; Hall et al., 2015).

When used as a functional test to assess ACL-injured patients, the forward lunge is suggested to be a less stressful test for patients compared to the single-leg hop (Alkjaer et al., 2002). It is an attractive exercise for patients because it can be done with only body weight as the sole source of resistance, does not compromise balance as both feet remain in contact with the floor, and simultaneously trains muscle groups (Flanagan et al., 2004; Jönhagen, Ackermann, & Saartok, 2009). The forward lunge involves flexion of the knee by the hamstring muscle group and extension of the knee by the quadriceps muscle group (Alkjaer, Wieland, Andersen,
Simonsen, & Rasmussen, 2012). When considering its feasibility as a clinical test to assess knee function, the forward lunge confers the benefit of being reliable as knee joint kinetics while lunging forward demonstrated acceptable test-retest reliability (Alkjaer, Henriksen, Dyhre-Poulsen, & Simonsen, 2009).

2.8 Muscles of the Thigh

Muscles of the thigh can be split into two compartments that are antagonist to one another: an anterior compartment called the quadriceps and a posterior compartment called the hamstrings (Moore & Dalley, 2005). The quadriceps muscle group is shown in Figure 2.2 and is comprised of the rectus femoris, vastus lateralis, vastus medialis, and the vastus intermedius muscles whereas the biceps femoris, semitendinosus, and semimembranosus muscles make up the hamstrings muscle group as shown in Figure 2.3 (Moore & Dalley, 2005).
All the muscles of the quadriceps primarily extend the leg at the knee joint (Moore & Dalley, 2005). The vastus lateralis, medialis, and intermedius muscles also have a role during knee rotation (Miller, Sedory, & Croce 1997; Moore & Dalley, 2005; Reed-Jones & Vallis, 2008). Thus, any agonistic deficiencies due to the quadriceps muscle group would be observed along the sagittal and transverse anatomical planes since the quadriceps act along these planes.

**Figure 2.2.** Muscles of the quadriceps (adapted from http://www.yoganatomy.com/2014/07/quadriceps-muscles/, 2014)
All the muscles of the hamstrings muscle group primarily flex the leg at the knee joint but differ in the direction they rotate the knee; the biceps femoris externally rotates the knee where the semitendinosus and semimembranosus muscles internally rotate the knee (Moore & Dalley, 2005).

2.8.1 Hamstrings and Their Relation to the ACL and the Frontal Plane

Antagonistically, muscles of the hamstrings tend to provide knee stability along the frontal plane (Lloyd & Buchanan, 2001). Increased hamstrings use has been associated with a reduced risk of ACL injury due to the dynamic knee stability the hamstrings provide (Hughes, 2014; Lloyd & Buchanan, 2001). Greater knee instability along the frontal plane has been associated with lower hamstring to quadriceps strength ratios during dynamic movement (Hughes, 2014). Greater knee valgus angles were observed in individuals with weaker hamstrings.
when maximum vertical and anterior-posterior ground reaction forces occurred making these individuals more susceptible to an ACL injury compared to those with stronger hamstrings (Hughes, 2014; Marshall et al., 2007). The mechanism behind the greater knee valgus angles observed is suggested to be a reduced ability to dynamically control knee alignment along the frontal plane elicited by the weak hamstrings (Hughes, 2014). Based on these findings, hamstring strength training is recommended in order to decrease excessive frontal plane motion of the knee and ACL injury risk (Hughes, 2014). However, despite the benefit of dynamic stabilization, there is potentially an unwanted side effect to an increased use of the hamstrings for stabilization purposes. The downside is the possible overloading of the hamstrings resulting in increased magnitude of shear forces exerted on the tibial plateau and subsequent ACL strain and menisci damage (Finsterbrush et al., 1990; Georgoulis et al., 2005; Hughes, 2014; Marcacci et al., 2014; Whiting & Zernicke, 2008).

### 2.9 Quadriceps Avoidance

Because of the muscle groups involved and the subsequent anatomical actions that occur when these muscle groups contract, ACLR individuals lunging forward may avoid using certain muscle groups to perform the movement. ACLR individuals often practice muscle guarding or more specifically, quadriceps avoidance (Andriacchi et al., 2000; Fink et al., 2000; Hart, Pietrosimone, Hertel, & Ingersoll, 2010; Huston & Wojtys, 2000; Siegel et al., 2012).

Quadriceps avoidance is defined as the minimization of quadriceps contraction which results in a decreased knee extension moment during movements that involve the lower limb (Andriacchi et al., 2000; Fink et al., 2000; Huston & Wojtys, 2000; Patel, Hurwitz, Andriacchi, Bush-Joseph, & Bach, 1997). Quadriceps avoidance was observed in individuals with a reconstructed ACL when compared to the contralateral uninvolved and healthy control limbs and
has been suggested as a protective mechanism for ACLR individuals (Georgoulis et al., 2003; Harkey, Gribble, & Pietrosimone, 2014; Hart et al., 2010; Kuenze et al., 2015; Timoney et al., 1993). The mechanism is suggested to function by reducing the activation of the quadriceps—a muscle group that is antagonistic to the ACL—and increasing the activation of the hamstrings—a muscle group that is agonistic to the ACL—which thereby reduces the translation of the tibia in the anterior direction and rotation relative to the femur resulting in increased stability at the knee joint and a decrease in shear forces on the knee (Andriacchi et al., 2000; Branch, Hunter, & Donath, 1989; Fink et al., 2000; Huston & Wojtys, 2000; Limbird et al., 1988; Timoney et al., 1993). The activities of the antagonistic muscle groups around the thigh recorded by electromyography (EMG) corroborate the suggested mechanism. Studies that used EMG found that patients with an ACL deficiency have a reduced activation of their quadriceps muscle group and an increased activation of their hamstrings muscle group during movement (Branch et al., 1989; Fink et al., 2000; Huston & Wojtys, 2000; Limbird et al., 1988). The increased activity of the hamstrings muscle group suggests that this muscle group attempts to restore translational and rotational stability in place of the torn ACL and prevent the knee from giving-way. These findings are likely to apply to ACLR individuals as well as they attempt to regain normal motor patterns after their reconstruction procedure.

Gait patterns have been the main area of concentration in quadriceps avoidance research involving ACL-injured and ACLR individuals who have returned to full physical activity (Andriacchi et al., 2000; Berchuk et al., 1990; Fink et al., 2000; Georgoulis et al., 2003; Hart et al., 2010; Huston & Wojtys, 2000; Knoll et al., 2004; Limbird et al., 1988; Patel et al., 1997; Timoney et al., 1993). Research focused on the gait of the ACL-injured and ACLR populations along the sagittal plane demonstrated that involved knees had an increased flexion moment and a decreased extension moment when compared to the contralateral uninvolved knees and healthy control knees throughout gait (Andriacchi et al., 2000; Berchuk et al., 1990; Fink et al., 2000;
Georgoulis et al., 2003; Hart et al., 2010; Huston & Wojtys, 2000; Knoll et al., 2004; Limbird et al., 1988). Partly contrary to the majority of studies regarding the gait of ACL-injured and ACLR individuals, a study by Patel et al. (1997) found that there was a decreased flexion moment at the involved knee only during the midstance phase of gait. The gait differences found between patients who underwent a reconstruction and healthy controls are lesser than the differences found between ACL-deficient individuals and healthy controls which suggests the gradual return of the normal gait pattern after ACL reconstruction (Knoll et al., 2004; Limbird et al., 1988). The degree of quadriceps avoidance is decreased after reconstruction and subsequent rehabilitation which further suggests that reconstruction is the best recourse to treat an ACL tear (Limbird et al., 1988).

While much attention regarding quadriceps avoidance has been given to the gait of ACL-injured and ACLR individuals, very few studies focus on quadriceps avoidance during more physically demanding functional movement carried out by these populations. One study that examined functional movement showed that during maximal dynamic knee extensions, ACL-deficient participants had an increased flexion moment about the knee similar to that in quadriceps avoidance gait (Alkjaer, Simonsen, Magnusson, Dyhre-Poulsen, & Aagaard, 2012). The results suggest that the participants use a compensatory strategy to stabilize their injured knee along the sagittal plane during knee extension (Alkjaer et al., 2012).
2.9.1 The Effects of Quadriceps Avoidance

Complications that adversely affect the knee can arise due to quadriceps avoidance and decrease the probability that a patient makes a full recovery after ACL reconstruction. While reconstructing a torn ACL reduces the risk of future knee complications, practicing abnormal compensatory mechanisms such as quadriceps avoidance can negate the aforementioned risk reduction and may further increase the risk of ACLR individuals experiencing future issues in and around the involved knee (Georgoulis et al., 2005; Hart et al., 2010; Ingersoll et al., 2008; Kuenze et al., 2015; Papadonikolakis, Cooper, Stergiou, Georgoulis, & Soucacos, 2003; Stergiou, Moraiti, Giakas, Ristanis, & Georgoulis, 2004; Tsepis, Giakas, Vagenas, & Georgoulis, 2004). Individuals who exhibit quadriceps avoidance decrease anterior tibial translation but are susceptible to future disorders of or around the knee such as rotational instability while performing everyday activities, poor muscle function, muscle weakness, chronic pain, and meniscal damage and other chondral injuries (Berchuk et al., 1990; Georgoulis et al., 2005; Hart et al., 2010; Ingersoll et al., 2008; Kobayashi et al., 2004; Kuenze et al., 2015; Lee, Seong, Jo, Park, & Lee, 2004; Mankin, 1982; Orsi et al., 2015; Papadonikolakis et al., 2003; Stergiou et al., 2004; Tsepis, et al., 2004). Meniscal damage can arise from shear forces that result from movements and worsened when movements are done when instability in the knee is present (Finsterbrush et al., 1990; Georgoulis et al., 2005; Mankin, 1982; Marcacci et al., 2014; McDaniel & Dameron, 1983; Whiting & Zernicke, 2008). The consequences of mensical damage are an inability to safely absorb forces acting on the knee, possible progression to degenerative arthritis in the knee, and chronic pain (Finsterbrush et al., 1990; Ingersoll et al., 2008; Mankin, 1982; McDaniel & Dameron, 1983; Moore & Dalley, 2005; Whiting & Zernicke, 2008).

It has been documented that patients who participate in physical activity after ACL reconstruction do so using neuromuscular mechanisms that are not typical of healthy individuals (Georgoulis et al., 2005; Hart et al., 2010; Pfeifer & Banzer, 1999). Due to the more demanding
nature of physical activity compared to gait, exhibiting quadriceps avoidance during functional movements is postulated to yield more pronounced symptoms, accelerate the onset of knee disorders, and exacerbate experienced symptoms when compared to the effects brought upon by exhibiting quadriceps avoidance during gait (Andriacchi & Birac, 1993; Berchuk et al., 1990; Georgoulis et al., 2005; Hall et al., 2015; Schroeder et al., 2015). Patients who practice quadriceps avoidance attempt to prevent anterior tibial translation relative to the femur but at a cost of practicing inefficient gait and movement patterns which may be a precursor to asymmetrical imbalances that can potentially hinder physical activity performance and lead to adverse events (Georgoulis et al., 2005; Hart et al., 2010; Ingersoll et al., 2008; Papadonikolakis et al., 2003; Stergiou et al., 2004; Tsepis, et al., 2004). One way that could compromise the functionality of patients involves muscle co-contraction. The quadriceps and hamstrings muscle groups are an antagonistic muscle group pairing meaning that they provide dynamic stability to one another during contraction (Gribble, Mullin, Cothros, & Mattar, 2003). Thus in quadriceps avoidance, an individual may experience anterior-posterior and rotational knee instability during movement due to the lack of co-contraction resulting from the inactivity of the quadriceps muscle group.

2.10 Limitations of One Two-Dimensional Analysis

A single two-dimensional analysis allows for movement along only one anatomical plane to be examined; thus, the sensitivity of a two-dimensional analysis of the quadriceps avoidance biomechanics during movement along the sagittal plane is limited. A two-dimensional quadriceps avoidance analysis in the sagittal plane was typically done since the primary plane of action of the quadriceps muscle group is along the sagittal plane but a two-dimensional analysis in the sagittal plane does not comprehensively examine all the neuromuscular adaptations after an ACL
reconstruction and hence is unable to find true differences between healthy control and involved limbs (Andriacchi et al., 2000; Berchuk et al., 1990; Fink et al., 2000; Georgoulis et al., 2003; Hart et al., 2010; Huston & Wojtys, 2000; Knoll et al., 2004; Limbird et al., 1988; Moore & Dalley, 2005; Patel et al., 1997; Timoney et al., 1993). The rotational moment about the knee in ACLR patients has been found to be different than that of healthy control participants during gait and was suggested as an outcome measure along with the flexion-extension measures in future studies that investigate quadriceps avoidance during functional movement after an ACL reconstruction (Georgoulis et al., 2003). This suggestion is warranted since the quadriceps muscles have a role in rotating the knee along the transverse plane (Miller et al., 1997; Moore & Dalley, 2005; Reed-Jones & Vallis, 2008).

An analysis involving the frontal plane needs to be included due to a valgus knee being a risk factor for ACL rupture (Hughes, 2014; Marshall et al., 2007; Orsi et al., 2015). Due to their attachments to the lateral and medial aspects of the tibia, the hamstring muscles dynamically stabilize the knee along the frontal and transverse planes (Hughes, 2014; Lloyd & Buchanan, 2001). Because of the involvement of the transverse and frontal planes in addition to the sagittal plane in ACL injuries and in motion about the knee, a three-dimensional analysis rather than a two-dimensional analysis is required to evaluate the biomechanics of quadriceps avoidance in greater detail.
Chapter 3

Objectives

Currently, it remains largely unknown if altered knee joint mechanics are present in ACLR patients during the forward lunge functional movement that is prevalent in daily life and more strenuous physical activity after being cleared to resume full activity. Because of its prevalence, the forward lunge can be viewed as a reflection of the physical functional ability of individuals (Flanagan et al., 2004; Hall et al., 2015). Knowing the functional outcomes specifically whether an abnormal compensatory mechanism that may pose danger is present in ACLR individuals—when ideally and in theory there should not be—during an exercise that is commonly prescribed in physical therapy to improve muscle strength and overall physical function is warranted to optimize ACLR patient treatment and recovery. With the recommendation for clinicians to focus on functional deficiencies stemming from neuromuscular mechanisms during dynamic movements to minimize the risk of further injury (Marshall et al., 2015; Myer et al., 2006) and the knowledge regarding the consequences of partaking in full physical activity with quadriceps avoidance in mind (Kuenze et al., 2015), we saw a need for studies that investigate knee kinetics and neuromuscular mechanisms during functional movement. Many studies have focused on gait but it has been suggested that more complex functional movement likely requires more complex knee kinetics than those observed during gait in the ACLR population (Schroeder et al., 2015). It is possible that the observed kinetics and the neuromuscular mechanisms used in gait may differ to those of more complex functional movement.

Because of the role of the ACL in providing translational and rotational stability, the muscles of the thigh collectively having a role in all of the anatomical planes during movements that involve the lower extremity, and the valgus knee being a risk factor for ACL rupture, it was...
of interest to elucidate the three-dimensional kinetic characteristics of the knee during a forward lunge performed by the healthy control, ACLR, and contralateral uninvolved groups. Using an exploratory study approach, the purpose of this study was to determine whether individuals partaking in full physical activity with a reconstructed ACL demonstrated quadriceps avoidance, a known compensatory neuromuscular mechanism observed after ACL injury, during functional movement. The presence of quadriceps avoidance was quantitatively determined by computing sagittal, transverse, and frontal plane knee moments that resulted from a forward lunge. We hypothesized that there might be functional differences that would characteristically distinguish the healthy control, contralateral uninvolved, and ACLR limbs from one another in regards to the neuromuscular mechanism used to perform the functional forward lunge movement. By comparing knee moment characteristics, we hoped to make a conclusion regarding whether or not ACLR limbs were engaging in functional movement similarly to and thus had a risk of injury that was similar to limbs that have never experienced a torn ACL. Based on findings that quadriceps avoidance was observed during gait in recently operated-on individuals and during physical activity after being cleared following ACL reconstruction (Georgoulis et al., 2003; Kuenze et al., 2015; Patel et al., 1997), it was hypothesized that there would be differences between the groups in our study.
Chapter 4

Methods

4.1 Participants

A convenience sample from the student population at Queen’s University of 19 participants (13 healthy control, 6 ACLR) were recruited for this investigation. Testing took place in the Biomechanics and Ergonomics Laboratory in the School of Kinesiology and Health Studies building at Queen’s University. The study was approved by the Queen’s Research Ethics Board (Appendix A) and all participants gave written informed consent prior to testing (Appendix B).

