Passive Frontal Plane Knee Joint Laxity Following Anterior Cruciate Ligament Reconstruction Within 6 Months to 5 Years

by

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Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners. I understand that my thesis may be electronically available to the public.

Abstract

Following an anterior cruciate ligament rupture, surgical reconstructions aim to restore the joint stability. Increased frontal plane laxity has been observed in the anterior cruciate ligament deficient knee, intra-operatively immediately following reconstruction compared to contralateral knees, and in osteoarthritic knees. This indicates that surgical intervention may not have fully mitigated the increased frontal plane laxity associated with an anterior cruciate ligament tear.

The primary objective of this study was to compare passive frontal plane laxity in a relatively young study cohort (aged 19-24) across three knee statuses (anterior cruciate ligament reconstructed knees (between 6 months to 5 years post-operation), contralateral knees, and knees from a control group), taking into account sex. It was hypothesized that the anterior cruciate ligament reconstructed knees would have the greatest frontal plane laxity, followed by the contralateral knees, and finally the control knees, where females would have a greater laxity compared to males across all three knee statuses. A secondary objective of this study was to quantify the repeatability and sensitivity of the frontal plane measurement system following design modifications that: removed the effect of the gravitational force from the plane of measurement, applied a consistent load between participants, allowed rotation about the knee's natural joint center, and monitored muscle activity that ensured passive laxity measures. It was hypothesized that the frontal plane measurement system of this study would have a greater repeatability and sensitivity compared to previous designs reported in the literature.

Twenty-four university aged participants (twelve females mean age 20.5 ± 1.8 and twelve males mean age 21.7 ± 2.3) were recruited for this cohort study. There were two groups: twelve participants with one ACL reconstructed knee and one contralateral knee (that had no previous ACL tear or repair) and twelve age- and sex-matched controls. Of the ACL reconstructed participants, six received a bone-patellar tendon-bone autograft and six received a hamstring autograft during their ACL reconstruction. Passive bilateral lower limb kinematic data was collected using infrared marker clusters while vastus lateralis and vastus medialis electromyographic readings were recorded. The mean laxity from three trials was measured using a free moving sled apparatus. Frontal plane laxity was defined as the passive varus-valgus tibiofemoral angular excursion in response to a varus-valgus moment of 10 Nm. For controls, the knee with the greatest measured mean frontal plane laxity was used. The standard error of measurement and minimal detectable difference was calculated using the mean of the three repeated laxity measures for the right limb across all participants. The means of the three repeated laxity measures for each knee status (ACL reconstructed knees, contralateral knees, and controls knees) were used in one two-way mixed model analysis of variance between ACL reconstructed knees and contralateral knees (status x sex) with an alpha level of 0.05 and two additional two-way ANOVA between ACL reconstructed knees and controls knees, and contralateral knees and control knees (status x sex) with an alpha level of 0.05. One t-test with an alpha level of 0.05 was used to determine if there were any statistically significant differences between the type of surgical reconstruction (bone-patellar tendon-bone graft or hamstring graft).

The standard error of measurement and mean detectable difference was 0.7° and 1.8° respectively. No statistically significant knee status main effect, sex main effect and knee status x sex interaction occurred (all $p>0.05$). There was no significant difference in laxity between reconstruction types ($p>0.05$).

This sample population achieved normal frontal plane knee laxity at short-term follow-up. This supports the possibility that the laxity previously measured in long-term follow-up is not residual laxity from the anterior cruciate ligament rupture that was insufficiently addressed by the reconstruction procedure. Increased frontal plane laxity that has been observed in anterior cruciate ligament reconstructed and osteoarthritic knees may instead be an outcome of the disease itself or other risk factors.

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List of Abbreviations

ACL – anterior cruciate ligament

AM – anteromedial

ANOVA – analysis of variance

AP – anterior-posterior

BPTB – bone-patellar tendon-bone

EMG – electromyographic

MDD – minimal detectable difference

MVICs – maximal voluntary isometric contractions

PL – posterolateral

SEM – standard error of measurement

Chapter 1: Introduction

The anterior cruciate ligament (ACL) is one of the ligamentous tissues of the knee joint that stabilizes the knee during daily activities (McLean et al., 2015). Non-contact ACL tears are the most common mechanism of rupture (McLean et al., 2015), where an untreated ACL rupture can lead to significant instability and secondary damage including meniscus tears and articular cartilage injuries within the knee joint (Zantop et al., 2006). Treatment of an ACL rupture often requires surgical intervention to replace the tissue in order to return to a desired level of physical activity (McLean et al., 2015). Females are 2.4 to 4.1 times more likely to rupture their ACL compared to males (Arendt & Dick, 1995). The greater ratio of females to males sustaining an ACL rupture increases the ratio of females undergoing an ACL reconstruction. ACL reconstructed patients are also 1.63 times more likely to rupture their contralateral ACL than that of their reconstructed ligament (Magnussen et al., 2015), where females are more likely to experience a contralateral rupture than males (Sutton & Bullock, 2013). This unbalanced susceptibility has led to the consideration of sex differences when addressing risk factors associated with ACL reconstructed knees, where these surgical procedures overall increase the risk of post-traumatic osteoarthritic development in patients (Taruc-Uy & Lynch, 2013).

ACL reconstructions aim to surgically restore stability and kinematics of the injured knee joint, with the objective of protecting the knee from further developing severe meniscal tears, cartilage damage, and osteoarthritis (Xie et al., 2015; Zantop et al., 2006). However, an ACL tear and surgical reconstruction itself can predispose an individual to osteoarthritis (Imbert et al., 2015). Osteoarthritis is the most common degenerative joint disorder that remains challenging to treat due to evolving risk factors and pathophysiology that could lead to worsening of disease severity and progression over time (Martel-Pelletier et al., 2016). Osteoarthritis is classified into primary (idiopathic) or secondary forms (Martel-Pelletier et al., 2016; Taruc-Uy & Lynch, 2013), where secondary osteoarthritis can be attributed to predisposing causative factors such as trauma (Martel-Pelletier et al., 2016; Taruc-Uy & Lynch, 2013). Mechanical stress and trauma such as an ACL tear, repeated trauma to soft tissue, and surgery such as an ACL reconstruction, are some examples of factors that could lead to secondary, or post-traumatic, osteoarthritis (Taruc-Uy & Lynch, 2013). The complexity of an ACL tear results in increased mechanical stress to the knee and damage to the surrounding tissue (Louboutin et al., 2009), where surgical reconstruction aims to reduce these risk factors (Xie et al., 2015; Zantop et al., 2006). However, the grafts used for surgical reconstruction can be too elastic and can result in residual joint laxity (Smeets et al., 2017). Increased residual joint laxity increases joint instability, which has been reported as a risk factor for the development of osteoarthritis (Øiestad et al., 2009). The identification of residual joint laxity is important when trying to ensure optimal knee kinematics of the lower limb following an ACL reconstruction and decreasing the risk of osteoarthritic development.

Clinically, sagittal plane measures of laxity are assessed the most frequently, measured as either the AP translation or the angular range of motion of the tibia with respect to the femur (Aït Si Selmi et al., 2006; Salmon et al., 2006). Increased anterior-posterior (AP) laxity (assessed as AP translation via Lachman test) has been identified as having a statistically significant relationship with degenerative radiographic knee changes (Aït Si Selmi et al., 2006; Salmon et al., 2006). Post-operatively, it has been shown that AP laxity persists 6 months to 6 years following an ACL reconstruction (Shimizu et al., 2019).

In the frontal plane, the ACL acts as a constraint to excessive joint space between the tibia and femur in the medial and lateral compartments of the knee (Grood et al., 1981). Frontal plane (varus-valgus) knee laxity can manifest due to damage or impairment in the passive restraint system of ligamentous tissue (Sharma, Lou, et al., 1999). Following rupture, it had been shown that the frontal plane laxity increased the longer the wait for surgical repair (Signorelli et al., 2016), however post-operative measures have not been studied in detail. It has been speculated that increased frontal plane laxity may precede osteoarthritic development and raises the question on whether or not increased laxity may contribute to osteoarthritic progression (Sharma, Lou, et al., 1999).

The variance reported across frontal plane laxity measures throughout the literature has been attributed to the use of different frontal plane measurement system designs (Freisinger et al., 2017). Addressing and reducing design limitations such as inconsistent knee flexion angles (Freisinger et al., 2017), inconsistent applied loads at end range of motion (Sharma, Lou, et al., 1999; Shultz et al., 2007; van der Esch, Steultjens, Ostelo, et al., 2006), muscle activation (Sharma, Lou, et al., 1999), and measuring equipment with highly variable readings would further improve the repeatability and sensitivity in detecting measurement differences between sexes (Shultz et al., 2007).

Characterizing frontal plane knee joint laxity could assist in identifying a risk factor that might precede osteoarthritic development. There is a need for short to medium-term ACL reconstruction follow up in individuals without osteoarthritic symptoms, using a laxity measurement device that addresses the limitations of previous set-ups, to determine if increased frontal plane laxity can be detected before osteoarthritis development.

Chapter 2: Objectives and Hypotheses

The primary objective of this study was:

> *To compare passive frontal plane laxity in a relatively young study cohort (aged 19-24) across three knee statuses (anterior cruciate ligament reconstructed knees (between 6 months to 5 years post-operation), contralateral knees, and knees from a control group), between sexes across all three knee statuses.*

It was hypothesized that the anterior cruciate ligament reconstructed knees would have the greatest frontal plane laxity, followed by the contralateral knees, and finally the control knees, where females would have a greater laxity compared to male across all three knee statuses. This hypothesis was based on the following factors: ACL reconstructed knees have shown residual frontal plane knee joint laxity immediately following reconstruction (Imbert et al., 2015), increased residual joint laxity has been reported as a risk factor for the development of osteoarthritis (Øiestad et al., 2009), and there is a higher prevalence of moderate osteoarthritic development in ACL reconstructed knees compared to the contralateral knees without an osteoarthritic diagnosis fourteen years following an ACL reconstruction (Barenius et al., 2014).

A secondary objective of this study was:

> *To quantify the repeatability and sensitivity of the frontal plane measurement system following design modifications that: removed the effect of the gravitational force from the plane of measurement, applied a consistent load between participants, allowed rotation about the knee's natural joint center, and monitored muscle activity that ensured passive laxity measures.*

It was hypothesized that the frontal plane measurement system of this study would have a greater repeatability and sensitivity compared to previous designs reported in the literature. This hypothesis was based on the following factors: Using a consistent knee flexion angle most commonly used across the literature to reduce variance in measures (Freisinger et al., 2017), orientating the shank in a gravity neutral position to ensure total applied loads are consistent across participants compared to previous designs (Sharma, Lou, et al., 1999; Shultz et al., 2007; van der Esch, Steultjens, Ostelo, et al., 2006), allowing the shank to rotate about the knee's natural joint center instead of a fixed mechanical axis (Sharma, Lou, et al., 1999; Shultz et al., 2007; van der Esch, Steultjens, Ostelo, et al., 2006), monitoring muscle activation to confirm passive laxity was being monitored (Sharma, Lou, et al., 1999), and the use of motion capture to track laxity measures (Shultz et al., 2007) that reduced error in the measurements themselves as a result of recording system accuracy and variability reduction.