The healthy control group consisted of 12 female and 1 male participants and the ACLR group consisted of 6 female participants. The exclusion criteria was any self-reported on-going back and lower limb issues that would prohibit the participant from performing a forward lunge at the time of testing. All participants met the criteria of not suffering from low back pain or lower limb issues other than a reconstructed ACL. Before testing, the participant’s height, weight, sex, and leg length were recorded. Leg length was defined as the distance between the greater trochanter and the ground when the participant is standing barefoot (Moore & Dalley, 2005). For ACLR patients, their operated leg was also recorded (see Appendix C for the participant information sheet). Participant characteristics are listed in Table 4.1. All participants in the ACLR group returned to full physical activity and were at least 12 months removed from their ACL reconstruction procedure.
Table 4.1. Participant characteristics (mean ± standard deviation)

<table>
<thead>
<tr>
<th>Group</th>
<th>N</th>
<th>Age (years)</th>
<th>Height (cm)</th>
<th>Mass (kg)</th>
<th>Leg length (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Healthy control</td>
<td>13</td>
<td>21 ± 1.2</td>
<td>171 ± 7.4</td>
<td>67 ± 7.8</td>
<td>95 ± 5.1</td>
</tr>
<tr>
<td>Uninvolved/ACLR</td>
<td>6</td>
<td>20 ± 1.8</td>
<td>164 ± 5.4</td>
<td>61 ± 4.2</td>
<td>91 ± 3.3</td>
</tr>
</tbody>
</table>

4.2 Instrumentation and Calibration

Motion data were collected using an 8-camera Vicon 512 motion capture system (Vicon Motion Systems, Oxford, UK) while force platform data were collected with the AMTI BP6001200-1K model (AMTI, Watertown, MA, USA) using a custom LabVIEW 8.6 data acquisition program (National Instruments, Austin, TX, USA). All data were collected at a rate of 120Hz.
Participants were barefoot and wore tight-fitting clothing for better marker visibility. To capture motion using spherical reflective markers, the marker placement setup recommended in Robertson, Caldwell, Hamill, Kamen, & Whittlesey (2004) was followed. Markers were placed bilaterally on the following anatomical landmarks: first and fifth metatarsals, heel, lateral and medial malleoli, and lateral and medial femoral condyles. Three markers were attached to Velcro straps which were wrapped around the thighs and shanks. The participant wore a belt with three markers attached to it around their waist.

After marker placement was completed, a standing calibration trial where the participant stood quietly with their arms across their chest was recorded for two seconds. After the standing calibration trial, markers on the first metatarsals, medial malleoli, and lateral and medial femoral

Figure 4.1. Experimental setup of motion capture camera system and force platform
condyles were removed. Two hip joint centre calibration trials were then collected. The participant was asked to move their leg outwards to five different positions and back and make a circular motion in the clockwise direction and the counterclockwise direction with their leg 3 times in each direction. The hip joint centre calibration procedure was repeated for the contralateral leg.

Figure 4.2. Participant with motion capture markers attached to them standing upright
4.3 Forward Lunge Directions

A forward lunge is a movement along the sagittal plane that sequentially consists of taking a step forward from an upright standing posture, flexing at the knee of the leading leg, and returning to the starting position. To start participants stood behind the force platform and were asked to perform a forward lunge onto the force platform with their arms across their chest, keeping their upper body perpendicular to the floor, keep their trailing leg in contact with the floor throughout the trial, aim to bend the knee of their leading leg until their thigh is approximately parallel to the floor (approximately a 90° knee angle) and over their toes, and then extend the knee of the leading leg to push themselves back to the starting position (Fowler Kennedy Sports Medicine Clinic, 2009). Participants performed each lunge at a self-selected speed and at a self-selected effort level as if they were doing three sets of ten repetitions with a rest period in between sets (Noyes Knee Institute, 2011); the groups did not differ in the time taken to complete one forward lunge and in the time spent during any phase (Appendix E). The step length of the lunge—measured from the big toe of the trailing leg to the heel of the leading leg (Escamilla et al., 2010)—was 85% of the participant’s leg length since it was determined to be the step length that resulted in reproducible knee moments during a forward lunge (Schütz, List, Zemp, & Lorenzetti, 2012) and pilot testing showed that participants were comfortable with that length. The step length was marked on the force platform by a strip of masking tape. When given the verbal cue to start the forward lunge, participants lunged forward onto the force platform using the aforementioned technique. Ten trials were recorded for each leg. For the first trial, participants led with the leg randomly selected by the experimenter with legs alternating each trial.
4.4 Data Analysis

All motion capture and force platform data were processed using custom MATLAB (The MathWorks, Inc., Natick, MA, USA) programs. All collected data were low-pass filtered by a second order zero-lag Butterworth filter with a cutoff frequency of 6 Hz. This was based on the method used in the study by Alkjaer et al. (2009). A custom MATLAB program calculated the knee moments using a three-dimensional inverse dynamics approach during each lunge phase using the inverse dynamics computation methods described by Robertson et al. (2004) (see Appendix D). When calculating the moments about the knee in three dimensions, anthropometric data from de Leva (1996) were used to compute lower limb segment parameters that would be used in inverse dynamics computations. Knee moments were normalized to the body mass of the participant to make comparisons among participants fair and valid. Moment profiles of the knee
along the sagittal, transverse, and frontal planes were calculated for each participant and averaged within each group.

Based on the results of Patel et al. (1997) where it was found that quadriceps avoidance was exhibited during the mid-stance phase of gait rather than throughout the gait cycle and the findings of Andriacchi and Birac (1993) and Georgoulis et al. (2005) where they indicated that knees that have sustained an ACL injury internally rotate during the swing phase of gait, it was of interest to see if quadriceps avoidance, like gait, was exhibited during a particular phase(s) of the forward lunge. Knees internally rotating during the swing phase of gait suggest that the quadriceps muscle group may have been inactive and unable to counter the semitendinosus and/or semimembranosus hamstring muscles that likely internally rotated the knee (Moore & Dalley, 2005). The inactivity implies that quadriceps avoidance was possibly exhibited during this phase. If the quadriceps were active, it would likely counteract the hamstring muscles and prevent the knee from internally rotating during the swing phase of gait.

The forward lunge was divided into four phases: 1) initial phase – duration from when the sagittal plane velocity of the heel marker of the leading leg exceeded 0.01 m/s to the point when the force in the vertical z-direction exceeded a force platform threshold of 0.015 V by the leading leg swinging from rest and making contact with the force platform 2) stance down phase – duration from when the force in the z-direction exceeded a threshold of 0.015 V via contact with the force platform to when the knee of the leading leg reaches its maximum flexion as indicated by the sagittal knee angle; sagittal knee angle was calculated using the knee joint angle computation methods described in Vaughan, Davis, and O’Connor (1999) 3) stance up phase – duration from when maximum knee flexion is achieved as indicated by the sagittal knee angle to when the force in the z-direction fell below the threshold of 0.015 V by ceasing contact with the force platform 4) return phase – duration from when the force in the z-direction fell below the force platform threshold of 0.015 V to when the sagittal plane velocity of the heel marker of the
leading leg fell below 0.01 m/s as a result of the participant swing their leading leg and returning to quiet standing. The threshold values of 0.01 m/s and 0.015 V were chosen after inspecting each trial and concluding that random noise recorded by the instrumentation used during quiet standing did not exceed these specified threshold values.

In order to be able to extract desired information from trial data and thus be deemed acceptable for analysis, marker and force platform data needed to graphically resemble a quadratic function. Trials that had data that did not graphically resemble a quadratic function were discarded as they primarily contained invalid data in the form of random noise; valid values of desired parameters could not be obtained from these trials during data analysis.

Ten trials per leg were recorded for each participant but measures were taken to process and analyze data that were acceptable for analysis. For each trial, peak knee moments were obtained by extracting the greatest and smallest knee moments that each participant experienced in a given phase in all three anatomical planes. Mean peak knee moments were calculated for each lunge phase from the trials of each participant. The peak knee moment means of each participant was categorized accordingly to the applicable group. A group dataset of mean peak knee moment values was created with each participant contributing one value. Statistical analysis was conducted with the group datasets. The average number of trials that were taken into account for each group during analysis is shown in Appendix E.

4.5 Statistical Analysis

Statistical analysis was performed using SPSS software (IBM Corporation, Armonk, NY, USA). The objective of the statistical analysis was to compare the peak moment about the knee along the sagittal, transverse, and frontal planes for each lunge phase of healthy control limbs, contralateral uninvolved limbs, and ACLR limbs using a one-way analysis of variance.
(ANOVA). The same type of trials of each participant was averaged and each participant contributed one score to the results of the applicable experimental group.

Because there is no absolute knee moment value that indicates the presence of quadriceps avoidance, whether or not quadriceps avoidance was exhibited can only be deduced relatively. The presence of quadriceps avoidance in ACLR limbs can only be concluded by comparing the knee moment characteristics of the ACLR group to those of the healthy control and contralateral uninvolved groups.

ACLR limbs are considered to be of a different population than healthy control or uninvolved limbs since they have undergone an ACL reconstruction procedure whereas healthy control and contralateral uninvolved limbs have not. Peak values were compared because they indicated the greatest moment magnitudes that were experienced during the forward lunge. Peak values give beneficial insight into possible compensatory mechanisms that are used by ACLR patients and thus were compared between groups (Reed-Jones & Vallis, 2008). Any outcome measure that was found to be significant by a one-way ANOVA was subject to a Bonferroni post-hoc correction in order to identify which groups’ mean values of said outcome measure differed.

The Bonferroni post-hoc correction was selected as the procedure to be conducted because it is considered to be conservative (Field, 2009). Statistical power is lost with the Bonferroni correction but more control of the Type I error (i.e. false positive) rate is exerted and as a result, the chance of committing a Type I error is reduced (Field, 2009).

The experimental groups were compared to see if any of them exhibited quadriceps avoidance relative to one another. The presence of quadriceps avoidance can only be concluded via a comparison to another group. Thus for a group to have exhibited quadriceps avoidance, differences in peak knee moment along the sagittal, transverse, and/or frontal planes would have been observed during any of the phases when compared to another group.
4.6 Sample Size Calculation

Sample size for the healthy control, uninvolved, and ACLR groups were determined by an a priori analysis using G*Power 3.1.5 software (Heinrich-Heine-Universität, Kiel, Germany). Using the results from Noehren, Wilson, Miller, and Lattermann (2013), who compared the knee moment during gait between healthy controls and ACLR patients, the a priori analysis resulted in a sample size of 5 for each group. 13 healthy control and 6 ACLR participants that met the inclusion criteria were able to be recruited from the Queen’s University student population.
Chapter 5

Results

5.1 Comparison between Examined Knees

This study investigated the functional outcomes of limbs of people with a surgically repaired ACL (involved) who have been cleared and have returned to full physical activity by comparing their quadriceps avoidance characteristics to the limb opposite to the repaired knee that has never experienced an ACL tear (uninvolved) and to limbs of people who have never experienced an ACL tear (healthy control). Quadriceps avoidance characteristics were characterized by examining the differences in the peak moments about the knee along the sagittal, transverse, and frontal anatomical planes. Group means were compared to determine if differences existed among the three types of limbs that were examined. Results are shown in Tables 5.1, 5.2, and 5.3. Significance was set at $p < 0.05$. 

Table 5.1. Group mean and standard deviation values for peak sagittal knee moment magnitudes of experimental groups during each defined forward lunge phase. Moment units: Nm/kg

<table>
<thead>
<tr>
<th></th>
<th>Healthy control</th>
<th>Uninvolved</th>
<th>ACLR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial phase</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>flexion moment</td>
<td>0.24 ± 0.12</td>
<td>0.17 ± 0.12</td>
<td>0.15 ± 0.029</td>
</tr>
<tr>
<td>extension moment</td>
<td>-0.25 ± 0.37</td>
<td>-0.17 ± 0.21</td>
<td>-0.12 ± 0.048</td>
</tr>
<tr>
<td>Stance down phase</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>flexion moment</td>
<td>1.20 ± 0.38</td>
<td>1.04 ± 0.083</td>
<td>1.16 ± 0.37</td>
</tr>
<tr>
<td>extension moment</td>
<td>-0.34 ± 0.17</td>
<td>-0.26 ± 0.13</td>
<td>-0.28 ± 0.10</td>
</tr>
<tr>
<td>Stance up phase</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>flexion moment</td>
<td>1.00 ± 0.32</td>
<td>0.75 ± 0.20</td>
<td>0.82 ± 0.20</td>
</tr>
<tr>
<td>extension moment</td>
<td>-0.55 ± 0.14</td>
<td>-0.64 ± 0.61</td>
<td>-0.40 ± 0.15</td>
</tr>
<tr>
<td>Return phase</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>flexion moment</td>
<td>0.23 ± 0.21</td>
<td>0.15 ± 0.040</td>
<td>0.16 ± 0.034</td>
</tr>
<tr>
<td>extension moment</td>
<td>-0.20 ± 0.11</td>
<td>-0.12 ± 0.027</td>
<td>-0.14 ± 0.050</td>
</tr>
</tbody>
</table>
**Table 5.2.** Group mean and standard deviation values for peak transverse knee moment magnitudes of experimental groups during each defined forward lunge phase. Moment units: Nm/kg

<table>
<thead>
<tr>
<th>Phase</th>
<th>Healthy control</th>
<th>Uninvolved</th>
<th>ACLR</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Initial phase</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Internal rotation</td>
<td>0.078 ± 0.037</td>
<td>0.085 ± 0.090</td>
<td>0.067 ± 0.028</td>
</tr>
<tr>
<td>External rotation</td>
<td>-0.055 ± 0.026</td>
<td>-0.059 ± 0.064</td>
<td>-0.048 ± 0.036</td>
</tr>
<tr>
<td></td>
<td>Stance down phase</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Internal rotation</td>
<td>0.30 ± 0.14</td>
<td>0.36 ± 0.16</td>
<td>0.23 ± 0.067</td>
</tr>
<tr>
<td>External rotation</td>
<td>-0.091 ± 0.10</td>
<td>-0.072 ± 0.066</td>
<td>-0.13 ± 0.18</td>
</tr>
<tr>
<td></td>
<td>Stance up phase</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Internal rotation</td>
<td>0.20 ± 0.098</td>
<td>0.25 ± 0.099</td>
<td>0.17 ± 0.066</td>
</tr>
<tr>
<td>External rotation</td>
<td>-0.48 ± 0.14</td>
<td>-0.32 ± 0.29</td>
<td>-0.33 ± 0.30</td>
</tr>
<tr>
<td></td>
<td>Return phase</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Internal rotation</td>
<td>0.068 ± 0.029</td>
<td>0.049 ± 0.011</td>
<td>0.065 ± 0.037</td>
</tr>
<tr>
<td>External rotation</td>
<td>-0.058 ± 0.026</td>
<td>-0.033 ± 0.013</td>
<td>-0.047 ± 0.025</td>
</tr>
</tbody>
</table>
Table 5.3. Group mean and standard deviation values for peak frontal knee moment magnitudes of experimental groups during each defined forward lunge phase. Moment units: Nm/kg

<table>
<thead>
<tr>
<th>Phase</th>
<th>Healthy control</th>
<th>Uninvolved</th>
<th>ACLR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial phase</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Valgus moment</td>
<td>0.11 ± 0.081</td>
<td>0.10 ± 0.11</td>
<td>0.065 ± 0.038</td>
</tr>
<tr>
<td>Varus moment</td>
<td>-0.19 ± 0.27</td>
<td>-0.13 ± 0.15</td>
<td>-0.097 ± 0.040</td>
</tr>
<tr>
<td>Stance down phase</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Valgus moment</td>
<td>0.65 ± 0.34</td>
<td>0.52 ± 0.42</td>
<td>0.47 ± 0.31</td>
</tr>
<tr>
<td>Varus moment</td>
<td>-0.46 ± 0.18</td>
<td>-0.29 ± 0.38</td>
<td>-0.37 ± 0.43</td>
</tr>
<tr>
<td>Stance up phase</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Valgus moment</td>
<td>0.53 ± 0.24</td>
<td>0.41 ± 0.34</td>
<td>0.39 ± 0.26</td>
</tr>
<tr>
<td>Varus moment</td>
<td>-0.48 ± 0.14</td>
<td>-0.32 ± 0.29</td>
<td>-0.33 ± 0.30</td>
</tr>
<tr>
<td>Return phase</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Valgus moment</td>
<td>0.12 ± 0.085</td>
<td>0.062 ± 0.028</td>
<td>0.064 ± 0.030</td>
</tr>
<tr>
<td>Varus moment</td>
<td>-0.11 ± 0.047</td>
<td>-0.076 ± 0.012</td>
<td>-0.10 ± 0.041</td>
</tr>
</tbody>
</table>

5.1.1 Differences between Values Obtained from Figures and Values Reported in Tables

There are differences in the peak values obtained from Figures 5.1 to 5.3 (pages 39-41) with the values reported in Tables 5.1 to 5.3 because each considers a different set of values. The figures represent ensemble averages of each experimental group where an average was computed with the value of each participant of a specified group at a particular time point. Hence, at a particular time point, a peak or non-peak value may have occurred depending on the participant but all were considered for that particular time point and an average was computed with these.
values. This method would be applied to other time points to generate a curve for the outcome measure of interest. The values reported in Tables 5.1 to 5.3 considered the peak value of each participant regardless of when it occurred; the values reported in Tables 5.1 to 5.3 were computed solely using the peak value of each participant. Because ensemble averaging considered non-peak values that occur at a particular time rather than only peak values that occur regardless of time, the peak values obtained from Figures 5.1 to 5.3 are smaller than the values reported in Tables 5.1 to 5.3.

Ensemble averaged knee moment curves along each examined anatomical plane were produced for each group and are presented below in Figures 5.1, 5.2, and 5.3. Positive moment values represent flexion, knee valgus, and internal rotation along the sagittal, frontal, and transverse planes respectively. Negative moment values represent extension, knee varus, and external rotation along the sagittal, frontal, and transverse planes respectively.

The phases of the healthy control, uninvolved, and ACLR groups are denoted by solid, dashed, and dotted vertical lines respectively. Inspecting left to right figures 5.1, 5.2, and 5.3, the phases of movement are denoted as such:

Initial phase: start of movement (0% lunge cycle) to first vertical line

Stance down phase: first vertical line to second vertical line

Stance up phase: second vertical line to third vertical line

Return phase: third vertical line to end of movement (100% lunge cycle)
Figure 5.1. Sagittal moment profiles of healthy control, uninvolved, and ACLR knees.
Figure 5.2. Transverse moment profiles of healthy control, uninvolved, and ACLR knees
Figure 5.3. Frontal moment profiles of healthy control, uninvolved, and ACLR knee
Chapter 6
Discussion

6.1 General Discussion

This study examined the quadriceps avoidance characteristics during the forward lunge functional movement by analyzing it along the sagittal, transverse, and frontal anatomical planes. The objective of this study was to determine whether there were differences in the computed knee moment outcome measures between the experimental groups. The results showed that there was no difference in the peak knee moment along any of the examined anatomical planes during the forward lunge meaning that the knee flexion-extension, rotation, and valgus-varus moments did not differ between healthy control, uninvolved, and ACLR limbs. These findings suggest that healthy control, uninvolved, and ACLR limbs are not different from each other. Therefore, we conclude that ACLR limbs do not exhibit quadriceps avoidance or any other potential mechanisms that would limit the ability to generate a moment about the knee using the quadriceps muscle group along the three examined anatomical planes during a forward lunge. Based on the moment results, it is likely that individuals with an ACLR knee that have been cleared to return to physical activity do not experience anterior tibial translation or rotational instability symptoms due to quadriceps avoidance. Therefore, healthy control, uninvolved, and ACLR limbs are similarly at risk for complications that may result from quadriceps avoidance.

The presence of quadriceps avoidance in gait in the ACLR population has been well-established in literature (Berchuck et al., 1990; Branch et al., 1989; Fink et al., 2000; Georgoulis et al., 2003; Huston & Wojtys, 2000; Patel et al., 1997). The results of our study show no indication of quadriceps avoidance exhibition during a lunge in ACLR limbs as there were no differences in sagittal knee moment. This difference in observations could be due gait and the
forward lunge having differing physical demands on ACLR individuals resulting in differing physical responses. The forward lunge entails the recruitment of the muscles of quadriceps to a greater degree than gait to stabilize the knee and eventually extend the knee from an angle that is deeper than what is typically achieved during gait. Thus, in order to perform a forward lunge, the quadriceps muscle group must be involved. If the quadriceps is not involved and quadriceps avoidance is exhibited, it would likely make it difficult for an individual to perform a forward lunge. Furthermore, quadriceps avoidance is not observed likely due to the participants being sufficiently recovered from their surgery. A study that observed quadriceps avoidance in gait examined participants who have been post-operative for a short time period and thus not cleared to return to full physical activity (Berkhuk et al., 1990). The difference in post-operative time of study participants and the fact that the participants of this study have returned to full physical activity may account for the differences in observations related to quadriceps avoidance.

When quantifying quadriceps avoidance through a knee moment outcome measure, a reduced extension moment through decreased quadriceps activity and/or an increased flexion moment through increased hamstrings activity can lead to the conclusion that a population exhibits quadriceps avoidance relative to another population. This was the reasoning behind comparing peak knee flexion and extension moments between groups. For example, during any movements that involve knee flexion and extension, it could be that an ACLR group exhibits a greater flexion moment and a reduced extension moment as seen in previous gait studies (Andriacchi et al., 2000; Berkhuk et al., 1990; Fink et al., 2000; Georgoulis et al., 2003; Hart, Pietrosimone, Hertel, & Ingersoll, 2010; Huston & Wojtys, 2000; Knoll et al., 2004; Limbird et al., 1988) or either a greater net flexion moment or a reduced net extension moment about the knee. To conclude that quadriceps avoidance is present in a population of interest, a greater net flexion moment or a reduced net extension moment must exist. This conclusion would mean that the quadriceps muscle group of the given population is not being used to generate an extension
moment about the knee to a degree that yields a similar net moment about the knee when compared to that of another population. A study that uses EMG is recommended for a future study to elucidate the mechanisms that bring about the observed quadriceps avoidance characteristics during the forward lunge.

The lack of quadriceps avoidance observations of this study where participants lunge forward and the presence of quadriceps avoidance reported in studies investigating gait may be explained by one of two possibilities: 1) independent of physical condition, quadriceps avoidance is not exhibited during a forward lunge due to the quadriceps avoidance-free neuromuscular mechanism involved in the forward lunge that is likely typical of healthy individuals being immediately restored by ACL reconstruction 2) individuals with a recently reconstructed ACL show signs of quadriceps avoidance during a forward lunge but with surgical reconstruction and over time physical therapy regain the quadriceps avoidance-free neuromuscular mechanism that is likely to be observed in the healthy population. The latter has been observed in studies where it was concluded that over time, quadriceps avoidance-free gait returns after completing physical therapy programs (Georgoulis et al., 2005). A cutoff time of approximately six to eight months after surgery was suggested as the point where normal gait returns to ACLR individuals (Georgoulis et al., 2005; Knoll et al., 2004).

It is of interest to note that our findings show that ACLR knees resemble healthy control and uninvolved knees which is likely attributable to rehabilitation progress made by patients over time. Previous studies have shown that flexion-extension, varus-valgus, and knee rotation differences occur between ACL injured knees and healthy knees and that the contralateral uninvolved and healthy knees are similar to one another when considering moment outcome measures (Alkjaer et al., 2002; Andriacchi & Birac, 1993; Georgoulis et al., 2005; Karrholm, Brandsson, & Freeman, 2000; Lafortune, Cavanagh, Sommer, & Kalenak, 1992; Mandeville, Osternig, Lantz, Mohler, & Chou, 2008; Zhang, Shiavi, Limbird, & Minorik, 2003). The
differences in sagittal knee moment that were observed in previous studies that focused on movement post-ACL reconstruction were ascribed to the hamstrings muscle group in an ACL injured limb having a limited ability to dynamically stabilize the knee during movements such as the forward lunge that entail eccentric quadriceps contractions controlling rapid knee flexion; as a result, knee angular acceleration was greater in ACL injured limbs compared to healthy limbs which in turn, led to an increased knee flexion moment and the subsequent observed differences in the knee moment between healthy and injured limbs (Alkjaer et al., 2002; Rudolph, Axe, & Snyder-Mackler, 2000).

The most relatable research to our study regarding frontal plane knee kinetics during functional movement is a study that investigated post-operative total knee replacement (TKR) patients during stair ascent (Mandeville, Osternig, Lantz, Mohler, & Chou, 2008). TKR patients during stair ascent, which like the forward lunge involves an initial limb swing, the limb coming down to make contact with a surface, and pushing off the leading limb, was found to have a smaller varus moment about the knee compared to control participants (Mandeville et al., 2008). This finding differs from our frontal plane knee moment finding where no differences existed among investigated groups. Based on the results of Mandeville et al. (2008), the movement component similarities of the forward lunge between stair ascent, and the role of the valgus knee as a risk factor for ACL injury knee, the presence of differences in frontal plane knee moment akin to those of Mandeville et al. (2008) were seen as possible. However, no differences were found in our study likely due to the sufficient recovery the ACLR group has made and/or due to the forward lunge and stair ascent potentially eliciting different frontal plane knee kinetics during movement. It could also be plausible that an ACL reconstruction and TKR procedures influence frontal plane knee kinetics in different ways even though ACL reconstruction and TKR both involve tibio-femoral complex of the knee (Mandeville et al., 2008). Knee procedures that involve the tibio-femoral complex are suggested to affect the frontal plane kinetics of the knee.
Why the frontal plane knee moment is affected is unclear but the findings of Schipplein and Andriacchi (1991) suggest that the medial aspect of the knee bears most of the load. Asymmetrical load bearing along the frontal plane can be a precursor to degenerative changes in the knee (Berchuk et al., 1990; Georgoulis et al., 2005; Hall et al., 2015; Hart et al., 2010; Ingersoll et al., 2008; Mankin, 1982; Orsi, et al., 2015; Schipplein & Andriacchi, 1991).

With regard to knee rotation differences, ACL injured knees are said to exhibit greater external rotation moments than healthy knees to compensate for an unstable knee (Georgoulis et al., 2005; Zhang et al., 2003). The loss of the ACL means that a mechanical restraint that secondarily serves to limit internal knee rotation is lost and must be compensated by externally rotating the knee to reduce instability (Whiting & Zernicke, 2008). Zhang et al. (2003) found the gait of ACL injured patients to externally rotate the involved knee more than healthy individuals. However, there have been studies that found ACL injured knees internally rotate throughout the gait cycle and during the swing phase of gait (Andriacchi & Birac, 1993; Georgoulis et al., 2005).

Similar to our study, no differences in knee rotation moments were found when examining knees that underwent an ACL reconstruction and healthy knees during gait (Georgoulis et al., 2005). Contrary to the outcomes from low-demanding activities such as gait, internal knee rotation was observed during high-demanding activities such as cutting and jogging (Branch et al., 1989; Georgoulis et al., 2005; Kanamori et al., 2000; Loh et al., 2003; Schroeder et al., 2015; Woo et al., 2002). These findings are corroborated by the suggestion that unlike high-demanding activities, during low-demanding activities, ACLR knees do not show any signs of rotational abnormality (Andriacchi & Birac, 1993; Georgoulis et al., 2005; Schroeder et al., 2015). The lack of abnormality was attributed to surgical reconstruction restoring normal knee functionality and preventing rotational instability and subsequent knee complications (Georgoulis et al., 2005). Based on similar findings from our study when comparing healthy and ACLR knees
to those from investigating gait, we suggest that normal knee functionality during gait and more physically demanding movements such as a forward lunge is also restored by current reconstruction and physical therapy methods.

6.2 Limitations and Future Research

Limitations that should be acknowledged were present in this study. The main limitation is the inadequate statistical power of this study. This study did not achieve adequate statistical power to detect differences between examined groups due to the sample size that was used (see Appendix F for post-hoc power analysis results). Thus, any conclusions made based on the results of this study should be considered tentative due to the small sample size. An adequate sample size would have yielded acceptable statistical power and subsequently may have resulted in differences being observed among the outcome measures.

This study only examined the knee moment kinetics of the knee during a forward lunge. The main issue with joint moments is that they only reflect the net effect of the activity at a particular joint (Alkjaer et al., 2002; Robertson et al., 2004). A knee moment is determined by knee flexor and extensor activation (Rousanoglou, Herzog, & Boudolos, 2010). Reflecting only the net effect at a joint means that muscle co-contraction which commonly occurs as a dynamic stabilizing mechanism, is hidden and the degree of agonistic and antagonistic muscle contractions about a joint is unknown (Gribble et al., 2003). Recording EMG activity of the muscles about the knee in future research is recommended in an effort to supplement future kinetic data. This method has the potential to wholesomely examine functional movement and enable a more in-depth understanding of functional movement.

The performance characteristics of the forward lunge can be limitations as well. Participants performed the lunge at a self-selected speed which may have influenced segment
accelerations and in turn, eventually affect force measurements and joint kinetics. A greater absolute movement speed would likely result in a larger force measurements and joint moments due to the greater segment accelerations required to achieve such a movement speed starting from rest. Participants likely varied in the speed in which they performed the forward lunge; this may have influenced knee moment results.

We hypothesize that the daily activity level of participants may have influenced the ability of participants to do a forward lunge and subsequently affected knee moment results. Some participants may not have been active enough to optimally perform the forward lunge while others may have been so. Since all our ACLR participants have returned to full physical activity, the ACLR findings of this study may not be reflective of the greater ACLR population as the participants of this study were at least 12 months removed from their reconstruction procedure and likely have the ability to perform a forward lunge. However, previous research has found that movement time and overall physical function as indicated by movement and reaction times indicate that individuals who were classified to be physically active on a regular basis are superior to individuals who were classified as physically inactive (Spirduso, 1975). It is possible that the activity level of participants influenced the manner in which participants performed the forward lunge which subsequently may have affected results. Not accounting for the activity level of participants decreased the experimental control and may limit the results of this study.

Examining whether exhibiting quadriceps avoidance during a forward lunge increases the risk of future ACL injuries may be of benefit. A longitudinal study where the functional ability of post-reconstruction patients is tracked throughout their physical rehabilitation and after they have been cleared to return to full physical activity can be examined. The profile outlining the regression of quadriceps avoidance throughout recovery may provide insight into the characteristics of a limb that successfully recovers and never experiences a subsequent injury to the reconstructed ACL and of a limb that suffers a re-tear of the ACL. These results may allow
clinicians to identify through a functional test whether a patient is at risk for re-injury and take proactive measures to minimize the risk of future ACL injuries.