Chapter 3: Literature Review

3.1 ACL Anatomy and Etiology of Rupture

3.1.1 Anatomy

The ACL is an oblique intra-articular ligament of the knee (Petersen & Zantop, 2007) that arises from the anterior intercondylar area of the tibia and just posterior to the medial meniscus, attaching to the posterior part of the medial aspect of the lateral femoral condyle (Duthon et al., 2006). This ligament is composed of two bundles, the anteromedial and posterolateral bundles (Duthon et al., 2006; Petersen & Zantop, 2007; Zantop et al., 2006). Each respective bundle is named in relation to the attachment of is fibers on the tibial plateau (Figure 3.1) (Norwood & Cross, 1979; Zantop et al., 2006). Both bundles often have fiber attachments to the lateral meniscus; the anteromedial bundle may have attachments to the anterior horn of the lateral meniscus, whereas the posterolateral bundle may have attachments to the posterior root of the lateral meniscus (Irarrázaval et al., 2017).

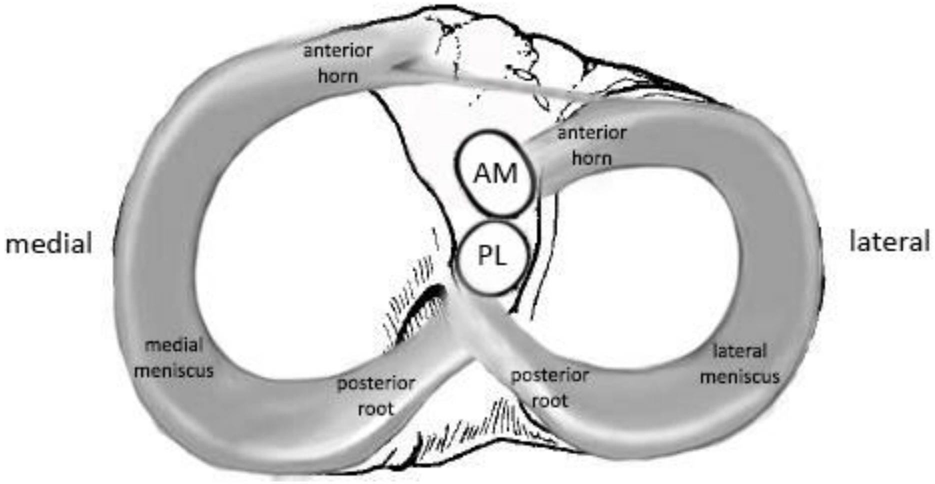

Figure 3.1: The anteromedial (AM) and posterolateral (PL) bundle insertion points on the tibial plateau in respect to the medial and lateral menisci.

The middle genicular artery provides blood supply to the ACL; however, the distal aspect of the ligament is poorly supplied, giving presence to poor vascularity in correlation with the low healing potential of the ACL following damage (Duthon et al., 2006). Fibrocartilage is also present in the anterior aspect of the tibial attachment of the ACL, further avascular and impacting the healing process post injury to warrant surgical intervention to prevent joint and tissue degeneration (Duthon et al., 2006).

3.1.2 Function

The ACL does not function as a simple band of fibers under constant tension as the knee moves through its full range of motion (Amis & Dawkins, 1991; Zantop et al., 2006). This ligament acts as the primary restraint to anterior tibial translation (Petersen & Zantop, 2007) and the secondary stabilizer to rotatory instabilities (Norwood & Cross, 1979) and constraint to excessive joint space between the tibia and femur in the medial and lateral compartments of the knee (Grood et al., 1981). In the frontal plane, the major motion that the ACL restricts is varus movement, where this ligament carries a substantial role in restraining varus-valgus rotation of an intact knee (Ohori et al., 2017).

3.1.3 Mechanism of Injury – A Perspective into Joint Degeneration

The complete rupture of the ACL can result in pathological knee conditions that include knee instability, meniscal damage, damage to the chondral surfaces, and predisposition to knee osteoarthritis (Yu & Garrett, 2007). Ligament rupture can result from two mechanisms of injury, contact and non-contact ACL tears (Salem et al., 2018). Contact ACL tears are a result of a direct external force to the knee by another person or object (Salem et al., 2018). Contact tears have a higher incidence of collateral ligament and articular cartilage injuries with an association of higher injury severity (Salem et al., 2018). Lateral femoral condyles are especially prevalent to chondral injury upon arthroscopy (Salem et al., 2018).

Non-contact ACL tears are the most common mechanisms of ligament rupture, occurring when individuals generate excessive force, moments, and loading on the ACL than it is capable of withstanding (Yu & Garrett, 2007). This mechanism of injury is in the absence of external forces other than ground reaction forces and result in multiplanar knee loading (Shimokochi & Shultz, 2008). The "position of no return" (Figure 3.2) is defined as the combined motions of hip adduction and internal rotation, external rotation of the tibia relative to the femur, internal rotation of the tibia on the foot, and forefoot pronation all occurring concurrently (Alentorn-Geli et al., 2009; Shimokochi & Shultz, 2008). In this position, there is high likelihood of ACL injury.

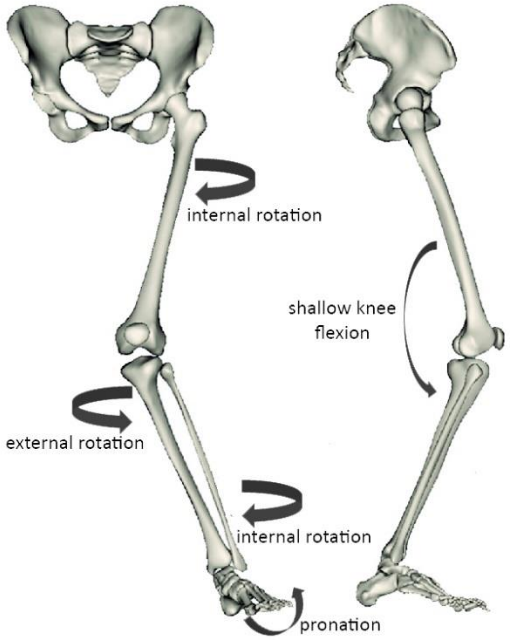

Figure 3.2: Mechanism of non-contact ACL injury defined as "position of no return".

Regardless of the mechanism of injury, a torn ACL has limited repair capabilities (McLean et al., 2015) due to the native tissue's poor vascularity. Pathologically, an ACL rupture can lead to significant instability and secondary damage including meniscus tears and articular cartilage injuries within the knee joint (Zantop et al., 2006). ACL deficient knees that are left untreated have been shown to develop increased mean contact stress on the posterior medial and lateral compartments of the joint due to an increased anterior tibial translation and internal tibial rotation without restraint (Simon et al., 2015). Excessive anterior tibial displacement results in shearing forces that are applied primarily on the medial compartment, with the posterior horn of the medial meniscus splitting between the tibia and posterior condyle of the femur (Louboutin et al., 2009). The degeneration of the posterior horn of the medial meniscus contributes to increased anterior tibial displacement on the femur as shear forces increase on the articular surfaces of the joint, leading to a loss of articular cartilage (Louboutin et al., 2009) . These series of events almost act as a positive feedback loop (Figure 3.3) to expose bone and accelerate osteophyte development (Louboutin et al., 2009) . The overall lack of a primary restraint to anterior tibial translation results in greater knee joint loading and increases the susceptibility to degeneration (Simon et al., 2015). Radiographic signs of osteoarthritis and limitations in activities of daily living are greatest in patients with conservative treatment without surgical interventions and combined cumulative knee injuries (Simon et al., 2015). This often requires the complete surgical replacement of the tissue in order to return to a moderate level of physical activity (McLean et al., 2015). Patients who are symptomatic with meniscal or cartilage damage following ligament rupture, or experience joint instability, are at an increased risk of developing osteoarthritis if surgical reconstruction is delayed as cumulative loading worsens the state of the joint (Louboutin et al., 2009).

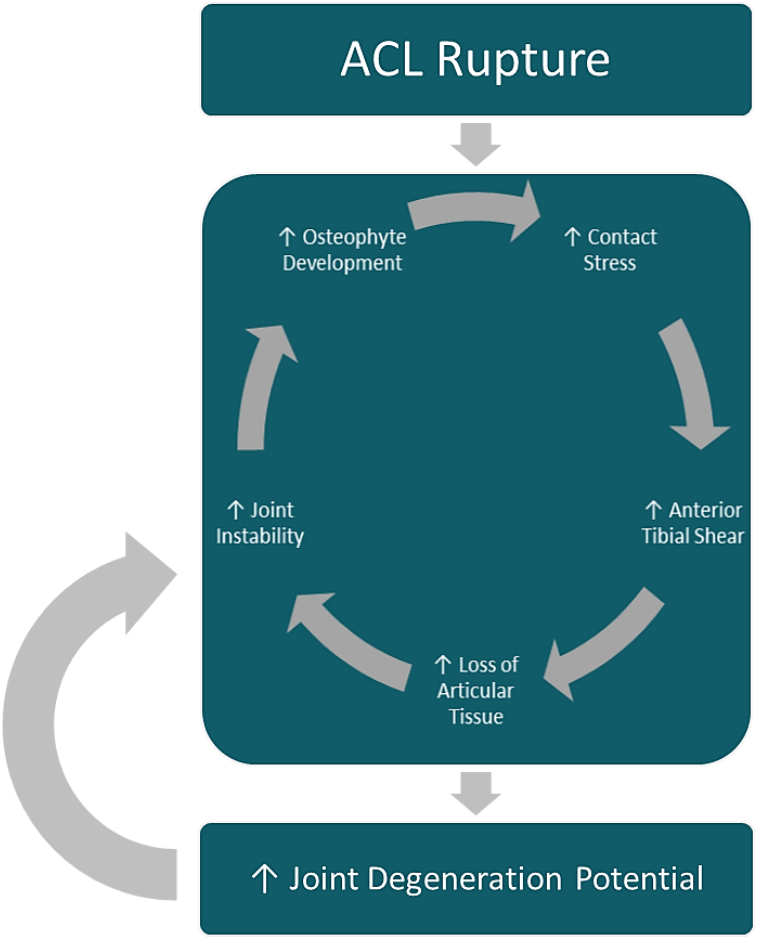

Figure 3.3: Summary of the positive feedback loop that increases the potential of knee joint degeneration following a complete ACL rupture.

ACL reconstructions aim to surgically restore joint stability, re-establish optimal knee kinematics, and protect the knee from further developing severe meniscal tears, cartilage damage, and osteoarthritis (Xie et al., 2015; Zantop et al., 2006). However, the grafts used for surgical reconstruction can be too stiff and can over-constrain the joint, restricting the range of motion (Dargel et al., 2007; Mae et al., 2010), or can be too elastic and can result in residual joint laxity (Smeets et al., 2017). These are two examples of potential initiators of the cascade of events that lead to degenerative joint disease. Increased residual joint laxity increases joint instability, which has been reported as a risk factor for the development of osteoarthritis (Øiestad et al., 2009). Identification of residual joint laxity is important when trying to ensure optimal knee kinematics of the lower limb and decreasing the risk of osteoarthritic development.