Based on the absence of quadriceps avoidance when investigating gait and now the forward lunge and the presence of quadriceps avoidance that was observed during jogging and cutting, we postulate that the forward lunge is a functional movement that is more physically demanding than gait but not as demanding as jogging or cutting (Andriacchi & Birac, 1993; Berchuk et al., 1990; Branch et al., 1989; Georgoulis et al., 2005; Kanamori et al., 2000; Loh et al., 2003; Woo et al., 2002). Collectively, these findings suggest that protective mechanisms are demonstrated in certain movements because these movements are physically demanding. Therefore, future studies can examine quadriceps avoidance characteristics during movements such as jogging or cutting for the benefit of indicating whether such an abnormal compensatory mechanism that can have detrimental effects is exhibited by ACLR patients during high-demanding, physically strenuous movements which ACLR patients execute after being allowed to return to full physical activity. These studies may illustrate the need for surgical reconstruction, physical therapy, and assessment methods to be improved in order to withstand the rigors of physically strenuous and demanding activities.

To minimize quadriceps avoidance characteristics and its effects after ACL reconstruction, treatment methods should focus on limiting intra-articular knee joint effusion because knee joint effusion has been suggested be a cause of quadriceps avoidance (Torry, Decker, Viola, O’Connor, & Steadman, 2000). Knee joint effusion is the swelling of the knee due to a collection of fluid around the knee and can cause discomfort of the knee (Torry et al., 2000). Knee joint effusion has been observed in ACLR individuals and has been found to be causative factor of quadriceps avoidance (Torry et al., 2000; Yamamoto, Ishibashi, Muneta, Furuya, & Mizuta, 1992). Thus, knee effusion may induce quadriceps avoidance that is observed in ACLR individuals (Torry et al., 2000). Torry et al. (2000) compared the gait kinetics of healthy
individuals before and after undergoing intra-articular saline injections of the knee joint and found that the participants exhibited a quadriceps avoidance gait after the injections compared to the gait patterns before saline injections were administered. Knee joint effusion being a cause of quadriceps avoidance demonstrates a need to develop techniques that are effective in treating effusion in the ACL-injured population. Such techniques to limit knee joint effusion have the potential to help prevent quadriceps avoidance in ACLR patients and should be undertaken in effort to minimize the practice of quadriceps avoidance and maximize functional ability.

The feasibility of the forward lunge as an acceptable clinical tool to objectively determine if post-operative patients are ready to return to full physical activity should be investigated. To confirm that the forward lunge as a FPT that is used to assess patients is sensitive to rehabilitation progression, a study that measures and compares an outcome measure such as the moment about the knee between individuals who have recently undergone ACL reconstruction procedure but have not been cleared to return to full physical activity and individuals who have no history of ACL injuries should be conducted. Knees with a recently reconstructed ACL likely have not sufficiently recovered and likely would not demonstrate the same degree of function a healthy knee would demonstrate. In this scenario, if the forward lunge is sensitive in distinguishing healthy and ACLR knees as indicated by differences in kinetic outcome measures between examined groups, the forward lunge may be feasible and thus be developed into a test for clinicians to use in order to objectively assess the functional ability of ACLR patients in a safer manner when compared to the single-leg hop for maximum distance test. If no differences are found in this suggested future study, we can conclude that the forward lunge as a FPT is not sensitive enough to detect differences in quadriceps avoidance between healthy and ACLR knees and thus cannot be used as an objective assessment test to determine if an ACLR patient can be cleared to return to restriction-free physical activity.
References


Appendix A

Ethics Approval
QUEEN'S UNIVERSITY HEALTH SCIENCES & AFFILIATED TEACHING HOSPITALS RESEARCH ETHICS BOARD-DELEGATED REVIEW
December 06, 2012

Mr. Marchiano Oh
School of Kinesiology & Health Studies
Queen’s University

Dear Mr. Oh

Study Title: PHE-129-12 Assessing the Functional Ability of Patients after Anterior Cruciate Ligament (ACL) Surgery

File # 6007430

Co-Investigators:  Dr. D. Bardana, Dr. P. Costigan

I am writing to acknowledge receipt of your recent ethics submission. We have examined the protocol, Psychology questionnaire, participant release of questionnaire data form and the information/consent form for your project (as stated above) and consider it to be ethically acceptable. This approval is valid for one year from the date of the Chair’s signature below. This approval will be reported to the Research Ethics Board. Please attend carefully to the following listing of ethics requirements you must fulfill over the course of your study:

Reporting of Amendments: If there are any changes to your study (e.g. consent, protocol, study procedures, etc.), you must submit an amendment to the Research Ethics Board for approval. Please use event form: HSREB Multi- Use Amendment/Full Board Renewal Form associated with your post review file # 6007430 in your Researcher Portal (https://eservices.queensu.ca/romeo_researcher/)

Reporting of Serious Adverse Events: Any unexpected serious adverse event occurring locally must be reported within 2 working days or earlier if required by the study sponsor. All other serious adverse events must be reported within 15 days after becoming aware of the information. Serious Adverse Event forms are located with your post- review file 6007430 in your Researcher Portal (https://eservices.queensu.ca/romeo_researcher/)

Reporting of Complaints: Any complaints made by participants or persons acting on behalf of participants must be reported to the Research Ethics Board within 7 days of becoming aware of the complaint. Note: All documents supplied to participants must have the contact information for the Research Ethics Board.

Annual Renewal: Prior to the expiration of your approval (which is one year from the date of the Chair's signature below), you will be reminded to submit your renewal form along with any new changes or amendments you wish to make to your study. If there have been no major changes to your protocol, your approval may be renewed for another year.

Yours sincerely,

Arthur J. Clark

Chair, Research Ethics Board
December 06, 2012
Investigators please note that if your trial is registered by the sponsor, you must take responsibility to ensure that the registration information is accurate and complete.
The membership of this Research Ethics Board complies with the membership requirements for Research Ethics Boards and operates in compliance with the Tri-Council Policy Statement; Part C Division 5 of the Food and Drug Regulations, OHRP, and U.S DHHS Code of Federal Regulations Title 45, Part 46 and carries out its functions in a manner consistent with Good Clinical Practices.
Federalwide Assurance Number: #FWA00004184, #IRB00001173

Current 2012 membership of the Queen's University Health Sciences & Affiliated Teaching Hospitals Research Ethics Board:

Dr. A.F. Clark, Emeritus Professor, Department of Biochemistry, Faculty of Health Sciences, Queen's University (Chair)

Dr. H. Abdollah, Professor, Department of Medicine, Queen's University

Dr. R. Brison, Professor, Department of Emergency Medicine, Queen's University

Dr. C. Cline, Assistant Professor, Department of Medicine, Director, Office of Bioethics, Queen's University, Clinical Ethicist, Kingston General Hospital

Dr. M. Evans, Community Member

Dr. S. Horgan, Manager, Program Evaluation & Health Services Development, Geriatric Psychiatry Service, Providence Care, Mental Health Services, Assistant Professor, Department of Psychiatry

Ms. J. Hudacin, Community Member

Dr. B. Kisilevsky, Professor, School of Nursing, Departments of Psychology and Obstetrics and Gynaecology, Queen's University

Dr. J. MacKenzie, Pediatric Geneticist, Department of Paediatrics, Queen's University

Mr. D. McNaughton, Community Member

Ms. P. Newman, Pharmacist, Clinical Care Specialist and Clinical Lead, Quality and Safety, Pharmacy Services, Kingston General Hospital

Ms. S. Rohland, Privacy Officer, ICES-Queen's Health Services Research Facility, Research Associate, Division of Cancer Care and Epidemiology, Queen's Cancer Research Institute

Dr. B. Simchison, Assistant Professor, Department of Anesthesiology and Perioperative Medicine, Queen's University

Dr. J. Tang, Medical Resident, Department of Emergency Medicine, Queen's University

Ms. K. Weisbaum, LL.B. and Adjunct Instructor, Department of Family Medicine (Bioethics)
Appendix B

Letter of Information and Consent Form
Introduction to Study and Ethics Consent Form

Assessing the Functional Ability of Patients after Anterior Cruciate Ligament (ACL) Surgery

This letter is an invitation to participate in a research study aimed at developing improved procedures for the assessment of musculoskeletal disorders. The goal is to improve clinical assessment methods for patients who have suffered an anterior cruciate ligament (ACL) rupture and undergone an ACL reconstruction surgery. The goal is to help surgeons identify when it is safe for ACL injured patients to return to full activity.

Before you decide whether you would like to participate in this study, please familiarize yourself with the research procedures below and with any potential risks and benefits. Please keep this letter for future reference. If you would like to obtain more details about this study, please do not hesitate to contact me at your earliest convenience.

Study Description

The main objective is to develop a battery of functional tests for the assessment of muscle and knee function following an anterior cruciate ligament (ACL) surgery. The equipment that will be used are force platforms, motion capture systems, and an angle measuring device that will examine the functional abilities of your knees.

Males and females with and without an ACL injury are being invited to participate in this study. Testing will take place either at the Human Motion Performance Laboratory, Hotel Dieu Hospital or at the Biomechanics and Ergonomics Laboratory, School of Kinesiology and Health Studies building, Queen’s University, Kingston, Ontario. This study has been reviewed for ethical compliance by the Queen’s University Health Sciences and Affiliated Teaching Hospitals Research Ethics Board.

Study Procedures

You will be asked to wear shorts for all testing sessions. Before physical testing begins, you will have the test procedures and instructions explained to you and your height, weight, and dominant leg will be recorded. Before, during and after the testing session, your questions will be happily answered.

The protocol of the forward lunge physical test is outlined in detail below.
Forward Lunge:

Before the forward lunge test, spherical markers for motion capture will be attached to you using double-sided tape. Markers will be attached to your ankles and knees. Also, marker triads will be strapped around your thighs, lower legs, and around your waist using Velcro straps.

You will be asked to perform a forward lunge with your upper body upright and to the best of your ability without compromising comfort. You will be leading with a randomly selected leg onto a force plate embedded in the floor. This procedure will alternate between legs and will be repeated until 5 repetitions for each leg has been completed. You will be allowed to have 2 practice repetitions before testing begins to familiarize yourself with the protocol.

Risks of Participation:

Please read this section carefully and consider all of the risks before deciding to participate in this study. This study involves performing exercises that require muscular effort and motor control. Although improbable, this could potentially result in an injury or a re-injury following your operation. To ensure maximal safety during testing, we would like you to let us know if you feel any discomfort or fear of injury. If you feel that you have been injured, all testing will be stopped immediately. You will be taken to the emergency room for additional treatment and your surgeon (if applicable) will be notified.

For those who have undergone and ACL reconstruction surgery, prior to testing, your surgeon will confirm that you have recovered sufficiently to be able to safely participate in this study.

Please be aware that your muscles may be tired after testing. This could cause delayed onset muscle soreness. The soreness should disappear within a few days. If it persists, please seek medical help for your condition.

Benefits of Participation:

Please note that we do not anticipate any direct benefits from your participation. However, your participation may contribute to a better assessment of your functional ability and injury status of those with ACL injuries. The data obtained from this study will be used to develop new methods of assessing joint function in patients with a knee injury. This will allow surgeons to better evaluate the optimal time for a patient to return to their normal athletic and work activities.

Voluntary Participation and Withdrawal

Your participation in this study is voluntary. You may decline to participate and are free to withdraw from the trial at any time without reason, penalty, or loss of benefits to which you are otherwise entitled. Please note that you can also request that any of the data collected up to the point of your withdrawal be discarded. By signing this consent form you do not waive your legal rights, nor release the investigators and sponsors from their legal and professional responsibilities.

Confidentiality

All information obtained during the course of this study is strictly confidential and your anonymity will be protected in all data analyses and publications. The collected data will be assigned an anonymous code number and the computer file will be encrypted. Additionally the collected data will be protected by passwords and will be stored on computers that will only be accessible to the research team. In publications, only summary data will be used so that no individual can be identified.

Contacts:

If at any time you have further questions, problems or adverse events, you can contact:
Marchiano Oh, Graduate Student, School of Kinesiology and Health Studies. Queen’s University  (613) 533-6000 /79019

Dr. Pat Costigan, Associate Professor, School of Kinesiology and Health Studies. Queen’s University  (613) 533-6000 /79037

Dr. Davide Bardana, Orthopedic Surgeon, Department of Orthopedic Surgery. Attending staff Kingston General Hospital and Hotel Dieu Hospital  (613) 549-6666 /6333

Dr. John Rudan, Head Department of Surgery. Attending staff Kingston General Hospital, Hotel Dieu Hospital, St. Mary’s of the Lake Hospital  (613) 549-6666 /3671

If you have any questions regarding your rights as a research participant, you can contact:
Dr. Albert Clark, Research Ethics Board Chair  (613) 533-6081
What does my signature mean?

By signing below, I am indicating that:

- I have read, understood and had my questions answered about the study.
- I understand that I can withdraw at any time without penalty or coercion.
- I was given a copy of the Information and Ethics Consent Letter to read and keep.
- I understand that my personal data will be kept confidential.
- I know that I can contact any of the individuals mentioned in this letter if I have questions, concerns or complaints.
- By signing this consent form I do not wave my legal rights, nor release the investigator and sponsors from their legal and professional responsibilities.

Thank you.

Marchiano Oh, B.Sc.

For both your records and our records, we will ask you to sign the Consent Form.

____________________________________  ________________
Signature of Participant                  Date

____________________________________  ________________
Person Obtaining Consent                  Date
Appendix C

Participant Information Sheet
Participant Information Sheet

Participant Code: __________________________

Height (cm): __________________________

Weight (kg): __________________________

Sex: M F

Involved Leg (if applicable): L R

Leg Length (cm): __________________________

Step Length (85% of leg length in cm): __________________________

Notes:
____________________________________________________________________________
____________________________________________________________________________
____________________________________________________________________________
____________________________________________________________________________
____________________________________________________________________________
Appendix D

MATLAB Analysis Program
processScript

directory='C:\Users\Marchiano\Documents\MATLAB\Marchiano Lunge\All Raw Data\';
subjects={'S01','S02','S03','S04','S05','S06','S07','S09','S10','...
'S11','S12','S13','S15','S17','S18','S19','S20','...
'S21'};

for i=1:size(subjects,2)
    vm_data=prepareStatic([directory subjects{i}]); % get vm unit vectors for all landmarks except for hips
    hips=processHip([directory subjects{i}]); % get vm unit vectors for hips
    mkrdata=buildData(vm_data,hips,[directory subjects{i}]);
    fpdata=filterFP([directory subjects{i}]); % filter raw force plate data
end

prepareStatic

function vm_data=prepareStatic(directory)
% function mdata=prepareStatic(directory)
% take in directory with static trial data and output vm (unit vectors)
% of all markers that are to be virtually tracked
% vm_data is in the form
% [vm for lmma; vm for llep; vm for lmep; vm for rmma; vm for rlep; vm for rmep]

static=dir([directory 'static.csv']);

mdata=importdata(static.name,','); % mdata (marker data) is a structure because importdata outputs it that way

pages=floor(size(mdata.data,2)/3);

static=zeros(size(mdata.data,1),3,pages);
for j=1:pages
    static(:,:,j)=mdata.data(:,j*3-1:j*3+1);
end