Females are 2.4 to 4.1 times more likely to rupture their ACL compared to their male counterparts in a 5-year study period (Arendt & Dick, 1995). Subsequently, the greater ratio of females to males sustaining an ACL rupture increases the risk of mechanical stress to the knee, cartilage damage to the surrounding tissue, risk of joint instability, and risk of developing osteoarthritis (Louboutin et al., 2009) if left untreated with this particular sex. With a minimum follow-up of 10 years from receiving an ACL reconstruction, patients are overall 1.63 times more likely to rupture their contralateral ACL than that of their reconstructed ligament (Magnussen et al., 2015), where females are more likely to experience a contralateral rupture than males (Sutton & Bullock, 2013). The overall greater ACL rupture ratio in females also creates an increased ratio females to males receiving surgical reconstructions, where surgical reconstructions themselves increase the risk of post-traumatic osteoarthritic development (Taruc-Uy & Lynch, 2013). Sex differences must be considered when addressing risk factors associated with ACL reconstructed knees, such as residual joint laxity, and the development of osteoarthritis.

3.2 Knee Osteoarthritis Following an ACL Tear

3.2.1 Knee Osteoarthritis

Osteoarthritis is a joint disorder, characterized by cell stress and extracellular matrix degradation that is initiated by micro- and macro-injury, activating maladaptive repair responses and pro-inflammatory pathways (March et al., 2016). First manifesting as abnormal joint tissue metabolism, it is followed by anatomic and/or physiologic imbalances to cartilage, bone remodelling, osteophyte formation, joint inflammation, and loss of joint function, that can culminate in illness (March et al., 2016). It is the most common degenerative joint disorder that remains challenging to treat due to evolving risk factors and pathophysiology that could lead to worsening of disease severity and progression over time (Martel-Pelletier et al., 2016). Osteoarthritis can be classified into primary (idiopathic) or secondary forms (Martel-Pelletier et al., 2016; Taruc-Uy & Lynch, 2013). Primary osteoarthritis can result from a combination of risk factors such as the wear and tear on the cartilage with increasing age (Taruc-Uy & Lynch, 2013) and obesity (Martel-Pelletier et al., 2016). Secondary osteoarthritis can be attributed to predisposing causative factors such as trauma (Martel-Pelletier et al., 2016; Taruc-Uy & Lynch, 2013). Mechanical stress, repeated trauma to soft tissue, and surgery, are some examples of factors that can lead to secondary or post-traumatic osteoarthritis (Taruc-Uy & Lynch, 2013). The complexity of an ACL tear can result in increased mechanical stress to the knee and damage to the surrounding tissue (Louboutin et al., 2009), where surgical reconstruction aims to reduce these risk factors (Xie et al., 2015; Zantop et al., 2006). However, surgical intervention itself is an additional predisposing risk factor to the development of osteoarthritis, resulting in joint trauma but also residual joint laxity (Smeets et al., 2017). The grafts used for surgical reconstruction can be too elastic and can result in residual joint laxity (Smeets et al., 2017), where increased residual joint laxity increases joint instability, which has been reported as a risk factor for the development of osteoarthritis (Øiestad et al., 2009).

3.2.2 Instability and Laxity

Joint instability and increased joint laxity have been reported as a risk factor for the development of osteoarthritis (Øiestad et al., 2009). Acute instability following rupture can become a chronic instability, resulting in greater knee joint loading and increasing the susceptibility to osteoarthritic degeneration (Simon et al., 2015). One important factor in restoring knee joint stability is correcting the increased knee joint laxity that results from an ACL tear (Xie et al., 2015; Zantop et al., 2006).

AP Laxity

AP laxity is clinically assessed the most, measured as either the AP translation or the angular range of motion of the tibia with respect to the femur (Aït Si Selmi et al., 2006; Salmon et al., 2006). Pre-operatively following rupture, it has been shown that AP laxity increased as a higher injury-to-surgery time was presented (Signorelli et al., 2016). Post-operatively, it has been shown that AP laxity persists 6 months to 6 years following an ACL reconstruction (Shimizu et al., 2019). Increased AP laxity (assessed as AP translation via Lachman test) has been identified as having a statistically significant relationship with degenerative radiographic knee changes (Aït Si Selmi et al., 2006; Salmon et al., 2006). Sustaining an ACL rupture increases the anterior tibial translation and internal tibial rotation (Simon et al., 2015), resulting in an increase of knee joint instability and laxity.

3.3 Frontal Plane Laxity

Frontal plane laxity can be defined as the passive, frontal plane angular range of motion with an application of a varus-valgus moment (Sharma, Lou, et al., 1999; van der Esch et al., 2005). In the frontal plane, the ACL acts as a constraint to excessive joint space between the tibia and femur in the medial and lateral compartments of the knee (Grood et al., 1981). Frontal plane (varus-valgus) knee laxity can manifest due to the damage or impairment in the passive restraint of the system of ligamentous tissue (Sharma, Lou, et al., 1999) such as an ACL rupture. It has been speculated that a portion of increased frontal plane laxity measured in osteoarthritic patients may precede osteoarthritic development and raises the question on whether increased frontal plane laxity may contribute to osteoarthritis progression (Sharma, Lou, et al., 1999).

ACL ruptured knees were found to have an increased frontal plane laxity as rupture-to-surgery time increased between a duration of 2 to 220 months (Signorelli et al., 2016). When comparing the ACL ruptured knee to the contralateral knees of patients, it was found that there was a significantly larger laxity in the ACL deficient knees (Figure 3.4) (Imbert et al., 2015). It was suggested that performing early surgical reconstruction might prevent the deterioration of knee stability over time, prior to and following surgical intervention (Signorelli et al., 2016). Immediately following surgical reconstruction, it was found that the ACL reconstruction did not restore frontal plane laxity to the level of the undiagnosed contralateral knees of patients, indicating residual laxity in the reconstructed knee (Imbert et al., 2015). Unfortunately, there was no further follow-up to determine if, or for how long this residual laxity persisted post-operatively (Imbert et al., 2015).

Fourteen years following an ACL reconstruction there was a higher prevalence of moderate osteoarthritic development in the ACL reconstructed knee compared to the contralateral knees without an osteoarthritic diagnosis for a cohort ranging between 29-57 years of age (Barenius et al., 2014).

Comparing frontal plane knee joint laxity between osteoarthritic patients and healthy controls has reported that frontal plane laxity was greater in knees with mild osteoarthritis and in the contralateral knees (that did not have an osteoarthritic diagnosis) compared to the control (Sharma, Lou, et al., 1999). In that study, controls were not age matched, and they were older than the osteoarthritic cohort (mean 71.4 versus 62.6 years of age), where controls had a sample size of N=25 and osteoarthritic had N = 164 (Sharma, Lou, et al., 1999). As the Kellgren and Lawrence grade increased for the severity of knee osteoarthritic changes, the mean frontal plane laxity increased (Sharma, Lou, et al., 1999). Both joint space narrowing, and malalignment of the knee have been associated with higher frontal plane knee joint laxity values in those diagnosed with knee osteoarthritis for an mean time of 10 years for patients 66.5 ± 10.3 years of age (van der Esch et al., 2005). When stress radiographs were taken following the application of a 15N force at the knee to create a varus and valgus motion, it was found that patients (50.3 ± 7.4 years of age) with medial compartmental osteoarthritis and genu varum had greater frontal plane laxity and instability compared to age- and gender-matched controls without osteoarthritis (Lewek et al., 2004).

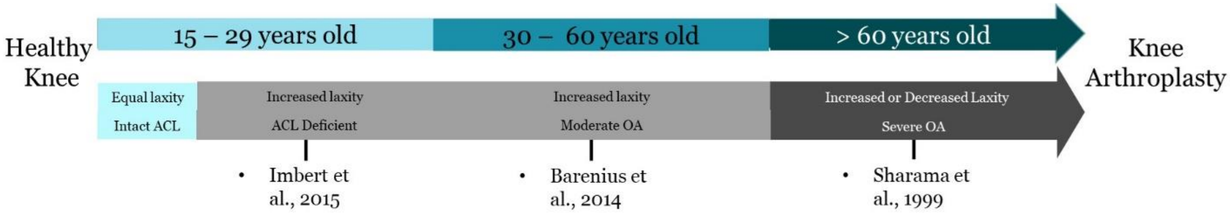

Figure 3.4: A summary of previously published literature examining frontal plane laxity and osteoarthritic development through a timeline of aging. Imbert et al. (2015) examined frontal plane laxity prior to and immediately following an ACL reconstruction. Barenius et al. (2014) found moderate osteoarthritic development in knees 14-years following an ACL reconstruction. Sharma et al. (1999) examined increasing frontal plane laxity as osteoarthritis severity increased as defined by the Kellgren and Lawrence grading system.

Across most studies above, authors reported samples sizes with a greater number of females than males but neglected to include sex comparisons (Barenius et al., 2014; Sharma, Lou, et al., 1999; van der Esch et al., 2005). There was also limited follow-up after ACL reconstruction to determine if, or for how long residual laxity persisted (Imbert et al., 2015). Furthermore, most patients undergoing an ACL reconstruction were 14-21 years of age for females or 18-25 years for males (Csintalan et al., 2008), whereas previous frontal plane laxity studies examined patients that were approaching middle age or older (participant ages were ≥33 years) and had already developed osteoarthritis (Lewek et al., 2004; Pottenger et al., 1990; Sharma, Lou, et al., 1999; van der Esch et al., 2005). This age range omits the examination of young adults who most frequently sustain an ACL tear and subsequent surgical reconstruction, a population that have tissue joint trauma that place them at a greater susceptibility to osteoarthritic development with sex differences (Louboutin et al., 2009; Martel-Pelletier et al., 2016; Taruc-Uy & Lynch, 2013).

3.4 Frontal Plane Laxity Measurement System Designs

Physician examinations have been reported to have poor interobserver reliability (Cushnaghan et al., 1990), where instrumented frontal plane laxity measurement devices were required to measure repeatable angles. Frontal plane measurement systems have been designed to assess laxity of the knee and minimize major sources of variation commonly seen during physical examination tests (Sharma, Lou, et al., 1999). The thigh is immobilized while the shank is supported and rotated along the transverse axis about the knee joint with the application of a fixed moment from the knee (Sharma, Lou, et al., 1999; Shultz et al., 2007; van der Esch et al., 2005). The application of this fixed moment occurs both in the abduction and adduction directions separately, along the frontal plane to create varus and valgus angular deviations, and then combined to get the total frontal plane laxity (Sharma, Lou, et al., 1999; van der Esch et al., 2005). However, the key attribution to the variance in reported measures was the use of different measurement system parameters across study devices (Freisinger et al., 2017).

Previous literature has used varying laxity system designs for the examination of passive frontal plane laxity in the knee joint (Table 3.1) of young adults using the right lower limb. The SEM has been used to measure how repeatable the measurement scores where, whereas the MDD was used to identify the smallest difference or change that the system could detect.

Table 3.1: Comparison of standard error of measurement (SEM) and minimal detectable difference (MDD) for frontal plane laxity measurement systems in the literature with young adults.

	Number of Participants (N)	**Sex**	**Measurement Method**	**Laxity (°)**	**Session Design for Determining MDD and SEM**	**SEM (°)**	**MDD (°)**
(Mines, 2016)	10	5M/5F	Motion Tracking	7.67 (2.4)	Same day	0.44	1.22
(Shultz et al., 2007)	10	5M/5F	Motion Tracking	9.6 (3.0)	Between-day	0.67	1.86
(van der Esch, Steultjens, Ostelo, et al., 2006)	20	10M/10F	Electrical Goniometer	5.92 (2.6)	Between-day	1.55	4.30

Measurement of frontal plane laxity using an electrical goniometer resulted in a MDD that was up to approximately 73% of the of the average frontal plane laxity values recorded (van der Esch, Steultjens, Ostelo, et al., 2006). When the error of the system is a high proportion of the measurements themselves, it can obscure differences in laxity measurements recorded by the system. However, when using a motion capture system and same day testing, improved repeatability and sensitivity occurs as reflected by a smaller SEM and MDD (Mines, 2016).