% left side
holder=[static(:,:,6),static(:,:,9),static(:,:,10),static(:,:,11),static(:,:,3),static(:,:,5),static(:,:,12),static(:,:,13),static(:,:,14)];
for i=1:size(holder,2)
    holder(:,i)=fillNaN(holder(:,i)); % fill NaNs in data set
end

holder=filterData(holder); % filter left side data

mean_data(1,:)=mean(holder,1); % calculate mean of filtered left side data

% right side
holder=[static(:,22),static(:,25),static(:,26),static(:,27),static(:,19),static(:,21),static(:,28),static(:,29),static(:,30)];
for i=1:size(holder,2)
    holder(:,i)=fillNaN(holder(:,i));
end

holder=filterData(holder); % filter right side data

mean_data(2,:)=mean(holder,1); % calculate mean of filtered right side data

% use mean_data to generate vms; want to track 6 markers in total (3 left, % 3 right)
vm_data(1,:)=defineVM(mean_data(1,1:3),mean_data(1,4:6),mean_data(1,7:9),mean_data(1,10:12)); % vm for L med mal
vm_data(2,:)=defineVM(mean_data(1,13:15),mean_data(1,19:21),mean_data(1,22:24),mean_data(1,25:27)); % vm for L lat epi
vm_data(3,:)=defineVM(mean_data(1,16:18),mean_data(1,19:21),mean_data(1,22:24),mean_data(1,25:27)); % vm for L med epi
vm_data(4,:)=defineVM(mean_data(2,1:3),mean_data(2,4:6),mean_data(2,7:9),mean_data(2,10:12)); % vm for R med mal
vm_data(5,:)=defineVM(mean_data(2,13:15),mean_data(2,19:21),mean_data(2,22:24),mean_data(2,25:27)); % vm for R lat epi
vm_data(6,:)=defineVM(mean_data(2,16:18),mean_data(2,19:21),mean_data(2,22:24),mean_data(2,25:27)); % vm for R med epi

end

processHip

function hdata=processHip(directory)

hips=dir([directory '*hip.csv']);

hdata=zeros(2,3);

for i=1:length(hips)
    side=hips(i).name(4);
    if side=='l'
        hdata(1,:)=getHip(hips(i).name,'l');
    elseif side=='r'
        hdata(2,:)=getHip(hips(i).name,'r');
    end
end

buildData

function mkrd=buildData(vm_data,hips,directory)
% function mkrd=buildData(vm_data,hips,directory)
% take in directory with all subject's files
% output "new raw marker file" to be used in LSM processing
% output is in the order:
% [MT5, heel, ankle joint centre, shank1, shank2, shank3, knee joint centre, 
%  thigh1, thigh2, thigh3, hip]

files=dir([directory '*v.csv']);
files(end+1)=dir([directory 'static.csv']);

for i=1:length(files)
    mdata=importdata(files(i).name,','); % mdata (marker data) is a structure because importdata outputs it that way

    pages=floor(size(mdata.data,2)/3);

    data=zeros(size(mdata.data,1),3,pages);
    for j=1:pages
        data(:,:,j)=mdata.data(:,j*3-1:j*3+1);
    end

    side=files(i).name(4);

    if side=='l'
        shank=[data(:,:,9),data(:,:,10),data(:,:,11)];
        for k=1:size(shank,2)
            shank(:,k)=fillNaN(shank(:,k));
        end
        shank=filterData(shank);

        thigh=[data(:,:,12),data(:,:,13),data(:,:,14)];
        for k=1:size(thigh,2)
            thigh(:,k)=fillNaN(thigh(:,k));
        end
        thigh=filterData(thigh);

        l_mmal=findJoint(vm_data(1,:),shank);
        l_lepi=findJoint(vm_data(2,:),thigh);
        l_mepi=findJoint(vm_data(3,:),thigh);
        l_hip=findJoint(hips(1,:),thigh);

        foot=[data(:,:,8),data(:,:,2),data(:,:,4)];
        for k=1:size(foot,2)
            foot(:,k)=fillNaN(foot(:,k));
        end
        foot=filterData(foot);

        mkrdata=[foot,l_mmal,shank,l_lepi,l_mepi,thigh,l_hip];

        ankle=((mkrdata(:,7:9)-mkrdata(:,10:12))/2)+mkrdata(:,10:12);
        knee=((mkrdata(:,22:24)-mkrdata(:,25:27))/2)+mkrdata(:,25:27);

    elseif side=='r'
        shank=[data(:,:,25),data(:,:,26),data(:,:,27)];
        for k=1:size(shank,2)
            shank(:,k)=fillNaN(shank(:,k));
        end
        shank=filterData(shank);

        thigh=[data(:,:,28),data(:,:,29),data(:,:,30)];
        for k=1:size(thigh,2)
            thigh(:,k)=fillNaN(thigh(:,k));
        end
        thigh=filterData(thigh);

        mkrdata=[foot,l_mmal,ankle,mkrdata(:,13:21),l_lepi,l_mepi,knee,mkrdata(:,28:39)];
    end
thigh = filterData(thigh);

r_mmal = findJoint(vm_data(4,:),shank);
r_lepi = findJoint(vm_data(5,:),thigh);
r_mepi = findJoint(vm_data(6,:),thigh);
r_hip = findJoint(hips(2,:),thigh);

foot = [data(:,:,24), data(:,:,18), data(:,:,20)];
for k = 1:size(foot,2)
    foot(:,k) = fillNaN(foot(:,k));
end
foot = filterData(foot);

mkrdata = [foot, r_mmal, shank, r_lepi, r_mepi, thigh, r_hip];

ankle = ((mkrdata(:,7:9) - mkrdata(:,10:12))/2) + mkrdata(:,10:12);
knee = ((mkrdata(:,22:24) - mkrdata(:,25:27))/2) + mkrdata(:,25:27);

mkrdata = [foot, r_mmal, ankle, mkrdata(:,13:21), r_lepi, r_mepi, knee, mkrdata(:,28:39)];

else
    lshank = [data(:,:,9), data(:,:,10), data(:,:,11)];
    for k = 1:size(lshank,2)
        lshank(:,k) = fillNaN(lshank(:,k));
    end
    lshank = filterData(lshank);

    lthigh = [data(:,:,12), data(:,:,13), data(:,:,14)];
    for k = 1:size(lthigh,2)
        lthigh(:,k) = fillNaN(lthigh(:,k));
    end
    lthigh = filterData(lthigh);

    l_mmal = findJoint(vm_data(1,:),lshank);
l_lepi = findJoint(vm_data(2,:),lthigh);
l_mepi = findJoint(vm_data(3,:),lthigh);
l_hip = findJoint(hips(1,:),lthigh);

    lfoot = [data(:,:,8), data(:,:,2), data(:,:,4)];
    for k = 1:size(lfoot,2)
        lfoot(:,k) = fillNaN(lfoot(:,k));
    end
    lfoot = filterData(lfoot);

    lmkrdata = [lfoot, l_mmal, lshank, l_lepi, l_mepi, lthigh, l_hip];

    lankle = ((lmkrdata(:,7:9) - lmkrdata(:,10:12))/2) + lmkrdata(:,10:12);
lknee = ((lmkrdata(:,22:24) - lmkrdata(:,25:27))/2) + lmkrdata(:,25:27);

    lmkrdata = [lfoot, l_mmal, lankle, lmkrdata(:,13:21), l_lepi, l_mepi, lknee, lmkrdata(:,28:39)];
rshank=[data(:,25),data(:,26),data(:,27)];
for k=1:size(rshank,2)
    rshank(:,k)=fillNaN(rshank(:,k));
end
rshank=filterData(rshank);

rthigh=[data(:,28),data(:,29),data(:,30)];
for k=1:size(rthigh,2)
    rthigh(:,k)=fillNaN(rthigh(:,k));
end
rthigh=filterData(rthigh);

r_mmal=findJoint(vm_data(4,:),rshank);
r_lepi=findJoint(vm_data(5,:),rthigh);
r_mepi=findJoint(vm_data(6,:),rthigh);
r_hip=findJoint(hips(2,:),rthigh);

rfoot=[data(:,24),data(:,18),data(:,20)];
for k=1:size(rfoot,2)
    rfoot(:,k)=fillNaN(rfoot(:,k));
end
rfoot=filterData(rfoot);
rmkrdata=[rfoot,r_mmal,rshank,r_lepi,r_mepi,rthigh,r_hip];

rankle=((rmkrdata(:,7:9)-
    rmkrdata(:,10:12))/2)+rmkrdata(:,10:12);
rknee=((rmkrdata(:,22:24)-
    rmkrdata(:,25:27))/2)+rmkrdata(:,25:27);

mkrdata=[lmkrdata,rfoot,r_mmal,rankle,rmkrdata(:,13:21),r_lepi,r_mepi,r
    knee,rmkrdata(:,28:39)];
end
csvwrite([directory 'new_' files(i).name],mkrdata)
end
end

filterFP

function fpdata=filterFP(directory)
% function fpdata=filterFP(fpdata)
% filter columns 2 to 7 of force plate data from directory; not
% filtering
% switch signal column
files=dir([directory '*f.csv']); % get all force plate files
for i=1:length(files)
    fpdata=importdata(files(i).name,'',');
    fpdata(:,2:7)=filterData(fpdata(:,2:7)); % filter force plate data
    csvwrite([directory 'filtered_' files(i).name],fpdata)
end
end

fillNaN
function [ data ] = fillNaN( data )
% function [ data ] = fillNaN( data )
% fill NaNs in dataset

for page=1:size(data,3)
    for axes=1:size(data,2)
        if sum(isnan(data(:,axes,page)))<size(data,1) % check to see if the entire column is filled with NaNs; if sum is less than number of rows, column has non NaN data points and can be interpolated
            data(:,axes,page)=naninterp(data(:,axes,page));
        end
    end
end
end

function X = naninterp(X)
% Interpolate over NaNs
% See INTERP1 for more info
X(isnan(X)) = interp1(find(~isnan(X)), X(~isnan(X)), find(isnan(X)),'cubic');
end

filterData

function fdata=filterData(data)
% function data=filterData(data)
% zero-lag, low-pass filters raw marker and force plate data at 6Hz cutoff
% frequecy

global SAMPLE_RATE CUTOFF

SAMPLE_RATE=120;
CUTOFF=6;

wn=CUTOFF/(SAMPLE_RATE/2);
[b,a]=butter(1,wn);

fdata=filtfilt(b,a,data);
end

defineVM

function vm=defineVM(ant_marker,rb1,rb2,rb3)
% function vm=defineVM(ant_marker,rb1,rb2,rb3)
% ant_marker is average marker of joint during STATIC TRIAL that is to be virtually tracked
% rb1, rb2, rb3 are average of rigid body markers
% vm is unit vector expressing location relationship of ant_marker to rigid
% body triad

rb_cs=makeCS(rb1,rb2,rb3);
vm=(ant_marker-rbl)*rb_cs; % rbl is the origin; location coordinates are now in the LCS via translation
% multiplying by cs inverse to convert to GCS from LCS
end

getHip

function vm=getHip(hip_trial,side)
% function coordinates=getHip(hip_trial)
% coordinates are the average of estimated hip centre coordinates from sphereFit function
% coordinates from each of the triad markers on the thigh are calculated
% and averaged

triad=importdata(hip_trial,'',');
if side=='l'
data=[triad.data(:,35:37),triad.data(:,38:40),triad.data(:,41:43),triad.data(:,44:46),triad.data(:,47:49),triad.data(:,50:52)];
elseif side=='r'
end
for i=1:size(data,2)
data(:,i)=fillNaN(data(:,i));
end
data=filterData(data); % filter hip trial data

correct_thigh=zeros(size(data,1),9); % preallocate for thigh marker tracking
for i=1:size(data,1)
pelvis_cs=makeHipCS(data(i,10:12),data(i,13:15),data(i,16:18));
thigh=[data(i,1:3)-data(i,10:12);data(i,4:6)-data(i,10:12);data(i,7:9)-data(i,10:12)]*pelvis_cs.';
correct_thigh(i,:)=[thigh(1,:),thigh(2,:),thigh(3,:)]
end
c1=sphereFit(correct_thigh(:,1:3));
c2=sphereFit(correct_thigh(:,4:6));
c3=sphereFit(correct_thigh(:,7:9));

centre=mean([c1;c2;c3],1);
points=mean(correct_thigh(:,1:9),1);

vm=defineVM(centre,points(1,1:3),points(1,4:6),points(1,7:9));
end

findJoint

function coordinates=findJoint(vm,rb)
% function coordinates=findJoint(vm,rb)
coordinates=zeros(size(rb,1),3);
for i=1:size(rb,1)
    rb_cs=makeCS(rb(i,1:3),rb(i,4:6),rb(i,7:9));
    coordinates(i,:)=vm*rb_cs+rb(i,1:3);
end
end

makeCS

function cs=makeCS(m1,m2,m3)
% function cs=makeCS(m1,m2,m3)
% 3 markers on rigid body to generate coordinate system
% each marker is a 1x3 row matrix
% unit vector is used to express anatomical joint marker with respect
% to
% the rigid body

x=m2-m1;
yy=m3-m1;
z=cross(x,yy);
y=cross(z,x);

x=x/norm(x); % trans: int/ext rotation
y=y/norm(y); % front: ab/ad
z=z/norm(z); % sag: flex/ext

cs=[y;z;x];
end

makeHipCS

function cs=makeHipCS(m1,m2,m3)
% function cs=makeHipCS(m1,m2,m3)
% 3 markers on rigid body to generate coordinate system
% each marker is a 1x3 row matrix
% unit vector is used to express anatomical joint marker with respect
% to
% the rigid body

x=m2-m1;
yy=m3-m1;
z=cross(x,yy);
y=cross(z,x);

x=x/norm(x);
y=y/norm(y);
z=z/norm(z);

cs=[x;y;z];
end

finalLSMScript

% set global variables
setFemaleGlobals;
setMaleGlobals;
subjects={'S01','S02','S03','S04','S05','S06','S07','S08','S09','S10',
'S11','S12','S13','S15','S16','S17','S18','S19','S20'};

mass=[72.73,57.95,64.32,60.91,62.95,61.14,74.43,82.73,67.95,75.23,60.91,
60,62.73,61.32,60.91,59.55,65,54.54];

subjects={'S21'};

mass=[78];

for subject=1:length(subjects)
    DIRECTORY=['C:\Users\Marchiano\Documents\MATLAB\Marchiano Lunge\All Raw Data\' subjects{subject}]; % set specific directory
    MASS=mass(subject); % set subject mass

    % get all list of all the vicon files
    files=dir([DIRECTORY 'new_*v.csv']);
    static=dir([DIRECTORY 'new_*static.csv']);

    % calculate angle bias from static trial
    compiled_bias=getStaticEuler(static.name);

    % process each file
    for file=1:length(files)
        setStructure; % set LSM structure
        vname=files(file).name; % get the vicon filename
        fpname=['filtered_' vname(5:end-5) 'f.csv']; % set the force plate filename

        if vname(8)=='l'
            bias=compiled_bias(1,:);
        else
            bias=compiled_bias(2,:);
        end

        % get data ready
        [vdata,fpdata]=getData(vname,fpname);
        [vdata,fpdata]=clipData(vdata,fpdata);

        % link segment model - load data
        segments=loadSegmentEndpts(segments,vdata);

        % link segment model - convert V to N and calculate COP
        [fdata,cop]=calcFP(fpdata);

        % link segment model - calculate CS for each segment
        segments=calcFootCS(segments,vdata(:,1:3),vdata(:,4:6),vdata(:,7:9));
        segments=calcShankCS(segments,vdata(:,16:18),vdata(:,19:21),vdata(:,22:24));
        segments=calcThighCS(segments,vdata(:,34:36),vdata(:,37:39),vdata(:,40:42));
% link segment model - calculate segment parameters
segments=calcCOM(segments);
segments=calcCOMAcc(segments);
segments=calcSegmentMass(segments);
segments=calcSegmentMOI(segments);

% link segment model - load forces and COP
segments(1).dist_force=fdata(:,FX-1:FZ-1);
segments(1).dist_force_loc=cop;

% link segment model - calculate proximal force for each segment
segments=calcProxForce(segments);

% link segment model - calculate angular parameters
segments=calcAngDisp(segments);
segments=calcAngAcc(segments);

% link segment model - calculate proximal moment for each segment
segments=calcProxMom(segments);

% calculate knee joint parameters
knee_angle=getEulerKnee(segments);
knee_angle=knee_angle-repmat(bias,size(knee_angle,1),1);

knee_ang_vel=central_diff(knee_angle,1/SAMPLE_RATE);

knee_power=segments(2).prox_mom.*knee_ang_vel; % calculates the knee power generated

% mark phases
phases=markPhase(fpdata,knee_angle(:,1),bias(1));

% change to shank LCS
segments(2).prox_mom=convert2LCSMatch(segments,segments(2).prox_mom,vname(8));

knee_angle=convert2LCSMatch(segments,knee_angle,vname(8));

knee_ang_vel=convert2LCSMatch(segments,knee_ang_vel,vname(8));

knee_power=convert2LCS(segments,knee_power);