Previous studies also report using varying knee flexion angles from when measurements were taken (Freisinger et al., 2017), where 20° of knee flexion was seen to be the most common (Sharma, Lou, et al., 1999; Shultz et al., 2007; van der Esch et al., 2005). Designs combined gravitational force and applied loads as a result of the shank not being orientated horizontally, where individuals would experience different total applied loads at their end range of motion (Sharma, Lou, et al., 1999; Shultz et al., 2007; van der Esch, Steultjens, Ostelo, et al., 2006). These previous designs also forced the shank to rotate about a fixed mechanical axis rather than the knee's natural joint center (Shultz et al., 2007), potentially limiting the range of rotation. Finally, in previous work, stabilizing muscles that cross the knee joint were not monitored to confirm that they remained passive during the laxity measurement and thus that passive laxity was being measured (Sharma, Lou, et al., 1999; Shultz et al., 2007; van der Esch, Steultjens, Ostelo, et al., 2006). Only visual cues and palpation of the muscles supporting the lower limb was completed to assess muscle contraction and passive laxity measurement (Sharma, Lou, et al., 1999).

Overall, when examining frontal plane laxity there was a lack of focus on sex differences (Barenius et al., 2014; Sharma, Lou, et al., 1999; van der Esch et al., 2005) and young adults who most frequently sustain an ACL tear and subsequent surgical repair (Csintalan et al., 2008). Investigations of frontal plane laxity as a risk factor for the development of osteoarthritis have only been carried out when osteoarthritic development has already occurred at long-term follow-up (Lewek et al., 2004;

Pottenger et al., 1990; Sharma, Lou, et al., 1999; van der Esch et al., 2005), and not under short-term examination with an ACL reconstructed population that has a greater susceptibility to osteoarthritic degeneration (Simon et al., 2015). Addressing frontal plane measurement system design limitations, by ensuring a consistent knee flexion angle and total applied moment, rotation about the knee's natural joint center, and examination of muscle activation for passive laxity, would further improve the repeatability and detectability of laxity values. Adopting motion tracking into the measurement system used to record these values would also be more repeatable with a higher sensitivity in detecting measurement differences (Shultz et al., 2007) to examine populations at greater susceptibility of osteoarthritic degeneration.

In summary, both increased frontal plane laxity and ACL rupture/reconstruction are linked to osteoarthritis development. Increased frontal plane laxity has been observed in ACL deficient knees, reconstructed knees immediately following reconstruction, and in knees with (not necessarily post-traumatic) osteoarthritis. However, it's unclear if the laxity observed immediately following surgery persists, therefore potentially preceding and contributing as a factor for knee OA development in ACL reconstructed knees. This study addresses the short term follow up time frame after surgery to determine if frontal plane laxity persists and uses methodology for measuring frontal plane laxity that addresses some of the limitations of previous work.

Chapter 4: Methods

4.1 Study Population

Twenty-four university aged participants (twelve females mean age 20.5 ± 1.8 and twelve males mean age 21.7 ± 2.3) were recruited for this cohort study with approval from the institutional ethics board and provided informed consent. There were two groups: twelve participants with one ACL reconstructed knee and one contralateral knee (that had no previous ACL tear to repair) and twelve age- and sex-matched controls. ACL reconstructed participants were eligible to participate had they sustained a complete ACL rupture isolated to one knee, with at least six months since reconstructive surgery (Ajuied et al., 2014; Barenius et al., 2014; Hoffelner et al., 2012; Imbert et al., 2015; Sharma, Lou, et al., 1999; van der Hart et al., 2008). ACL reconstructed participants were required to self-report that their contralateral knee was free of injury (Imbert et al., 2015) had no previous surgery (van der Hart et al., 2008), and was asymptomatic (Hoffelner et al., 2012); showing no symptoms of pain, swelling, stiffness, or evidence of knee osteoarthritis (Signorelli et al., 2016). Evidence of osteoarthritis was assessed using the American College of Rheumatology Clinical Criteria (Wolfe et al., 1990). The contralateral knee with no osteoarthritis diagnosis represents the best possible reference for comparison purposes and has been used for comparison with both ACL deficient and ACL reconstructed knees (Hoffelner et al., 2012). Control participants knees were required to meet the same criteria as the contralateral knees for those with an ACLR knee. Participants were excluded if they had a history of unpredictable clicking, locking, or buckling, known meniscal tears, known joint fractures, known cartilage injury or Baker’s cyst, or if they had additional surgical procedures in either knee aside from one ACLR (Imbert et al., 2015; Sharma, Lou, et al., 1999). All ACLR participants were varsity athletes, sustaining their sports related ACL tear in soccer, basketball, or rugby. One participant chose not to report the specific date of when their operation was held, however they confirmed that it was at least six months prior to study participation.

4.2 Instrumentation and Experimental Design

4.2.1 Instrumentation

All participants were fitted with rigid body clusters (Figure 4.1) that attached bilaterally to the thigh, shank, and foot using an optoelectronic system (Certus, NDI, Waterloo, Canada), used to collect kinematic data sets recorded at 64Hz.

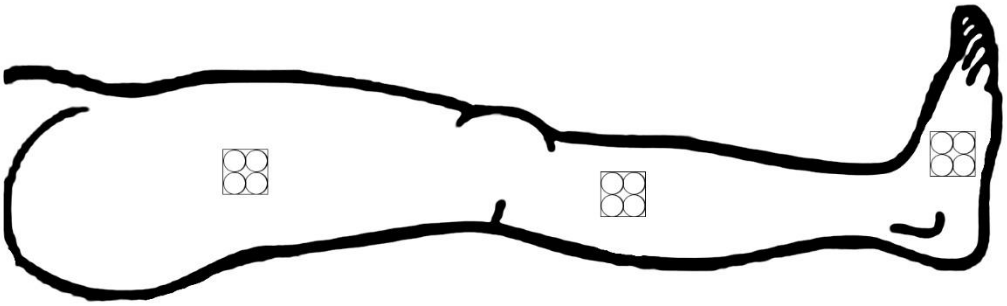

Figure 4.1: Optoelectronic system (Certus, NDI, Waterloo, Canada) rigid body clusters locations, attached to the lateral aspect of the thigh, shank, and foot.

Electromyographic (EMG) activity was monitored bilaterally from the vastus lateralis and vastus medialis using bipolar Ag/AgCl electrodes (BlueSensor N, Ambu Inc., Glen Burnie, MD, USA) that were affixed following SENIAM guidelines (Hermens et al., 1999). Raw EMG signals were sampled at 2048 Hz.

4.2.2 Experimental Design

Maximal voluntary isometric contractions (MVICs) for the vastus lateralis and vastus medialis were recorded with participants attempting seated leg extensions (two per leg) against resistance at approximately 60° of knee flexion (measured from full extension) (Becker & Awiszus, 2001) using a leg extension machine. ACL reconstructed participants with patellar tendon autografts were advised by surgeons to refrain from leg extension machine use, therefore they attempted leg extensions in a leg press machine at approximately 90° of knee flexion instead, as minimal ACL forces have been reported with this exercise (Escamilla et al., 2012).

The frontal plane laxity device (Figure 4.2) consisted of a chair and backrest (Chang et al., 2014; van der Esch et al., 2005) with the seat tilted to allow the tibia to be fixated horizontally to a free-moving sled (van der Esch et al., 2005) as designed by Mines (2016). The horizontal orientation of the tibia allowed gravity to act perpendicular to the frontal plane, eliminating a gravitational moment that would be inconsistent in magnitude between subjects (Chang et al., 2014). The tilted seat combined with a horizontally fixed tibia produced 20° (Sharma, Lou, et al., 1999; Shultz et al., 2007; van der Esch et al., 2005) of knee flexion and the sled allowed frontal plane rotation of the tibia without the fixation to a specific mechanical axis, that has been seen in previous laxity device designs (Sharma, Lou, et al., 1999; van der Esch et al., 2005). The sled that hosted the tibia was constructed with a LEXAN^{TM} base, that could slide over a LEXAN^{TM} surfaced table, covered in 4mm zinc-plated ball bearings. The ball bearings between the sled and table minimized friction (Sharma, Lou, et al., 1999; van der Esch et al., 2005) during sled motion. Femoral condylar clamps were located at the end of the seat to secure the femur while a low-friction cable-pulley system located 0.45m distal to the clamps was fixated to the table.

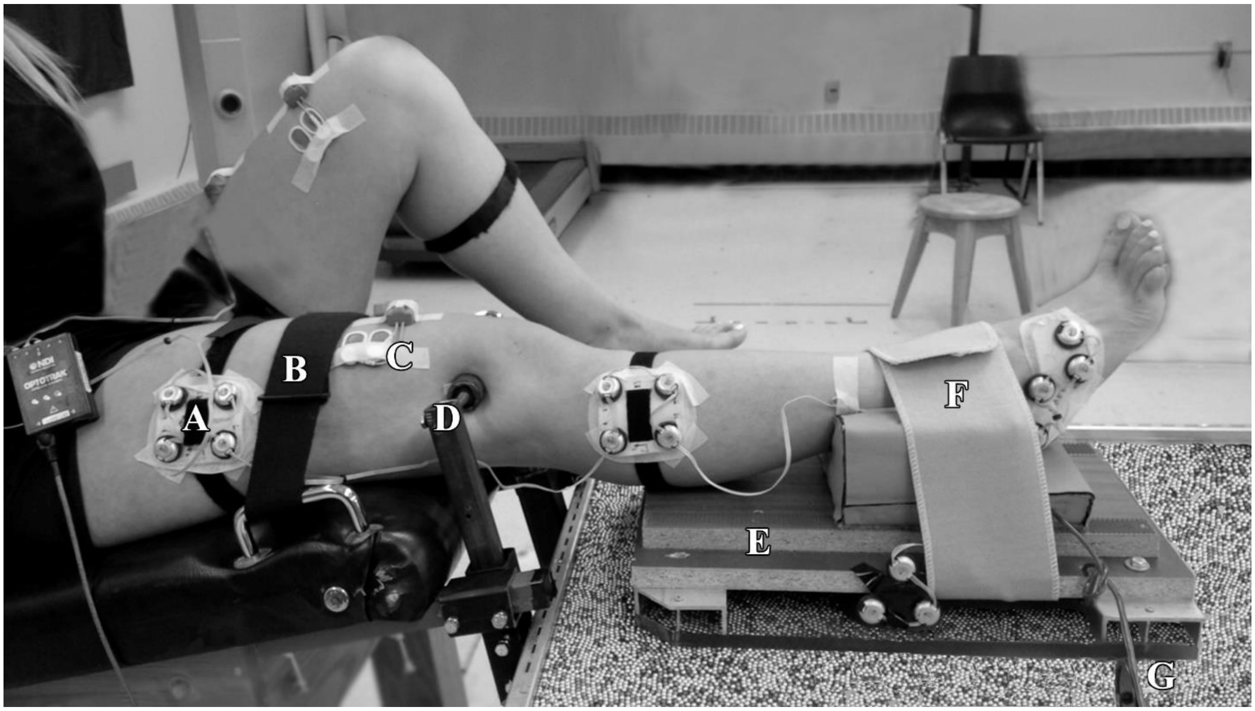

Figure 4.2: Participant seated in free-moving laxity measurement apparatus to record passive frontal plane laxity in response to a 10Nm varus/valgus moment designed by Mines (2016). A) Infrared light emitting electrodes for motion capture (Certus, NDI, Waterloo, Canada). B) Thigh strap. C) EMG electrodes for vastus lateralis (or vastus medialis, not shown). D) Femoral condylar clamps. E) Free-moving sled with Velcro attached shank cradle that can move (left to right in photograph) to support shank regardless of leg length F) Shank strap. G) Fixed low-friction cable-pulley system with a cable attached to the free-moving sled to maintain same distance of force application to create a 10N/m moment.