% calculate total time to lunge and time spent in each phase
count=tabulate(phases);
time=[count(1,2)/SAMPLE_RATE count(2,2)/SAMPLE_RATE
count(3,2)/SAMPLE_RATE count(4,2)/SAMPLE_RATE
count(1,2)/SAMPLE_RATE+count(2,2)/SAMPLE_RATE+count(3,2)/SAMPLE_RATE+count(4,2)/SAMPLE_RATE];

% calculate knee moment and Fz normalized to body mass
segments(2).prox_mom=segments(2).prox_mom/MASS;

knee_power=knee_power/MASS;
impact = fdata(:, FZ-1)/MASS;

%% calculate peak parameters
outcomes = [segments(2).prox_mom knee_angle knee_ang_vel knee_power];
initial = outcomes(phases==1,:);
stance_down = outcomes(phases==2,:);
stance_up = outcomes(phases==2.5,:);
returnp = outcomes(phases==3,:);

norm_cycle = timeNorm([outcomes], 101); % normalize data to %
cycle; only for ensemble averaging purposes

optima = [max(initial) min(initial) max(stance_down)
min(stance_down) max(stance_up) min(stance_up) max(returnp)
min(returnp)];

%% write outcome measures to a csv file
csvwrite([DIRECTORY 'final_' vname(5:end-5) '.csv'], outcomes
phases); % calculated variables for every sample
csvwrite([DIRECTORY 'outcomes_' vname(5:end-5) '.csv'], optima
time]); % all peaks and mins written here
csvwrite([DIRECTORY 'normalized_' vname(5:end-5)
'.csv'], norm_cycle);
end

%% calculate means of outcomes and write to a csv file
writeOutcomes;
writeMeans;
compileNormalized;
end

setFemaleGlobals

% set global variables for a female subject
clear all;
close all;
clc;

global FX FY FZ MX MY MZ SWITCH ON G COM_LOCATION SEGMENT_MASS K_RATIO
SAMPLE_RATE THRESHOLD DIRECTORY MASS;
FX = 2;
FY = 3;
FZ = 4;
MX = 5;
MY = 6;
MZ = 7;
SWITCH = 1;
ON = 4;
G = [0,0,-9.81];

% define segments as 1=foot, 2=shank, 3=thigh
% anthropometric data is from de Leva (1996) with the exception of foot
segment mass and COM data which is from Dempster on pg 57 in
Robertson's book

% com locations from the proximal end as a fraction of segment length
COM_LOCATION=[0.5,0.4416,0.3612];

% segment mass as a fraction of the total body mass
SEGMENT_MASS=[0.0145,0.0481,0.1478];

% segment's moment of inertia as a function of segment length
K_RATIO=[0.299,0.271,0.369;
0.139,0.093,0.162;
0.279,0.267,0.364];

SAMPLE_RATE=120;

THRESHOLD=0.015; % force plate threshold voltage

setMaleGlobals

% set global variables for a male subject
clear all;
close all;
clc;

global FX FY FZ MX MY MZ SWITCH ON G COM_LOCATION SEGMENT_MASS K_RATIO
SAMPLE_RATE THRESHOLD DIRECTORY MASS;

FX = 2;
FY = 3;
FZ = 4;
MX = 5;
MY = 6;
MZ = 7;
SWITCH = 1;
ON = 4;
G = [0,0,-9.81];

% define segments as 1=foot, 2=shank, 3=thigh

% anthropometric data is from de Leva (1996) with the exception of foot
segment mass and COM data which is from Dempster on pg 57 in
Robertson's book

% com locations from the proximal end as a fraction of segment length
COM_LOCATION=[0.5,0.4459,0.4095];

% segment mass as a fraction of the total body mass
SEGMENT_MASS=[0.0145,0.0433,0.1416];

% segment's moment of inertia as a function of segment length
K_RATIO=[0.257,0.255,0.329;
0.124,0.103,0.149;
0.245,0.249,0.329];

SAMPLE_RATE=120;

THRESHOLD=0.015; % force plate threshold voltage
setStructure

clearvars('segments')

% define the default segment and set all fields to zero or empty
default.mass            = 0;
default.length          = 0;
default.moi             = 0;  % moment of inertia for given segment
[k_longitudinal;k_sagittal;k_transverse]
default.dist_col        = 0;
default.prox_col        = 0;
default.dist_pnt        = [];
default.prox_pnt        = [];
default.cs              = [];
default.ang_disp        = [];
default.ang_acc         = [];  % a n (number of frames) by 3 matrix (sagittal,long,transverse)
default.com_pnt         = [];
default.com_acc         = [];
default.dist_force      = [];
default.dist_force_loc  = [];
default.dist_mom        = [];
default.prox_force      = [];
default.name            = '';    

segment_names={'foot','shank','thigh'};
dist_start=[1,13,31];  % column where distal point starts
prox_start=[13,31,43]; % column where proximal point starts

% a structure to hold all the segments
for segment=1:3
    segments(segment)=default;
    segments(segment).name=char(segment_names(segment));
    segments(segment).dist_col=dist_start(segment);
    segments(segment).prox_col=prox_start(segment);
end

dataGet

function [vdata,fpdata]=getData(vname,fpname)
% function [vdata,fpdata]=getData(vname,fpname)

global DIRECTORY SWITCH ON FX FZ MZ THRESHOLD;

fpdata=csvread([DIRECTORY fpname]); % get force plate data
fpdata=fpdata(fpdata(:,SWITCH)>ON,:); % limit force plate data to just when the switch is on
fpdata(fpdata(:,FZ)<THRESHOLD,FX:MZ)=0; % replace force plate data with 0 when the participant was not on the force plate

vdata=csvread([DIRECTORY vname]); % get vicon data
vdata=vdata./1000;  % convert to metres

shortest=min(length(vdata),length(fpdata)); % limit both data sets to the one with the shortest length
vdata=vdata(1:shortest,:);
fpdata=fpdata(1:shortest,:);
end
clipData

function [vclipped,fclipped]=clipData(vdata,fpdata)
% function [vclipped,fclipped]=clipData(vdata,fpdata)
% take in new vdata and calculate y z velocity vector of the heel
% marker and clip non-lunge
% data at start and end of vdata

global SAMPLE_RATE

target=vdata(:,5:6);

yvel=central_diff(target(:,1),1/SAMPLE_RATE);
zvel=central_diff(target(:,2),1/SAMPLE_RATE);

vel_vector=sqrt(yvel.^2+zvel.^2);
vel_vector=vel_vector(50:end-10);

vdata=vdata(50:end-10,:);
fpdata=fpdata(50:end-10,:);

markedpts=find(vel_vector>0.01);

vclipped=vdata(markedpts(1)-1:markedpts(end)+1,:);
fclipped=fpdata(markedpts(1)-1:markedpts(end)+1,:);
end

loadSegmentEndpts

function segments=loadSegmentEndpts(segments,markers)
% function segments=loadSegmentEndpts(segments,markers)
% reads xyz data (markers) from the marker file and populates the
% segment
% endpoints with marker data

for segment=1:3

segments(segment).dist_pnt=markers(:,segments(segment).dist_col:segments(segment).dist_col+2); % all rows, 3 columns

segments(segment).prox_pnt=markers(:,segments(segment).prox_col:segments(segment).prox_col+2); % all rows, 3 columns

    % set the distal force location to be the segment distal point
    segments(segment).dist_force_loc=segments(segment).dist_pnt;
end
end

calcFP

function [fdata,cop]=calcFP(raw_fdata)
% function [fdata,cop]=calcFP(raw_fdata)
% calibrates the force plate data and then calculates x,y,z COP
% coordinates
% fdata output is in N and Nm and COP coordinates are in m

global FX FZ MX MY MZ;
% The Sensitivity matrix for SI units (N and Nm) from AMTI
cal_matrix = [1.4851 -0.0042 -0.0087  0.0079  0.0064  0.0102;
  0.0076  1.4965  0.0120  -0.0028  0.0026  -0.0183;
  0.0037 -0.0045  5.8246  0.0111  0.0009  -0.0001;
 -0.0008 -0.0033  0.0226  1.3385  -0.0073  -0.0070;
 -0.0033  0.0007  0.0061  0.0010  0.9387  0.0021;
 -0.0045 -0.0033  0.0002  -0.0003  -0.0015  0.6155];

gain=100; % assume excitation of 10, gain of 1000, net gain = 100
% set in the amplifier

% map the force plate axes directions to the vicon axes directions
coord_adjust=[-1,1,1,-1,-1,1];

% convert raw_fdata from volts to N and Nm
fdata=(raw_fdata(:,FX:MZ)*cal_matrix)*gain;

% adjust forces to match vicon coordinate system
coord_adjust=repmat(coord_adjust,size(fdata,1),1);
fdata=fdata.*coord_adjust;

% calculate centre of pressure coordinates
cop(:,1)=fdata(:,MY-1)./fdata(:,FZ-1); % minus 1 to account for
dropping switch column
cop(:,2)=fdata(:,MX-1)./fdata(:,FZ-1);
cop(:,3)=0;
cop(isnan(cop(:,1)),:)=0;
end

calcFootCS

function segments=calcFootCS(segments,MT5,heel,lmal)
  % function segments=calcFootCS(segments,MT5,heel,lmal)

  foot_cs=zeros(size(heel,1)*3,3);
  for frame=1:size(heel,1)
    cs=makeCS(MT5(frame,:),heel(frame,:),lmal(frame,:));
    foot_cs(frame*3-2:frame*3,:)=[cs(3,:);cs(2,:);cs(1,:)];
  end

  segments(1).cs=foot_cs;
end

calcShankCS

function segments=calcShankCS(segments,tri1,tri2,tri3)
  % function segments=calcShankCS(segments,tri1,tri2,tri3)

  shank_cs=zeros(size(tri1,1)*3,3);
  for frame=1:size(tri1,1)
    shank_cs(frame*3-2:frame*3,:)=makeCS(tri1(frame,:),tri2(frame,:),tri3(frame,:));
  end

  segments(2).cs=shank_cs;
calcThighCS

function segments=calcThighCS(segments,tri1,tri2,tri3)
% function segments=calcThighCS(segments,tri1,tri2,tri3)

thigh_cs=zeros(size(tri1,1)*3,3);
for frame=1:size(tri1,1)
    thigh_cs(frame*3-2:frame*3,:)=makeCS(tri1(frame,:),tri2(frame,:),tri3(frame,:));
end
segments(3).cs=thigh_cs;
end

calcCOM

function segments=calcCOM(segments)
% function segments=calcCOM(segments)
% computes the location of the centre of mass of a segment
% com_location holds the location of the centre of mass for each segment as
% a function of segment length

global COM_LOCATION;

% using each segments distal and proximal point
for segment=1:3
end
end

calcCOMAcc

function segments=calcCOMAcc(segments)
% function segments = calcCOMAcc(segments)
% computes the acceleration of the centre of mass

global SAMPLE_RATE;

for segment=1:3
    vel=central_diff(segments(segment).com_pnt,1/SAMPLE_RATE);
    segments(segment).com_acc=central_diff(vel,1/SAMPLE_RATE);
end
end

calcSegmentMass

function segments=calcSegmentMass(segments)
% function segments=calcSegmentMass(segments)
% calculate the mass of each segment in kg as a function of subject mass

global SEGMENT_MASS MASS;
for segment=1:3
    segments(segment).mass=SEGMENT_MASS(segment)*MASS;
end
end

calcSegmentMOI

function segments=calcSegmentMOI(segments)
% function segments=calcSegmentMOI(segments)

global K_RATIO;

for segment=1:3
diff=mean(segments(segment).dist_pnt-segments(segment).prox_pnt,1);
    length=sqrt(sum(diff.^2));

    segments(segment).length=length;

    segments(segment).moi=[segments(segment).mass*(K_RATIO(1,segment)*length)^2 segments(segment).mass*(K_RATIO(2,segment)*length)^2 segments(segment).mass*(K_RATIO(3,segment)*length)^2];
end
end

calcProxForce

function segments=calcProxForce(segments)
% function segments=calcProxForce(segments)
% calculate the proximal force sum(F) = ma
% we have: Fd + Fp + mg = ma
% therefore Fp = ma - mg - Fd
% Fd = GRF for first segment
% Fd = Fp of preceding segment for all other segments

global G;

for segment=1:3
    if isempty(segments(segment).dist_force)
        segments(segment).dist_force=zeros(size(segments(1).dist_pnt));
    end
    ma=segments(segment).mass*segments(segment).com_acc;

    g=repmat(G,size(ma,1),1);
    mg=segments(segment).mass*g;

    segments(segment).prox_force=ma-mg-segments(segment).dist_force;

    % add this segment's proximal force to the next segments distal force
    % as an opposite
    if (segment~=3)
        segments(segment+1).dist_force=-segments(segment).prox_force;
    end
end
end
calcAngDisp

function segments=calcAngDisp(segments)
% function segments=calcAngDisp(segments)
% compute the angular displacement of the segments in radians using
% Cardan angles

seg_cardan=zeros(size(segments(1).cs,1)/3,3);

for segment=1:3
    cs=segments(segment).cs;
    
    for frame=1:size(seg_cardan,1)
        frame_cs=cs(frame*3-2:frame*3,:);
        
        y_cardan=asin(-frame_cs(3,2));
        x_cardan=asin(frame_cs(3,1)/cos(y_cardan));
        if frame_cs(3,3)<0
            x_cardan=pi-x_cardan;
        end
        
        z_cardan=asin(frame_cs(1,2)/cos(y_cardan));
        if frame_cs(2,2)<0
            z_cardan=pi-z_cardan;
        end
        
        seg_cardan(frame,:)=[x_cardan,y_cardan,z_cardan];
    end
    
    segments(segment).ang_disp=seg_cardan;
end
end

calcAngAcc

function segments=calcAngAcc(segments)
% function segments=calcAngAcc(segments)
% computes the angular acceleration of all segments
% acceleration in planes [sag front trans]

global SAMPLE_RATE;

omega=zeros(size(segments(1).ang_disp,1),3);

for segment=1:3
    disp=segments(segment).ang_disp;
    vel=central_diff(disp,1/SAMPLE_RATE);
    
    for frame=1:size(omega,1)
        omega(frame,1)=vel(frame,1)*cos(disp(frame,2))*sin(disp(frame,3)) + vel(frame,2)*cos(disp(frame,3));
        omega(frame,2)=vel(frame,1)*cos(disp(frame,2))*cos(disp(frame,3)) - vel(frame,2)*sin(disp(frame,3));
        omega(frame,3)=-vel(frame,1)*sin(disp(frame,2))+vel(frame,3);
    end
end
\( \omega = [\omega(:,2), \omega(:,1), \omega(:,3)] \);

\[
\text{acc} = \text{central\_diff}(\omega, 1/\text{SAMPLE\_RATE})
\]

\[
\text{segments}(\text{segment}).\text{ang\_acc} = \text{acc}.
\]

end

calcProxMom

function segments=calcProxMom(segments)

\[
% \text{calculate the proximal moment sum}(M) = I_a \\
% \text{so } M_p = I_a - F_d r - F_p r - M_d
\]

for segment=1:3

\[
I_a = \text{repmat}(\text{segments}(\text{segment}).\text{moi}, \text{size}(\text{segments}(\text{segment}).\text{prox\_force},1),1) ;
\]

\[
\text{dist\_mom\_arm} = \text{segments}(\text{segment}).\text{dist\_force\_loc} - \text{segments}(\text{segment}).\text{com\_pnt} ;
\]

\[
\text{dist\_force\_mom} = \text{cross}(\text{dist\_mom\_arm}, \text{segments}(\text{segment}).\text{dist\_force}) ;
\]

\[
\text{prox\_mom\_arm} = \text{segments}(\text{segment}).\text{prox\_pnt} - \text{segments}(\text{segment}).\text{com\_pnt} ;
\]

\[
\text{prox\_force\_mom} = \text{cross}(\text{prox\_mom\_arm}, \text{segments}(\text{segment}).\text{prox\_force}) ;
\]

\[
I_a = I_a \times \text{segments}(\text{segment}).\text{ang\_acc} ;
\]

if isempty(segments(\text{segment}).\text{dist\_mom})

\[
\text{segments}(\text{segment}).\text{dist\_mom} = 0 ;
\]

end

\[
\text{segments}(\text{segment}).\text{prox\_mom} = I_a - \text{dist\_force\_mom} - \text{prox\_force\_mom} - \text{segments}(\text{segment}).\text{dist\_mom} ;
\]

% add this segment's proximal moment to the next segment's distal
% moment as an opposite
if (segment~=3)

\[
\text{segments}(segment+1).\text{dist\_mom} = -\text{segments}(\text{segment}).\text{prox\_mom} ;
\]

end
end

generateKnee

function euler\_angle = getEulerKnee(segments)

\[
% \text{calculate knee Euler angles in RADIANS along 3 axes given 2 rigid body triads} \\
% \text{input is XYZ coordinate data of 2 rigid body triads and side 'l' or 'r'} \\
% \text{proximal = thigh, distal = shank} \\
% \text{alpha = flexion/extension} \\
% \text{beta = abduction/adduction} \\
% \text{gamma = axial or internal/external rotation}
\]

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prox = segments(3).cs;
dist = segments(2).cs;
euler_angle = zeros(size(prox,1)/3,3);

for frame = 1:size(euler_angle,1)
    i_prox = prox(frame*3,:);
k_prox = prox(frame*3-1,:);
i_dist = dist(frame*3,:);
k_dist = dist(frame*3-1,:);

    l_knee = cross(k_prox, i_dist);
l_knee = l_knee / norm(l_knee);

    alpha = -asin(dot(l_knee, i_prox));
    beta = asin(dot(k_prox, i_dist));
    gamma = -asin(dot(l_knee, k_dist));

    euler_angle(frame,:) = [alpha, beta, gamma];
end
end

central_diff

function [ vel, errmsg ] = central_diff ( disp, dt )
% function [ vel, errmsg ] = central_diff ( disp, dt )
% Differentiates the matrix 'disp' using the central difference formula.
% Using the central difference means that differentiated values cannot be
% determined for the first and last rows of data. To account for this a single
% additional sample is added to the front and back of 'disp'. The additional
% data is estimated using 'polyfit' with a quadratic over the 5 consecutive
% samples. The result is no change in length after differentiation. The
% resulting 'vel' has the same number of rows and the original 'disp'.
% disp - the data to be differentiated
% dt - step between samples, or 1/samplerate
% vel - the differentiated data
% USAGE: ang_velocity = CentralDifference (angles, (1/samplerate));
% we assume more rows than columns - data is in the rows
% transpose if more columns than rows

    rotate = size(disp, 2) > size(disp, 1);
    if rotate
        disp = disp';
    end
disp = AddEndpoints (disp); % add data at start and end

disp2 = disp; % make a copy
disp2(1:2,:) = []; % and delete the first 2 rows
disp(end-1:end,:) = []; % delete last two rows
% disp and disp2 are now alinged so that original frame 1 aligns with
% original frame 3 and both are the same length
vel = (disp2 - disp) ./ (2 * dt); % compute the velocity

% rotate back to rows if required
if rotate
vel = vel';
end
end

function [ padded_data ] = AddEndpoints ( data )
% Adds a new initial and final point to a dataset using polyfit.
warning ('off', 'MATLAB:polyfit:RepeatedPointsOrRescale');
ncols = size(data, 2);
blank_row = zeros(1, ncols);
padded_data = [blank_row; data; blank_row]; % initially pad
with zeros
% get a point before the start
x = [2:6]'; % samples to extract
for col = 1:ncols % do each column
coeff = polyfit (x, padded_data(x, col), 2); % 2nd order = quadratic
padded_data(1, col) = polyval (coeff, 1);
end
% do the same for the last point
nrows = size (padded_data, 1);
x = [nrows-5:nrows-1]'; % samples at the end of the data set
for col = 1:ncols % do each column
coeff = polyfit (x, padded_data(x, col), 2); % 2nd order = quadratic
padded_data(end, col) = polyval (coeff, nrows);
end
warning ('on', 'MATLAB:polyfit:RepeatedPointsOrRescale');
end

markPhase

function indicator=markPhase(fpdata,angle,bias)
% function indicator=markPhase(fpdata,angle)
% pass in filtered force plate data
% returns a matrix that indicates the lunge phase
% 1=initial  2=initial stance (up to the point where the greatest angle occurs) 2.5=return stance (greatest angle to right when participant comes off force plate) 3=return
% lunge phase: initial swing, initial stance (phase has high Fz value), return stance, return swing

global THRESHOLD

% use find to index rows where participant was on force plate
row=find(fpdata(:,4)>THRESHOLD);

[~,loc]=findpeaks(angle,'MINPEAKHEIGHT',1.3-bias);

if isempty(loc)
    [~,loc]=findpeaks(angle,'MINPEAKHEIGHT',1.1-bias);
    if length(loc)>1
        endpt=loc(end);
    else
        endpt=loc(1);
    end
else
    if length(loc)>1
        endpt=loc(end);
    else
        endpt=loc(1);
    end
end
indicator(1:row(1)-1,1)=1;
indicator(row(1):endpt,1)=2;
indicator(endpt+1:row(end),1)=2.5;
indicator(row(end)+1:size(fpdata,1),1)=3;
end

function converted=convert2LCSMatch(segments,parameter,side)
    % function converted=convert2LCSMatch(segments,parameter,side)
    cs=segments(2).cs;
    converted=size(parameter);
    converted=zeros(converted(1,1),converted(1,2));
    for i=1:size(parameter,1)
        converted(i,:)=parameter(i,:)*[cs(i*3-1,:);cs(i*3-2,:);cs(i*3,:)];
    end
    if side=='l'
        converted=converted.*repmat([1 -1 -1],size(parameter,1),1);
    end
end

function converted=convert2LCS(segments,parameter)
    % function converted=convert2LCS(segments,parameter)
    cs=segments(2).cs;
    converted=size(parameter);
converted=zeros(converted(1,1),converted(1,2));
for i=1:size(parameter,1)
    converted(i,:)=parameter(i,:)*[cs(i*3-1,:);cs(i*3-2,:);cs(i*3,:)];
end
end
timeNorm

function newSignal=timeNorm(origSignal,nPoints)
% function newSignal=timeNorm(origSignal,nPoints)
% normalizes the origSignal to the number of points represented by nPoints

nLength=length(origSignal);
origX=1:nLength;
ewX=linspace(1,nLength,nPoints);
newSignal=interp1(origX,origSignal,newX);
end
mergeMeans
directory='C:\Users\Marchiano\Documents\MATLAB\Marchiano Lunge\';
files=dir([directory 'means_*']);
for i=1:length(files)
data=csvread(files(i).name);
    reshaped(1,:)=[data(1,1:end-1) data(2,1:end-1) data(3,1:end-1)
data(4,1:end-1)];
    reshaped(2,:)=[data(5,1:end-1) data(6,1:end-1) data(7,1:end-1)
data(8,1:end-1)];
    reshaped(3,:)=[data(9,1:end-1) data(10,1:end-1) data(11,1:end-1)
data(12,1:end-1)];
    csvwrite([directory 'merged_' files(i).name],reshaped);
end
timeWriter

subjects={'S01','S03','S04','S05','S06','S07','S09','S10','S11','S12','S15','S17','S18','S19','S20','S21'};
for subject=1:length(subjects)
    str=subjects{subject};
    DIRECTORY=['C:\Users\Marchiano\Documents\MATLAB\Marchiano Lunge\All Raw Data' str];
    % get a list of all left and right outcome files
    l_files=dir([DIRECTORY 'outcomes_*l*']);
    r_files=dir([DIRECTORY 'outcomes_*r*']);
    lmain=zeros(length(l_files),5);
    rmain=zeros(length(r_files),5);
    for num=1:length(l_files)
data=csvread(l_files(num).name);
lmain(num,:)=data(:,end-4:end);
end

for num=1:length(r_files)
data=csvread(r_files(num).name);
rmain(num,:)=data(:,end-4:end);
end

time(1,:)=mean(lmain,1);
time(2,:)=mean(rmain,1);
time(3,:)=mean(vertcat(lmain,rmain),1);

csvwrite(['C:\Users\Marchiano\Documents\MATLAB\Marchiano Lunge\mean_time_' str(1:end-1) '.csv'],time);
end

writeOutcomes

% get a list of all left and right outcome files
l_files=dir([DIRECTORY 'outcomes_*l*']);
r_files=dir([DIRECTORY 'outcomes_*r*']);

l_data=zeros(length(l_files),size(csvread(l_files(1).name),2));
r_data=zeros(length(r_files),size(csvread(r_files(1).name),2));

for number=1:length(l_files)
    l_data(number,:)=csvread(l_files(number).name);
end

for number=1:length(r_files)
    r_data(number,:)=csvread(r_files(number).name);
end

peak_results(1,:)=max(l_data,1);
peak_results(2,:)=max(r_data,1);
peak_results(3,:)=max(vertcat(l_data,r_data),1);

csvwrite(['C:\Users\Marchiano\Documents\MATLAB\Marchiano Lunge\leg_optima_1 DIRECTORY(end-3:end-1) '.csv'],peak_results); % one file per subject with averaged peaks and mins per leg
% row 1: left leg  row 2: right leg  row 3: both legs (for controls only)

writeMeans

subjects={'S01','S03','S04','S05','S06','S07','S09','S10','S11','S12','S15','S16','S17','S18','S19','S20','S21'};

for subject=1:length(subjects)
    str=subjects(subject);
    DIRECTORY=['C:\Users\Marchiano\Documents\MATLAB\Marchiano Lunge\All Raw Data' str];
    % get a list of all left and right outcome files
    l_files=dir([DIRECTORY 'final_*l*']);
    r_files=dir([DIRECTORY 'final_*r*']);
l_strike=zeros(length(l_files),size(csvread(l_files(1).name),2));
l_whole=[];
l_toeoff=l_strike;
l_phase1=l_whole;
l_phase2d=l_whole;
l_phase2u=l_whole;
l_phase3=l_whole;

for number=1:length(l_files)
    final_data=csvread(l_files(number).name);
    ldata1=final_data(final_data(:,end)==1,:);
    ldata2d=final_data(final_data(:,end)==2,:);
    ldata2u=final_data(final_data(:,end)==2.5,:);
    ldata3=final_data(final_data(:,end)==3,:);

    l_phase1(size(l_phase1,1)+1:size(l_phase1,1)+size(ldata1,1),:)=ldata1;
    l_phase2d(size(l_phase2d,1)+1:size(l_phase2d,1)+size(ldata2d,1),:)=ldata2d;
    l_phase2u(size(l_phase2u,1)+1:size(l_phase2u,1)+size(ldata2u,1),:)=ldata2u;
    l_phase3(size(l_phase3,1)+1:size(l_phase3,1)+size(ldata3,1),:)=ldata3;
    l_whole(size(l_whole,1)+1:size(l_whole,1)+size(final_data,1),:)=final_data;
    tags=find(final_data(:,end)==2 | final_data(:,end)==2.5);
    l_strike(number,:)=final_data(tags(1),:);
    l_toeoff(number,:)=final_data(tags(end),:);
end

phase_mean(1,:)=mean(l_phase1,1);
phase_mean(2,:)=mean(l_phase2d,1);
phase_mean(3,:)=mean(l_phase2u,1);
phase_mean(4,:)=mean(l_phase3,1);
phase_mean(5,:)=mean(l_whole,1);

event(1,:)=mean(l_strike,1);
event(2,:)=mean(l_toeoff,1);

r_strike=zeros(length(r_files),size(csvread(r_files(1).name),2));
r_whole=[];
r_toeoff=r_strike;
r_phase1=r_whole;
r_phase2d=r_whole;
r_phase2u=r_whole;
r_phase3=r_whole;

for number=1:length(r_files)
    final_data=csvread(r_files(number).name);
    rdata1=final_data(final_data(:,end)==1,:);
    rdata2d=final_data(final_data(:,end)==2,:);
    rdata2u=final_data(final_data(:,end)==2.5,:);
rdata3 = final_data(final_data(:, end) == 3, :);

r_phase1(size(r_phase1, 1) + 1:size(r_phase1, 1) + size(rdata1, 1), :) = rdata1;
r_phase2d(size(r_phase2d, 1) + 1:size(r_phase2d, 1) + size(rdata2d, 1), :) = rdata2d;
r_phase2u(size(r_phase2u, 1) + 1:size(r_phase2u, 1) + size(rdata2u, 1), :) = rdata2u;
r_phase3(size(r_phase3, 1) + 1:size(r_phase3, 1) + size(rdata3, 1), :) = rdata3;
r_whole(size(r_whole, 1) + 1:size(r_whole, 1) + size(final_data, 1), :) = final_data;

tags = find(final_data(:, end) == 2 | final_data(:, end) == 2.5);

r_strike(number, :) = final_data(tags(1), :);
r_toeoff(number, :) = final_data(tags(end), :);

phase_mean(6, :) = mean(r_phase1, 1);
phase_mean(7, :) = mean(r_phase2d, 1);
phase_mean(8, :) = mean(r_phase2u, 1);
phase_mean(9, :) = mean(r_phase3, 1);
phase_mean(10, :) = mean(r_whole, 1);

phase_mean(11, :) = mean(vertcat(l_phase1, r_phase1), 1);
phase_mean(12, :) = mean(vertcat(l_phase2d, r_phase2d), 1);
phase_mean(13, :) = mean(vertcat(l_phase2u, r_phase2u), 1);
phase_mean(14, :) = mean(vertcat(l_phase3, r_phase3), 1);
phase_mean(15, :) = mean(vertcat(l_whole, r_whole), 1);

event(3, :) = mean(r_strike, 1);
event(4, :) = mean(r_toeoff, 1);

event(5, :) = mean(vertcat(l_strike, r_strike), 1);
event(6, :) = mean(vertcat(l_toeoff, r_toeoff), 1);

csvwrite(['C:\Users\Marchiano\Documents\MATLAB\Marchiano Lunge\means ' str1:end-1 ' .csv'], phase_mean); % write means for each phase in the order initial, down, up, return;
% row 1-5: left leg  row 6-10: right leg  row 11-15: both legs (for controls
% only)
csvwrite(['C:\Users\Marchiano\Documents\MATLAB\Marchiano Lunge\event ' str1:end-1 ' .csv'], event); % write mean strike and
toeoff data for each subject
% row 1 and 2: left mean  row 3 and 4: right mean
% row 5 and 6: both legs compiled mean (use for controls only)
end

compileNormalizedFinal

% compile time normalized data for each of the 3 groups

controls = csvread(['C:\Users\Marchiano\Documents\MATLAB\Marchiano Lunge\All Raw Data\normalized_control.csv']);
involved=csvread('C:\Users\Marchiano\Documents\MATLAB\Marchiano Lunge\All Raw Data\normalized_involved.csv');
uninvolved=csvread('C:\Users\Marchiano\Documents\MATLAB\Marchiano Lunge\All Raw Data\normalized_uninvolved.csv');
sag_mom=controls(1:9:end,:);
front_mom=controls(2:9:end,:);
trans_mom=controls(3:9:end,:);
sag_ang=controls(4:9:end,:);
front_ang=controls(5:9:end,:);
trans_ang=controls(6:9:end,:);
sag_power=controls(7:9:end,:);
front_power=controls(8:9:end,:);
trans_power=controls(9:9:end,:);

controls={[mean(sag_mom,1); mean(front_mom,1); mean(trans_mom,1); mean(sag_ang,1); mean(front_ang,1); mean(trans_ang,1); mean(sag_power,1); mean(front_power,1); mean(trans_power,1)]};