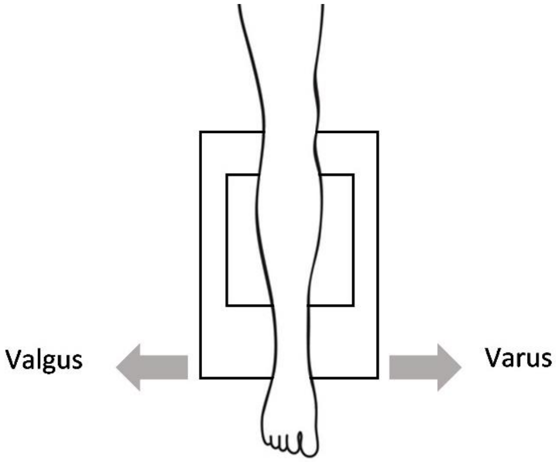

Figure 4.3 Frontal plane view of the shank cradled on the free-moving sled. Movement of the sled in the valgus or varus directions to measure valgus or varus laxity of the shank in respect to the femur.

Participants sat in the chair with their tibia fixed horizontally to the free-moving sled. The thigh was fastened to the chair and the femoral condylar clamps were positioned on the medial and lateral sides of the knee and engaged to minimize internal-external rotation of the femur (Chang et al., 2014). A 2.28kg load application to the low-friction pulley system occurred in two steps (1.14kg each) to create a maximum moment of 10Nm. Previous frontal plane laxity studies have applied a moment between 7.7Nm (van der Esch et al., 2005) - 12Nm (Sharma, Lou, et al., 1999). This 2.28kg load was applied to the medial and then lateral aspects of the tibial sled to exert a moment in each of the varus and valgus directions. Three laxity measurement tests were performed on each leg by the same single examiner across all participants.

4.3 Data Processing

Knee joint angles were calculated using previously defined (Chong et al., 2017) femoral and tibial coordinate systems and a Z-X-Y Euler sequence (flexion/extension- abduction/adduction-internal rotation/external rotation) (Visual3D, v6.01.07, C-motion, Germantown, MD) to link passive laxity to active laxity seen in gait and other lower limb activities (Mines, 2016). In a given pair of trials (one medial and one lateral load test), frontal plane laxity was defined as the sum of the maximum absolute varus and valgus deviations (in degrees) of the knee following application of the loads (Sharma, Lou, et al., 1999; van der Esch et al., 2005).

EMG was used only to confirm that the vastus lateralis and the vastus medialis in the measured leg were indeed passive (activity <5% MVC) during the laxity trials (Gajdosik et al., 2005) to omit the effects of muscle guarding on laxity measures. Raw EMG signals were mean-centered to remove DC offsets, full-wave rectified, and processed through a second order low-pass Butterworth filter at 6 Hz to create linear envelopes (Benoit et al., 2003) using a custom code generated in Matlab 9.5 (R2018b, The

Mathworks, Inc., Natick, MA). The linear enveloped EMG in the frame at which the peak laxity measure occurred in each laxity trial was checked to confirm it was below 5% MVIC (Gajdosik et al., 2005).

4.4 Statistical Analysis

To report the repeatability and sensitivity of the measurement system used in this study, the frontal plane laxity values recorded from the right limb was used for analysis (Shultz et al., 2007; van der Esch, Steultjens, Ostelo, et al., 2006). The standard error of measurement (SEM) and minimal detectable difference (MDD) was calculated. The mean of the three repeated laxity measures (collected consecutively in this study without the participant being removed from the measurement device) for the right limb across all participants was used for SEM (Eq1.) (Harvill, 1991) and MDD (Eq2.) (Mines, 2016) values.

Eq1. $Standard\ Error\ of\ Measurement\ (°) = \sqrt{within\ subject\ variance}$

Eq2. $Minimal\ Detectable\ Difference\ (°) = 1.96 \times \sqrt{2} \times SEM$

To determine if there were any statistically significant differences between knee statuses or sexes in frontal plane laxity, the means of the three repeated laxity measures for ACL reconstructed knees and contralateral knees were used in a two-way mixed model analysis of variance (ANOVA) (status x sex) with an alpha level of 0.05 using Statistical Package for the Social Sciences (SPSS) version 28.0 (SPSS, Chicago, IL, USA). A two-way ANOVA with an alpha level of 0.05 was used to compare both ACL reconstructed knees to control knees (status x sex), and contralateral knees to control knees (status x sex) using Statistical Package for the Social Sciences (SPSS) version 28.0 (SPSS, Chicago, IL, USA). The limb with the greatest mean frontal plane laxity measured was used for control participants.

A t-test with an alpha level of 0.05 was used to determine if there were a statistically significant difference between types of surgical reconstruction (bone-patellar tendon-bone graft or hamstring graft) using the means of the three repeated measures for each participant with an ACL reconstruction.

Chapter 5: Results

5.1 Participant Demographics

Twenty-four university aged participants (twelve females mean age 20.5 ± 1.8 and twelve males mean age 21.7 ± 2.3) were recruited for this study (Table 5.1). All ACL reconstructed participants were varsity athletes, sustaining their sports related ACL tear in soccer, basketball, or rugby. One participant chose not to report the specific date of when their operation was held, however they confirmed that it was at least six months prior to study participation.

Table 5.1: Participant demographics for the ACL reconstructed and control groups. The ACL reconstructed group had one ACL reconstructed knee and one contralateral healthy knee while the control group had two healthy knees. ACLR participants and controls were age matched to within the same calendar year.

Group	**Female (N=12)**		**Male (N=12)**	
	ACL Reconstructed (N=6)	**Control (N=6)**	**ACL Reconstructed (N=6)**	**Control (N=6)**
Height (m)	1.71 ± 0.05	1.63 ± 0.06	1.75 ± 0.05	1.74 ± 0.06
Mass (kg)	77.6 ± 8.4	64.9 ± 8.6	77.6 ± 10.1	77.0 ± 6.5
Age (yrs)	20.50 ± 1.80		21.70 ± 2.30	

5.2 Standard Error of Measurement (SEM) and Minimal Detectable Difference (MDD)

The SEM and MDD for the right leg using the mean of three repeated laxity measures for the right lower limb across all participants was 0.7° and 1.8° respectively (Table 5.2).

Table 5.2: Comparison of standard error of measurement (SEM) and minimal detectable difference (MDD) for frontal plane laxity measurement systems between the current study and previous designs in the literature with young adults.

	Number of Participants (N)	Sex	Measurement Method	Laxity (°)	Session Design for Determining MDD and SEM	SEM (°)	MDD (°)
Current Study	24	12M/12F	Motion Tracking	7.7 (2.3)	Same day	0.7	1.8
Mines (2016)	10	5M/5F	Motion Tracking	7.67 (2.4)	Same day	0.44	1.22
Shultz et al. (2007)	10	5M/5F	Motion Tracking	9.6 (3.0)	Between-day	0.67	1.86
Van der Esch (2006)	20	10M/10F	Electrical goniometer	5.92 (2.6)	Between-day	1.55	4.30

In comparison to previous designs, the SEM and MDD were similar (Shultz et al., 2007) or less than (van der Esch, Steultjens, Ostelo, et al., 2006) previous reports that used a different measurement system and a between-day design. Studies that used an electrogoniometer (van der Esch et al., 2007) showed greater SEM and MDD in comparison to motion tracking used in this study and by Shultz and colleagues (2007). The SEM and MDD in the current study was greater than previous experiments (Mines, 2016) using the same design system even though laxity means and standard deviations were similar in both studies (Mines, 2016).

5.3 Frontal Plane Laxity

5.3.1 Sex and Knee Status Comparisons

No statistically significant differences in frontal plane laxity were observed between ACL reconstructed and contralateral knees (p=0.260), ACL reconstructed knees and controls (p=0.314), contralateral knees and controls (p=0.273), or between sexes in the three ANOVAs (p=0.475 for ACL reconstructed and contralateral knees, p=0.299 for ACL reconstructed knees and controls, and p=0.313 for contralateral knees and controls). There was no significant knee status x sex interaction in any of the three ANOVAs (p=0.341 for ACL reconstructed and contralateral knees, p=0.433 for ACL reconstructed knees and controls, and p=0.273 for contralateral knees and controls). When comparing ACL reconstructed knees and controls, contralateral knees and controls, and ACL reconstructed knees and contralateral knees, differences in frontal plane knee joint laxity means were 1.3°, 2.1°, and 0.9°, respectively. The mean difference between male and female knees were 0.3°, 1.8°, and 2.3° for ACL reconstructed knees, contralateral knees, and control knees, respectively.

Table 5.3: Frontal plane laxity (mean and standard deviation) of ACL reconstructed knees, contralateral knees, and control knees. The knee with the greatest mean laxity for each control participant was used to calculate the mean. There were no significant main effects (knee status, sex) or interaction.

Group	Knee status	Female	Male	Total
ACLR	ACLR (°)	8.4 (3.7)	8.1 (2.5)	8.2 (3.0)
	CHK (°)	8.3 (1.9)	6.6 (2.5)	7.4 (2.3)
Control	Control (°)	10.7 (3.0)	8.4 (2.6)	9.5 (2.9)

5.3.2 Type of Surgical Reconstruction and Knee Status Comparisons

No statistically significant difference between reconstruction types (p=0.4492) was observed. When comparing ACL reconstructed knees and controls, contralateral knees and controls, and ACL reconstructed knees and contralateral knees, differences in frontal plane knee joint laxity means were 0.7°, 1.2°, and 1.9°, respectively for bone-patellar tendon-bone (BPTB) grafts and 3.2°, 3.0°, and 0.2°, for hamstring grafts, respectively (Table 5.4).

Table 5.4: Frontal plane laxity (mean and standard deviation) of ACL reconstructed knees using a bone-patellar tendon-bone (BPTB) graft, ACL reconstructed knees using a hamstring graft, contralateral knees, and control knees. The knee with the greatest mean laxity for each control participant was used to calculate the mean. There were no significant differences between participants who received a BPTB graft and those who received a hamstring graft.