involved=csvread('C:\Users\Marchiano\Documents\MATLAB\Marchiano Lunge\All Raw Data\normalized_involved.csv');
uninvolved=csvread('C:\Users\Marchiano\Documents\MATLAB\Marchiano Lunge\All Raw Data\normalized_uninvolved.csv');
sag_mom=involved(1:9:end,:);
front_mom=involved(2:9:end,:);
trans_mom=involved(3:9:end,:);
sag_ang=involved(4:9:end,:);
front_ang=involved(5:9:end,:);
trans_ang=involved(6:9:end,:);
sag_power=involved(7:9:end,:);
front_power=involved(8:9:end,:);
trans_power=involved(9:9:end,:);

involved={[mean(sag_mom,1); mean(front_mom,1); mean(trans_mom,1); mean(sag_ang,1); mean(front_ang,1); mean(trans_ang,1); mean(sag_power,1); mean(front_power,1); mean(trans_power,1)]};

statsSetup
directory='C:\Users\Marchiano\Documents\MATLAB\Marchiano Lunge\';
subjects={'S01','S02','S03','S04','S05','S06','S07','S09',...
whole=zeros(13,10); p1=whole; p2=whole; p3=whole; p4=whole; acls=zeros(6,10); contra=acls; p1a=acls; p1c=acls; p2a=acls; p2c=acls; p3a=acls; p3c=acls; p4a=acls; p4c=acls;

for i=1:length(subjects)
    means=[directory 'means_' subjects{i} '.csv'];
    optima=[directory 'mean_time_' subjects{i} '.csv'];
    mdata=csvread(means);
    odata=csvread(optima);
    whole(i,1:end-1)=[-1*mdata(end,1:3) mdata(end,4:6) -1*mdata(end,10:12)];
    p1(i,1:end-1)=[-1*mdata(end-4,1:3) mdata(end-4,4:6) -1*mdata(end-4,10:12)];
    p2(i,1:end-1)=[-1*mdata(end-3,1:3) mdata(end-3,4:6) -1*mdata(end-3,10:12)];
    p3(i,1:end-1)=[-1*mdata(end-2,1:3) mdata(end-2,4:6) -1*mdata(end-2,10:12)];
    p4(i,1:end-1)=[-1*mdata(end-1,1:3) mdata(end-1,4:6) -1*mdata(end-1,10:12)];
    whole(i,end)=odata(end,5);
    p1(i,end)=odata(end,1);
    p2(i,end)=odata(end,2);
    p3(i,end)=odata(end,3);
    p4(i,end)=odata(end,4);
end
xlswrite([directory 'controls_stats.xlsx'], whole,'whole');
xlswrite([directory 'controls_stats.xlsx'], p1,'initial');
xlswrite([directory 'controls_stats.xlsx'], p2,'down');
xlswrite([directory 'controls_stats.xlsx'], p3,'up');
xlswrite([directory 'controls_stats.xlsx'], p4,'return');

for i=1:length(lacl)
    means=[directory 'means_' lacl{i} '.csv'];
    optima=[directory 'mean_time_' lacl{i} '.csv'];
    mdata=csvread(means);
    odata=csvread(optima);
    acls(i,1:end-1)=[-1*mdata(5,1:3) mdata(5,4:6) -1*mdata(5,10:12)];
pla(i,1:end-1)=[-1*mdata(1,1:3) mdata(1,4:6) -1*mdata(1,10:12)];
p2a(i,1:end-1)=[-1*mdata(2,1:3) mdata(2,4:6) -1*mdata(2,10:12)];
p3a(i,1:end-1)=[-1*mdata(3,1:3) mdata(3,4:6) -1*mdata(3,10:12)];
p4a(i,1:end-1)=[-1*mdata(4,1:3) mdata(4,4:6) -1*mdata(4,10:12)];
contra(i,1:end-1)=[-1*mdata(10,1:3) mdata(10,4:6) -1*mdata(10,10:12)];
plc(i,1:end-1)=[-1*mdata(6,1:3) mdata(6,4:6) -1*mdata(6,10:12)];
p2c(i,1:end-1)=[-1*mdata(7,1:3) mdata(7,4:6) -1*mdata(7,10:12)];
p3c(i,1:end-1)=[-1*mdata(8,1:3) mdata(8,4:6) -1*mdata(8,10:12)];
p4c(i,1,end-1)=[-1*mdata(9,1:3) mdata(9,4:6) -1*mdata(9,10:12)];

acls(i,end)=odata(1,5);
p1a(i,end)=odata(1,1);
p2a(i,end)=odata(1,2);
p3a(i,end)=odata(1,3);
p4a(i,end)=odata(1,4);
contra(i,end)=odata(2,5);
plc(i,end)=odata(2,1);
p2c(i,end)=odata(2,2);
p3c(i,end)=odata(2,3);
p4c(i,end)=odata(2,4);
end

for i=1:length(racl)
    means=[directory 'means_' racl{i} '.csv'];
    optima=[directory 'mean_time_' racl{i} '.csv'];

    mdata=csvread(means);
    odata=csvread(optima);

    contra(i+3,1:end-1)=[-1*mdata(5,1:3) mdata(5,4:6) -1*mdata(5,10:12)];
    plc(i+3,1:end-1)=[-1*mdata(1,1:3) mdata(1,4:6) -1*mdata(1,10:12)];
    p2c(i+3,1:end-1)=[-1*mdata(2,1:3) mdata(2,4:6) -1*mdata(2,10:12)];
    p3c(i+3,1:end-1)=[-1*mdata(3,1:3) mdata(3,4:6) -1*mdata(3,10:12)];
    p4c(i+3,1:end-1)=[-1*mdata(4,1:3) mdata(4,4:6) -1*mdata(4,10:12)];

    acls(i+3,1,end-1)=[-1*mdata(10,1:3) mdata(10,4:6) -1*mdata(10,10:12)];
    plc(i+3,1:end-1)=[-1*mdata(6,1:3) mdata(6,4:6) -1*mdata(6,10:12)];
    p2a(i+3,1:end-1)=[-1*mdata(7,1:3) mdata(7,4:6) -1*mdata(7,10:12)];
    p3a(i+3,1:end-1)=[-1*mdata(8,1:3) mdata(8,4:6) -1*mdata(8,10:12)];
    p4a(i+3,1,end-1)=[-1*mdata(9,1:3) mdata(9,4:6) -1*mdata(9,10:12)];

    contra(i+3,end)=odata(1,5);
    plc(i+3,end)=odata(1,1);
    p2c(i+3,end)=odata(1,2);
    p3c(i+3,end)=odata(1,3);
    p4c(i+3,end)=odata(1,4);

    acls(i+3,end)=odata(2,5);
    plc(i+3,end)=odata(2,1);
    p2a(i+3,end)=odata(2,2);
    p3a(i+3,end)=odata(2,3);
    p4a(i+3,end)=odata(2,4);
end
calcShankStaticCS

function shank_cs=calcShankStaticCS(knee,lmal,mmal,ankle,side)
% function seg_cardan=calcShankCS(segments,knee,lmal,mmal,ankle,side)
shank_cs=zeros(size(knee,1)*3,3);
for frame=1:size(knee,1)
  i_axis=knee(frame,:)-ankle(frame,:);
  if side=='l'
    k_axis=lmal(frame,:)-mmal(frame,:);
  else
    k_axis=mmal(frame,:)-lmal(frame,:);
  end
  j_axis=cross(k_axis,i_axis);
  i_axis=i_axis/norm(i_axis);
  j_axis=j_axis/norm(j_axis);
  k_axis=k_axis/norm(k_axis);
  shank_cs(frame*3-2:frame*3,:)=[j_axis;k_axis;i_axis]; % ab/ad,flex/ext,int/ext
end
end

calcThighStaticCS

function thigh_cs=calcThighStaticCS(knee,lepi,mepi,hip,side)
% function segments=calcThighCS(segments,knee,lepi,mepi,hip,side)
thigh_cs=zeros(size(knee,1)*3,3);
for frame=1:size(knee,1)
  i_axis=hip(frame,:)-knee(frame,:);
  if side=='l'
    k_axis=lepi(frame,:)-mepi(frame,:);
  else
    k_axis=mepi(frame,:)-lepi(frame,:);
  end
  j_axis=cross(k_axis,i_axis);
  i_axis=i_axis/norm(i_axis);
\begin{verbatim}
  j_axis = j_axis/norm(j_axis);
  k_axis = k_axis/norm(k_axis);

  thigh_cs(frame*3-2:frame*3,:) = [j_axis;k_axis;i_axis];  
  \% ab/ad, flex/ext, int/ext
  end

sortFiles

function [controls, uninvolved, involved] = sortFiles(directory)
  % function sorted = sortFiles(directory)
  % get a list of files in the directory that start with prefix (a string)
  % and sort
  % files into controls, uninvolved, involved

  files = dir(directory);
  acls = {'s10r', 's12l', 's17l', 's18r', 's19l', 's20r'};
  contra = {'s10l', 's12r', 's17r', 's18l', 's19r', 's20l'};

  involved = [];
  uninvolved = [];
  controls = [];

  for i = 1:length(files)
    str = files(i).name;
    if any(ismember(acls, str(12:15))) == 1
      n = numel(involved);
      involved(n+1) = str;
    elseif any(ismember(contra, str(12:15))) == 1
      n = numel(uninvolved);
      uninvolved(n+1) = str;
    else
      n = numel(controls);
      controls(n+1) = str;
    end
  end

avgNorm

function normalized = avgNorm(files)
  % function normalized = avgNorm(files)
  % take in csv files of equal columns (already normalized data to cycle),
  % vertically concatenate data, and calculate average
  % average is calculated for each group

  normalized = [];

  for i = 1:size(files, 1)
    data = csvread(files(i).name);
    normalized(size(normalized, 1)+1, :) = data;
  end

  normalized = mean(normalized, 1);
end
\end{verbatim}
Appendix E

Participant Group Comparison
Table E1. **Participant group comparison**

<table>
<thead>
<tr>
<th></th>
<th>Healthy control</th>
<th>Uninvolved/ ACLR</th>
<th>t-test statistic (two-tailed)</th>
<th>p-value (two-tailed)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Age (years)</strong></td>
<td>21.05 ± 1.24</td>
<td>20.19 ± 1.81</td>
<td>1.20</td>
<td>0.245</td>
</tr>
<tr>
<td><strong>Height (cm)</strong></td>
<td>170.52 ± 7.43</td>
<td>164.26 ± 5.38</td>
<td>1.84</td>
<td>0.083</td>
</tr>
<tr>
<td><strong>Mass (kg)</strong></td>
<td>67.26 ± 7.78</td>
<td>61.48 ± 4.21</td>
<td>1.69</td>
<td>0.109</td>
</tr>
<tr>
<td><strong>Leg length (cm)</strong></td>
<td>95.48 ± 5.12</td>
<td>91.02 ± 3.29</td>
<td>1.95</td>
<td>0.068</td>
</tr>
</tbody>
</table>

Table E2. **Mean number of trials considered for each group**

<table>
<thead>
<tr>
<th></th>
<th>Healthy control</th>
<th>Uninvolved</th>
<th>ACLR</th>
<th>p-value (two-tailed)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mean number of trials considered</strong></td>
<td>18.15 ± 2.12</td>
<td>9.17 ± 0.75</td>
<td>9.67 ± 0.82</td>
<td></td>
</tr>
</tbody>
</table>

Table E3. **Mean individual phase and overall movement times (s)**

<table>
<thead>
<tr>
<th>Phase</th>
<th>Healthy control</th>
<th>Uninvolved</th>
<th>ACLR</th>
<th>p-value (two-tailed)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Initial swing</strong></td>
<td>0.83 ± 0.098</td>
<td>0.85 ± 0.10</td>
<td>0.86 ± 0.077</td>
<td>0.836</td>
</tr>
<tr>
<td><strong>Stance down</strong></td>
<td>0.74 ± 0.19</td>
<td>1.04 ± 0.34</td>
<td>1.01 ± 0.38</td>
<td>0.058</td>
</tr>
<tr>
<td><strong>Stance up</strong></td>
<td>0.41 ± 0.084</td>
<td>0.35 ± 0.073</td>
<td>0.36 ± 0.041</td>
<td>0.268</td>
</tr>
<tr>
<td><strong>Return swing</strong></td>
<td>0.83 ± 0.075</td>
<td>0.69 ± 0.12</td>
<td>0.76 ± 0.11</td>
<td>0.056</td>
</tr>
<tr>
<td><strong>Time taken to complete one forward lunge</strong></td>
<td>2.80 ± 0.30</td>
<td>2.93 ± 0.52</td>
<td>2.99 ± 0.44</td>
<td>0.597</td>
</tr>
</tbody>
</table>
Appendix F

Post-Hoc Power Analysis
**Table F1.** Effect size and statistical power achieved by the one-way ANOVA of each investigated outcome measure

<table>
<thead>
<tr>
<th>Outcome measure</th>
<th>Effect size</th>
<th>Power achieved</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial phase flexion moment</td>
<td>0.44</td>
<td>0.30</td>
</tr>
<tr>
<td>Initial phase extension moment</td>
<td>0.24</td>
<td>0.12</td>
</tr>
<tr>
<td>Stance down phase flexion moment</td>
<td>0.25</td>
<td>0.13</td>
</tr>
<tr>
<td>Stance down phase extension moment</td>
<td>0.28</td>
<td>0.15</td>
</tr>
<tr>
<td>Stance up phase flexion moment</td>
<td>0.47</td>
<td>0.34</td>
</tr>
<tr>
<td>Stance up phase extension moment</td>
<td>0.38</td>
<td>0.23</td>
</tr>
<tr>
<td>Return phase flexion moment</td>
<td>0.29</td>
<td>0.16</td>
</tr>
<tr>
<td>Return phase extension moment</td>
<td>0.50</td>
<td>0.38</td>
</tr>
<tr>
<td>Initial phase internal rotation moment</td>
<td>0.17</td>
<td>0.084</td>
</tr>
<tr>
<td>Initial phase external rotation moment</td>
<td>0.14</td>
<td>0.073</td>
</tr>
<tr>
<td>Stance down phase internal rotation moment</td>
<td>0.49</td>
<td>0.36</td>
</tr>
<tr>
<td>Stance down phase external rotation moment</td>
<td>0.25</td>
<td>0.13</td>
</tr>
<tr>
<td>Stance up phase internal rotation moment</td>
<td>0.41</td>
<td>0.27</td>
</tr>
<tr>
<td>Stance up phase external rotation moment</td>
<td>0.37</td>
<td>0.22</td>
</tr>
<tr>
<td>Return phase internal rotation moment</td>
<td>0.35</td>
<td>0.20</td>
</tr>
<tr>
<td>Return phase external rotation moment</td>
<td>0.53</td>
<td>0.43</td>
</tr>
<tr>
<td>Initial phase valgus moment</td>
<td>0.27</td>
<td>0.14</td>
</tr>
<tr>
<td>Initial phase varus moment</td>
<td>0.22</td>
<td>0.11</td>
</tr>
<tr>
<td></td>
<td>Stance down phase valgus moment</td>
<td></td>
</tr>
<tr>
<td>------------------</td>
<td>---------------------------------</td>
<td>---------</td>
</tr>
<tr>
<td></td>
<td>0.27</td>
<td>0.14</td>
</tr>
<tr>
<td></td>
<td>Stance up phase valgus moment</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.29</td>
<td>0.15</td>
</tr>
<tr>
<td></td>
<td>Return phase valgus moment</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.52</td>
<td>0.41</td>
</tr>
</tbody>
</table>

Post-hoc analysis was done using G*Power 3.1.5 software. To yield the most conservative post-hoc sample size analysis, the analysis was conducted with the investigated outcome measure that produced the smallest effect size. The external rotation moment during the initial phase yielded the smallest effect size with 0.14 and thus was used in the post-hoc power analysis to determine the required sample size to achieve the desired statistical power of 0.8. The analysis indicated that a statistical power of 0.073 was achieved and a sample size of 242 participants per group is needed to achieve the desired statistical power with significance set at $p < 0.05$. 
Appendix G

Compiled Three-Dimensional Knee Moment Curve
Figure G1. Compiled three-dimensional knee moment curve