Group	BPTB Graft (N=6)	BPTB Contralateral (N=6)	BPTB Control (N=6)	Hamstring Graft (N=6)	Hamstring Contralateral (N=6)	Hamstring Control (N=6)
Laxity (°)	9.09(3.45)	7.23(2.64)	8.41(2.98)	7.48(2.49)	7.63(2.17)	10.86(2.65)

5.4 Passive Motion

Kinematic and EMG data sets were time synchronized, where EMG at peak varus and valgus ranges was used to determine passive motions across trials. Vastus lateralis and vastus medialis activity during laxity measurements were less than 5% MVIC for all but one participant, whose left vastus medialis EMG activity was found to be 5.4% for all left leg varus and valgus measurements recorded. Muscle activity of <10% MVIC has been previously classified as passive (Fee Jr. et al., 2009; Rozzi, Lephart, & Fu, 1999; Rozzi, Lephart, Gear, et al., 1999), indicating that the vastus medialis of this participant was minimally activated during this study.

Chapter 6: Discussion

The primary objective of this study was to compare passive frontal plane laxity in a relatively young study cohort across three knee statuses (anterior cruciate ligament reconstructed knees (between 6 months to 5 years post-operation), contralateral knees, and knees from a control group), and between sexes for all three knee statuses. The secondary objective of this study was to characterize the frontal plane measurement system's repeatability and sensitivity. The primary and secondary objectives of this study were accomplished by applying a 2.28kg load to the medial and then lateral aspects of the tibial sled of the frontal plane measurement system to exert a 10Nm moment in each of the varus and valgus directions. Three laxity measurement tests were performed on each leg by the same single examiner across all participants, where the means of the three repeated measures were used for statistical analysis. It was found that there were no statistically significant knee status main effects (ACL reconstructed and contralateral knees (p=0.260), ACL reconstructed knees and controls (p=0.314), contralateral knees and controls (p=0.273)), sex main effects (p=0.475 for ACL reconstructed and contralateral knees, p=0.299 for ACL reconstructed knees and controls, and p=0.313 for contralateral knees and controls), nor knee status x sex interaction (p=0.341 for ACL reconstructed and contralateral knees, p=0.433 for ACL reconstructed knees and controls, and p=0.273 for contralateral knees and controls). There was also no statistically significant difference between the type of ACL reconstruction for participants who received a BPTB graft and those who received a hamstring graft (p=0.4492). The repeatability and sensitivity of the measurement system using the mean of three repeated measures from the right leg of all participants was found to have a SEM and MDD of 0.7° and 1.8°, respectively.

The following discussion will summarize the results found in this study, comparing and contrasting them to findings from previous literature and explain any implications to the objectives of this study.

6.1 Standard Error of Measurement (SEM) and Minimal Detectable Difference (MDD)

Throughout the literature there is the use of varying laxity system designs and methods for the examination of passive frontal plane laxity in the knee joint (Barenius et al., 2014; Sharma, Lou, et al., 1999; Shultz et al., 2007; van der Esch et al., 2005), where reported laxity measures vary as a whole across these studies (Freisinger et al., 2017). Large variations in laxity measurements continued to persist across studies even when comparing similar measurement system devices (Freisinger et al., 2017). The creation of a "gold standard" was suggested (Freisinger et al., 2017) to minimize the variations in measurement system design and laxity values themselves. Based on a review of previous system's limitations, a laxity measurement system should: measure laxity values at a consistent knee flexion angle; reduce muscle guarding for passive measurements; and apply consistent loads for varus and valgus manipulations of the shank (Cushnaghan et al., 1990; Markolf et al., 1981; Sharma, Lou, et al., 1999). The system used in the current study met these objectives in order to increase the repeatability and sensitivity in comparison to previous designs.

The SEM and MDD of the measurement system used in this study was 0.7° and 1.8° respectively. The only three studies (Mines, 2016; Shultz et al., 2007; van der Esch, Steultjens, Ostelo, et al., 2006) that reported the SEM and MDD values of their measurement system were Shultz et al. (2007), van der Esch et al. (2006), and Mines (2016) . The differences and similarities in SEM and MDD could be attributed to the differences in knee flexion used when values were recorded, muscle guarding, load application, and study timing protocols (between-day vs. same-day testing). Similar SEM and MDD values were seen between this study and Shultz et al. (2007) where motion capture was used in both studies to record kinematic data, although Shultz et al. (2007) used between-day sessions. van der Esch et al. (2006) had greater SEM and MDD values compared to this current study, potentially attributed to the removal and replacement of an electric goniometer between testing days. Mines (2016) used the same measurement system design used in this present study and found smaller SEM and MDD values (Table 5.2) compared to this present report (Mines, 2016). This current study and Mines (2016) had similar mean laxity and standard deviation values (Mines, 2016), so the difference in SEM and MDD could be attributed to the usage of a different equation to calculate SEM (the square root of within subject variance from a two-way mixed ANOVA), which subsequently affected the MDD calculated.

6.1.1 Knee Flexion Angle

Previous studies also report using varying knee flexion angles, ranging from maximum knee extension to maximum knee flexion (Freisinger et al., 2017). This wide range of knee flexion angles was identified as one potential limitation in recording repeatable values across studies (Freisinger et al., 2017). When examining previous designs, the most common knee flexion angle used was 20° (Sharma, Lou, et al., 1999; Shultz et al., 2007; van der Esch et al., 2005). This study adopted a similar methodology, of recording laxity values with the knee flexed to 20° to make similar comparisons across previous reports. It was expected that adopting a similar knee flexion angle as both Shultz et al. (2007) and van der Esch et al. (2006) would result in similar SEM and MDD values. However, this study had lower values of 0.85° and 2.5° when comparing SEM and MDD to van der Esch et al. (2006). Furthermore, when comparing mean laxity values, this study reported smaller standard deviations than that of van der Esch and colleagues (van der Esch, Steultjens, Knol, et al., 2006). Two main differences in experimental design could have contributed to this. An electronic goniometer was used (van der Esch, Steultjens, Knol, et al., 2006) as opposed to motion capture that was used in this study, where a goniometer could have potentially lead to greater variability in measurements recorded from removal of instrumentation between measurements due to between-day examination. Furthermore, between-day examination occurred (van der Esch, Steultjens, Ostelo, et al., 2006) compared to same-day in this study. Same-day variability is likely lower by design as other factors (exposures like stretching, hormonal factors, etc.) would not affect same-day measurements as much as they could affect between-day measurements.

6.1.2 Muscle Guarding

Muscle guarding has been previously identified as a major source of frontal plane laxity variation in osteoarthritic patients (Creaby et al., 2010; Sharma, Lou, et al., 1999). It has been suggested that participants might guard their knee by contracting muscles to stabilize the joint if they perceived increased knee joint pain or instability, subsequently making it unclear on whether laxity measures were taken during truly passive conditions during testing (Freisinger et al., 2017). Contraction of muscles during testing could have stabilized the knee to reduce varus-valgus laxity (Freisinger et al., 2017), where no previous study has measured muscle activity to gauge passive laxity. Sharma and colleagues (1999) instructed participants to relax while palpating musculature to quantify passive laxity, whereas another study assigned irregular measurements of varus-valgus laxity as sources of muscle guarding (Lim et al., 2008). This current study examined the EMG for each laxity trial of the vastus lateralis and vastus medialis of the right lower limb to check that activation levels were below 5% (Gajdosik et al., 2005) MVIC to deem varus and valgus angular deviations as passive. All trials collected from the right lower limb and used for SEM and MDD calculations were below 5% MVIC, indicating that the vastus lateralis and vastus medialis were minimally activated and that the laxity measures were under passive conditions. Trials used for frontal plane laxity comparisons were below 5% MVIC for all but one participant, whose left vastus medialis EMG activity was found to be 5.4% for all left leg varus and valgus measurements recorded. Muscle activity of <10% MVIC has been previously classified as passive (Fee Jr. et al., 2009; Rozzi, Lephart, & Fu, 1999; Rozzi, Lephart, Gear, et al., 1999), indicating that the vastus medialis of this participant was minimally activated during this study. Monitoring EMG ensured that muscle activation was below a 5%-10% MVIC threshold, eliminating muscle guarding across all participants and therefore reducing the variability of measuring reduced varus-valgus laxity that might have been from a stabilized knee (Freisinger et al., 2017).

6.1.3 Load Application

The degree of laxity measured is dependent on the load applied to the knee, where different load applications across studies (Appendix A) have made it challenging to standardize and compare data sets (Freisinger et al., 2017). Standardizing the load within a study increases the reliability of measurements and repeatability of applying the same conditions across participants. 7.7Nm (Knoop et al., 2012; van der Esch et al., 2005; van der Esch, Steultjens, Knol, et al., 2006), 8Nm (Chang et al., 2014; Lim et al., 2008; Wada et al., 1996; Wada & Kawahara, 2002), 12Nm (Creaby et al., 2010; Sharma et al., 2003; Sharma, Lou, et al., 1999) and 22.1Nm (Miyazaki & Uchida, 2012) moments have been used to create varus and valgus angular rotations and calculate frontal plane laxity without radiograph measurements. Increased loads typically result in smaller varus-valgus laxity measures (Freisinger et al., 2017). Following the application of a 22.1Nm moment, frontal plane laxities ranged from 5.99° - 6.98° across groups (Miyazaki & Uchida, 2012). Regardless of Kellgren and Lawrence grade for osteoarthritis severity, frontal plane laxity measured following the application of a 12Nm moment was between 4.4°-5.7° across groups (Sharma, Lou, et al., 1999), smaller than the frontal plane angular deviations measured in this study. On the other hand, the application of a 7.7Nm moment (Knoop et al., 2012; van der Esch et al., 2005; van der Esch, Steultjens, Ostelo, et al., 2006; Zwart et al., 2015) resulted in measurements ranging between 5.92° (van der Esch et al., 2005) to 8.0° (van der Esch et al., 2005; Zwart et al., 2015), a smaller applied moment that resulted in similar or greater ranges of laxity in comparison to the current study. This study applied a 10Nm moment that was between the ranges of 7.7Nm (van der Esch et al., 2005, 2012; van der Esch, Steultjens, Ostelo, et al., 2006; Zwart et al., 2015) and 12Nm (Sharma, Lou, et al., 1999) reported, where the mean laxity was 7.7° and between the reported ranges.

The variation and spread in laxity measurements could be due to the different applied moments used in each study or a result of differences in subject populations (Freisinger et al., 2017). Although there is natural variability between data sets and participants, the range in reported frontal plane laxity highlights the importance of using a standardized applied moment across studies to make appropriate comparisons.

6.2 Frontal Plane Laxity

There is a lack of sex-based examination when studying the frontal plane (Barenius et al., 2014; Sharma, Lou, et al., 1999; van der Esch et al., 2005). Females are more likely to rupture their ACL than males (Arendt & Dick, 1995), have increased risk of tissue damage and knee joint instability leading to the development of osteoarthritis (Louboutin et al., 2009), and are more likely to rupture their contralateral ACL following the reconstruction of an initial ruptured ACL (Sutton & Bullock, 2013). The overall greater ACL rupture ratio in females creates an increased ratio of females to males receiving surgical reconstructions, where surgical reconstructions themselves increase the risk of post-traumatic osteoarthritic development (Øiestad et al., 2009). Across studies examining an ACL reconstructed or osteoarthritic population, sample sizes contained greater ratios of females to males but neglected to include sex comparisons (Appendix A) (Barenius et al., 2014; Sharma, Lou, et al., 1999; van der Esch et al., 2005).

6.2.1 Between Sexes

The reported frontal plane laxity for females in this study was 8.4° ± 3.7°, 8.3° ± 1.9°, and 10.7° ± 3.0° for ACL reconstructed knees, contralateral knees, and control knees respectively, and 8.1° ± 2.5°, 6.6° ± 2.5°, and 8.4° ± 2.6° respectively for males. Although there were no statistically significant main effects of knee status groups or sex, and no interactions, mean laxities were greater across all female knee status groups compared to males. There is only one study that examined frontal plane laxity with sex-based comparisons, where females had statistically significant greater laxity in comparison to men in an osteoarthritic population of similar age (van der Esch et al., 2007). Applying a 7.7Nm moment and using a custom laxity measurement system with an electric goniometer, women were found to have a mean laxity of 7.7° ± 2.9° in comparison to men with 4.6° ± 2.2° (van der Esch et al., 2007), both means less than any of the laxities across knee status for either sex in the current study. These values contradicted the expectation that with the application of a moment smaller than 10Nm, the laxities measured should be greater than the values reported in this current study (Freisinger et al., 2017). Van der Esch and colleagues (2007) studied an osteoarthritic cohort with most participants having a Kellgren and Lawrence grade of 2 or greater. The development of osteoarthritis includes both joint laxity and osteophyte formation, which would result in opposing effects on the frontal plane passive joint range of motion (van der Esch et al., 2005). While increased laxity may enhance the osteoarthritic process, osteophyte development that can follow has a stabilizing effect on the knee, thereby decreasing laxity (van der Esch et al., 2005). Although unreported, it is possible that the osteoarthritic cohort studied by van der Esch and colleagues (2007) had increased osteophyte development with their increased Kellgren and Lawrence grading, resulting in a decreased frontal plane laxity in comparison to this current study. Additionally, muscle activation was not monitored, where muscle guarding and contraction of lower limb muscles surrounding the knee could have occurred to stabilize the joint (Freisinger et al., 2017) and decrease total frontal laxity in comparison to the current study that monitored muscle activation.

Overall, sex-related differences are understudied when examining the frontal plane, but females had significantly greater laxity compared to males (van der Esch et al., 2007). Furthermore, both young and old female control cohorts were found to have greater frontal plane laxities compared to men (Sharma, Lou, et al., 1999). It has been suggested that the increased laxity reported in females could be due to greater levels of circulating hormones such as estrogen and progesterone (van der Esch et al., 2007). When examining all previous literature studying frontal plane laxity, most studies have sample sizes comprised of more than 50% female (Appendix A) but do not include sex comparisons. It is possible that significant frontal plane laxity differences could be found amongst osteoarthritic populations if sex were examined or with greater sample sizes across knee statuses as seen in Appendix A.

6.2.2 Across Sexes Between Knee Statuses

The reported frontal plane laxity for this study was 8.2° ± 3.0°, 7.4° ± 2.3°, and 9.5° ± 2.9° for ACL reconstructed knees, contralateral knees, and control knees across sexes. There were no statistically significant knee status main effects, and no interactions involving knee status. These laxity values were within range of previous reports of 2.9° ± 1.0° (Sharma, Lou, et al., 1999) and 15.9° ± 5.4° (Wada et al., 1996) when measuring values using moments of 12Nm and 8Nm, respectively. Frontal plane laxity across knee statuses (controls and knee osteoarthritic severity) seen in Appendix A have shown little statistically significant differences. The only study that has shown a statistically significant difference between knee statuses was by Wada and colleagues (2002), comparing laxities of an osteoarthritic population to controls. Osteoarthritic patients had a statistically greater frontal plane laxity in comparison to a control group of similar mean age (71.5 years vs. 72.6 years) and sex demographic (91.3% female vs. 92.1% female) (Wada & Kawahara, 2002).

Comparing the mean laxity of control participants from this current study (9.5° ± 2.9°) across controls in previous literature, this study was between the range of 2.9° ± 1.0° (Sharma, Lou, et al., 1999) to 19.2° ± 6.5° (Creaby et al., 2010). However, a mean frontal plane laxity of 19.2° ± 6.5° (Creaby et al., 2010) contradicts the expectation of smaller laxity values when applying greater moments (Freisinger et al., 2017). Using a similar custom measurement design system and a dynamometer to record values, the same applied moment of 12Nm (Creaby et al., 2010; Sharma, Lou, et al., 1999), and similar sex demographic of 58.3% female (Sharma, Lou, et al., 1999) to 53% (Creaby et al., 2010), the only difference between studies was the mean age of participants (71.4 years ± 8.3 years vs 59.39 years

± 6.92 years respectively) and the number of repeated measures recorded (4 vs. 10 respectively). Repetitive elongation of a ligament to a constant load increases the total elongation and laxity of the tissue over more cycles (Solomonow, 2004). It is possible that the increased laxity of 19.2° ± 6.5° could be the result of passively moving the shank to a moment of 12Nm for 10 repeated measures (Creaby et al., 2010). Studies with similar frontal plane laxity measures that were ≥10° (Appendix A) all used the Genucom Knee Analysis System (Brage, Draganich, & Curran, 1994; Wada et al., 1996; Wada & Kawahara, 2002). The Genucom Knee Analysis System is no longer available for use but has previous reports of low repeatability, where up to 4.9mm of error could occur for varus-valgus testing and 17.5° of error for tibial rotation, both at 20° of knee flexion (Mcquade et al., 1989). The large range of error could be one attribution to the reported frontal plane laxities of control participants that were as great as double the laxity of this current study's finding of 9.5° ± 2.9°.

The contralateral knee with no osteoarthritic diagnosis represented the best possible baseline reference for comparison purposes and has been used for comparison with both ACL deficient and ACL reconstructed knees (Hoffelner et al., 2012). A comparison can be made between the undiagnosed contralateral knees of this current study to previous laxity reports of controls throughout the literature. The mean laxity of contralateral knees from this current study was 7.4° ± 2.3°, beyond the range of 2.9° ± 1.0° (Sharma, Lou, et al., 1999) to 7.1° ± 4.5° (Knoop et al., 2014) but within one standard deviation of previous of these studies (excluding laxity values from studies using the Genucom Knee Analysis System due to large ranges of error (Mcquade et al., 1989)). However, the laxity of the contralateral knees in this study also overlaps those seen in osteoarthritic knees (Appendix A), equal to (Knoop et al., 2012; van der Esch et al., 2012, 2008; Zwart et al., 2015) or greater than (Chang et al., 2014; Knoop et al., 2014; van der Esch et al., 2013; van der Esch, Steultjens, Knol, et al., 2006) previous reports. While some of these studies do not group osteoarthritic knees by Kellgren and Lawrence grades or osteoarthritic severity (Chang et al., 2014; Knoop et al., 2012; van der Esch et al., 2012; van der Esch, Steultjens, Knol, et al., 2006; Zwart et al., 2015), it is possible that an increase in severity and development of osteophytes could have stabilized the knee joints studied and resulted in smaller laxities measured (van der Esch et al., 2005).

There is further limited literature examining the frontal plane laxity of ACL reconstructed knees. Imbert and colleagues (2015) were the only study that examined ACL ruptured knees prior to surgery and immediately following surgical reconstruction. A mean laxity of ~4° following an intra-articular reconstruction and mean laxity of ~3° following an intra-articular reconstruction combined with an extra-articular anterolateral reinforcement was measured immediately following surgical intervention (Imbert et al., 2015). The frontal plane laxity immediately following the ACL reconstruction was half or less of the mean laxity of this present study, 8.2° ± 3.0°, 6 months to 5 years following surgery. The increase in laxity in this current study may indicate that over short-term follow-up, frontal plane laxity may increase.

When the frontal plane range of motion was measured intra-operatively immediately following surgical intervention, the laxity of the ACL reconstructed knee was greater than that of the contralateral knee (Imbert et al., 2015). Fourteen years following an ACL reconstruction, there was a higher prevalence of moderate osteoarthritic development in the ACL reconstructed knees compared to the contralateral knee (Barenius et al., 2014), although laxity was not measured. Another study showed that an osteoarthritic population had a decrease in frontal plane laxity between Kellgren and Lawrence grades 1 to 2, but then increased in laxity from grades 2 to 4 (Sharma, Lou, et al., 1999). Similarly, the increase of osteophyte formation grades showed both increase and decrease in frontal plane laxity at each grade (van der Esch et al., 2005). Other literature has shown decreased frontal plane laxity as osteoarthritic severity increased (Creaby et al., 2010; Miyazaki & Uchida, 2012). (Appendix A). While there is evidence that links laxity, ACL reconstructions, and knee osteoarthritis, this study did not support the theory that ACL reconstructed knees would have the greatest frontal plane laxity, followed by the contralateral knees, and finally the control knees, where females would have a greater laxity compared to males across all three knee statuses. Although females exhibited greater measures for frontal plane laxity when compared to males across all knee statuses, no statistically significant findings were made in this study. Referring back to the timeline in Figure 3.4 and incorporating the findings from the current study with the existing literature, the evidence thus far available points to the following laxity changes as time from ACL rupture increases to the point of having developed knee osteoarthritis: increased frontal plane laxity following ACL deficiency, increased laxity immediately following surgical intervention (Imbert et al., 2015), similar laxity values as contralateral limbs and control limbs as found in this thesis, and finally increased laxity again with higher Kellgren and Lawrence grades of osteoarthritis (Sharma, Lou, et al., 1999). This pattern is similarly seen in sagittal plane laxity, with increased laxity during ACL deficiency (Signorelli et al., 2016), increased laxity immediately following surgical intervention (Imbert et al., 2015), return to similar baseline standards (Brandsson et al., 2002), and increased laxity long-term (Leiter et al., 2014). It should be noted that each of these time points were studied in separate studies so a long-term ACL injury/reconstruction follow-up study would be required to confirm this timeline of events in a single cohort.

6.3 Limitations

6.3.1 Total Frontal Plane Range

Frontal plane laxity was reported as the total angular deviation of the tibia with respect to the femur without distinct separation between varus and valgus laxity (Freisinger et al., 2017). However, osteoarthritic development and unicompartimental knee arthroplasties most commonly occur in the medial compartment (Deschamps & Chol, 2011), where any significant differences in the medial and lateral compartments that may have existed in this study sample were not represented in the outcome measures. Studies using TELOS stress radiographs have been able to distinguish laxity between the medial and lateral compartments, reported in millimetres (Kumar et al., 2013; Lewek et al., 2004, 2005; Rudolph et al., 2007; Schmitt et al., 2008; Schmitt & Rudolph, 2007) (Appendix B). Radiographic studies have shown that the medial compartment of medial osteoarthritic patients was significantly greater in varus laxity when compared to age- and sex-matched controls (5.1mm±1.5mm vs. 3.1mm±1.0mm) (Lewek et al., 2004). This was further supported by additional studies who found the medial compartment of osteoarthritic knees to be significantly greater in laxity compared to the medial compartment of control participants (Kumar et al., 2013; Lewek et al., 2005; Schmitt & Rudolph, 2007). Though not the main objective of this thesis, medial and lateral compartmental laxity (Appendix C, Table C.1) was examined by using the measures from the angular varus and valgus deviations used to determine the frontal plane laxity of participants. The same three ANOVA designs were used on each of the varus and valgus deviations separately. A statistically significant knee status main effect (p=0.019) and a statistically significant sex main effect (p=0.019) were found in the two-way ANOVA comparing contralateral and control knees, with no other significant main effects or status x sex interactions. Since the ACL reconstructed knees had no significant differences in valgus or varus laxity when compared to either the contralateral or control knees, the results of this subsequent analysis agree with the findings regarding individuals who are 6 months to five years post ACL reconstruction. However, some participants did not have a consistent starting position (origin) between trials. The range of within-participant origin standard deviations was between 0.06° and 1.42°. This lack of consistency for some participants indicates that we can have more confidence in findings using the maximum range of motion (from maximum varus to maximum valgus deviation) than in varus deviations or valgus deviations separately. When comparing knees with medial osteoarthritis to both middle aged and older aged control groups, valgus laxity was significantly greater in the osteoarthritic group compared to all controls (Rudolph et al., 2007). However, these radiographic studies did not report any significant differences in laxity in the lateral compartment of the knee (Kumar et al., 2013; Lewek et al., 2004, 2005; Schmitt & Rudolph, 2007).

6.3.2 EMG Placement

In conjunction with the ACL, both the quadriceps and hamstring muscles cross the knee joint, directly supporting tibiofemoral biomechanics and preventing joint degeneration (Thomas et al., 2013). In this study, EMG measures were limited to the vastii, where EMG of the posterior leg muscles that crossed the knee joint could not be measured without components of the measurement device impinging the surface EMG placement. The failure to monitor EMG measures of the posterior lower limb muscles limited the ability to completely declare all muscles as passive during the laxity tests. The hamstrings are knee flexors that assist in restraining anterior tibial translation (Thomas et al., 2013) and in the absence of an intact ACL, they become the primary dynamic restraints to anterior tibial translation (Louboutin et al., 2009). Additionally, the muscle belly heads of the gastrocnemius from the triceps surae cross the knee joint and originate on the medial and lateral femoral condyles, acting as a smaller knee flexor and are a co-activated with the quadriceps during gait to assist in joint stability (Mengarelli et al., 2018). Modifying the seating of participants and adjusting the location of the tibial sled further distal from the heads of the gastrocnemius and making it smaller would allow for EMG electrode placement of the hamstrings and gastrocnemius muscles to completely monitor and classify laxity measurements under passive muscle conditions.

6.3.3 Sample Size and Post ACL Reconstruction Range

The presented study used a sample of 12 ACL reconstructed participants (6 females and 6 males) mean age of 20.5 ± 1.8 years, with a range of 6 months to 5 years post reconstruction, and 12 age- and sex-matched controls. Participants were obtained through a sample of convenience from the University of Waterloo, with approval from the institutional ethics board. Small sample sizes can amplify outlying observations and reduce the representativeness of the data set compared to those studied prior (Fok et al., 2015). The small sample size with follow-ups between 6 months to 5-year post ACL reconstruction meant that not all time points in that follow-up window could be represented. Only one participant studied was beyond 2.5 years post ACL reconstruction (Appendix D). While the data set from this study indicated that participants in this study had similar follow-up statuses, ensuring more participants nearing 5-years post reconstruction would further support the finding of normal frontal plane laxity between 6 months to 5 years following ACL reconstruction. Using a 95% confidence interval with a critical value of 1.96, control sample mean of 9.5°, standard deviation of 2.9° and sample size of 12, ACL reconstructed sample mean of 8.2°, standard deviation of 3.0°, and sample size of 12, and power of 80% (value 0.8416), a sample size of N=393 can be calculated using Bhalerao & Kadam (2010) (Appendix E). Future directions should work to increase the number of samples studied to observe a more representative sample in comparison to prior literature.

6.3.4 Frontal Plane and ACL Integrity

The presented study solely examined frontal plane laxity of ACL reconstructed knees, contralateral knees, and knees from age- and sex-matched controls. However, the frontal plane alone does not determine ACL integrity. Both the frontal plane and sagittal plane should be examined in conjunction to determine ACL integrity following a reconstruction as this ligament acts as the primary restraint to anterior tibial translation (Petersen & Zantop, 2007) along the sagittal plane. Examining ACL laxity along both the frontal and sagittal plane would allow for a holistic examination of ACL integrity following surgical intervention.

6.3.5 Femoral Clamp Rigidity

The frontal plane measurement system was designed to limit the mobility of the femur when the passive angular range of the tibia in respect the femur occurred. Femoral clamps were used to assist in the immobilization of the femur to prevent movement. Individuals with varying amounts of soft tissue distribution along the thigh may have had slightly different degrees of immobilization. The clamps were set as tight as possible without causing pain to participants.

Chapter 8: Future Directions and Contributions

The data set from this study indicates that, if the participants in this study have similar follow-up statuses to what has been previously observed in the literature (increased laxity and evidence of knee osteoarthritis at 14 years following ACL surgery (Barenius et al., 2014)), it would not be due to residual frontal plane laxity following reconstruction. These participants have demonstrated normal frontal plane laxity at follow-up times between 6 months and 5 years following ACL reconstruction. Young active individuals who commonly seek ACL reconstructive options typically place higher cumulative demands on their joints longitudinally (Davey et al., 2019). Between this study and long-term (e.g. 14 years) follow-up, there could be other factors, such as high BMI (Barenius et al., 2014), cartilage degeneration (Freisinger et al., 2017), and bone erosion (Freisinger et al., 2017), that affect the integrity of the ACL reconstruction or the articulating surfaces of the joint and result in increased frontal plane laxity and development of osteoarthritis.

This study successfully compared the frontal plane laxity between three different knee statuses and between sexes across these three knee statuses after ACL reconstruction. Future research should expand on the findings of this current study to include EMG electrode placement on the hamstrings and heads of the gastrocnemius to monitor and completely classify laxity measurements under passive muscle conditions. Modifying the laxity measurement system setup to avoid obstruction of the posterior thigh and posterior shank would assist in easier access for EMG placement. Furthermore, increasing the sample size of participants and including more individuals closer to 5-year post-reconstruction would reduce outlying observations and increase the representativeness of the data set. Expanding the sample and representativeness would further support the finding of normal frontal plane laxity between 6 months to 5 years following ACL reconstruction.

The current study provided contributions in the examination of a short-term follow up time frame after ACL reconstructive surgery to determine if frontal plane laxity persisted for an at risk of osteoarthritic development population. The only other known publication reporting frontal plane laxity for ACL reconstructed individuals studied participants immediately following surgical intervention, where there was residual laxity in the ACL reconstructed knee (Imbert et al., 2015). The current study is also the only study that examined young adults at risk of degenerative joint changes but prior to an when a potential osteoarthritic diagnosis would typically occur. All other previous frontal plane laxity studies examined patients that had already developed osteoarthritis and were ≥33 years of age (Lewek et al., 2004; Pottenger et al., 1990; Sharma, Lou, et al., 1999; van der Esch et al., 2005). A final contribution was the direct comparison of frontal plane knee joint laxity between three different knee statuses and across sexes in these three different knee statuses, where this study used age- and sex-matched controls. Previous examinations compared osteoarthritic knees to controls that were not age- or sex-matched (Creaby et al., 2010; Knoop et al., 2012; Sharma, Lou, et al., 1999; Wada et al., 1996) or to a contralateral knee that was already diagnosed with osteoarthritis (Sharma, Lou, et al., 1999; van der Esch et al., 2007, 2008, 2012). This study examined ACL reconstructed knees, contralateral knees, and age- and sex-matched controls for more direct comparisons. Most frontal plane laxity studies (Appendix A) had greater ratios of females to males but did not carry out any sex comparisons.

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Appendix A

Table A.1 Frontal plane knee joint laxity studies across the literature. Organized in increasing magnitude of moment (Nm) application. Shown is the population studied, age (mean years and standard deviation), number of females studied (number of females and the percentage of the total cohort studied), system used, and total frontal plane laxity (mean degrees and standard deviation).

Author	System	Sex Female (N,%)	Age (Years)	Moment (Nm)	Population	Laxity (°)
(van der Esch et al., 2005)	Custom System (Goniometer)	26(74)	66.5±10.4	7.7	JSN0	5.3(3.0)
					JSN1	9.3(4.7)
					JSN2	8.0(2.8)
					JSN3	8.0(3.7)
					OP0	8.0(3.7)
					OP1	8.0(3.9)
					OP2	7.4(3.2)
					OP3	9.6(3.0)
					All	8.0(4.1)
(van der Esch, Steultjens, Knol, et al., 2006)	Custom System (Goniometer)	65(76)	63.6±9.1	7.7	OA (Right Limb)	6.9(3.2)
					OA (Left Limb)	6.9(3.4)
(van der Esch et al., 2007)	Custom System (Goniometer)	65(75.6)	63±10	7.7	OA (Female)	7.7(2.9)
			64±7.3		OA (Male)	4.6(2.2)
(van der Esch et al., 2008)	Custom System (Goniometer)	48(76)	60±7.5	7.7	OA (Right Limb)	7.81(3.52)
					OA (Left Limb)	7.34(2.96)
(Knoop et al., 2012)	Custom System	181(64)	61.6±7.4	7.7	OA	7.3(4.0)
(van der Esch et al., 2012)	Custom System (Goniometer)	161(65)	61.0±7.9	7.7	OA (Right Limb)	7.46(3.92)
					OA (Left Limb)	7.36(3.98)
(van der Esch et al., 2013)	Custom System (Goniometer)	73(70)	61.4±6.9	7.7	OA	6.9(2.8)
(Knoop et al., 2014)	Custom System	44(56)	61.8±6.6	7.7	Controls	7.1(4.5)
		53(66)	62.1±7.6		OA	7.0(3.1)
(Zwart et al., 2015)	Custom System (Goniometer)	203(301)	61.5±8.3	7.7	OA	7.3(3.5)
(Wada et al., 1996)	Genucom Knee Analysis System	Unknown	71	8	Controls	12.0(3.8)
					K/L 1	11.5(5.4)
					K/L 2	11.9(4.3)
					K/L 3	15.1(5.1)

					K/L 4	15.9(5.4)
(Wada & Kawahara, 2002)	Genucom Knee Analysis System	21(91.3)	71.5	8	Controls	12(4.0)
		35(92.1)	72.6		OA	15(7.9)
(Lim et al., 2008)	Custom System (Dynamometer)	59(55)	64.6±8.4	8	OA	10.8(4.3)
(Chang et al., 2014)*	Custom System	8(57)	58.4±9.5	8	Controls	4.01(1.52)
		8(57)	60.0±8.7		OA	4.13(1.39)
		8(57)	58.4±9.5	12	Controls	6.49(1.92)
		8(57)	60.0±8.7		OA	6.83(2.15)
(Sharma, Hayes, et al., 1999)	Custom System (Dynamometer)	Unknown	62.6±11.5	12	OA (Right Limb)	5.1(1.9)
					OA (Left Limb)	4.6(1.8)
(Sharma, Lou, et al., 1999)	Custom System (Dynamometer)	Unknown	Unknown	12	Controls (Young)	3.4(1.1)
		14(58.3)	71.4±8.3		Controls (Old)	2.9(1.0)
		118(80)	62.6±11.5		K/L 1	4.9(0.35)
					K/L 2	4.4(0.16)
					K/L 3	5.1(0.22)
					K/L 4	5.7(0.30)
(Sharma et al., 2003)	Custom System (Dynamometer)	126(73.7)	64.0±11.0	12	OA	5.32(2.03)
(Creaby et al., 2010)	Custom System (Dynamometer)	17(53)	59.39±6.92	12	Controls	19.2(6.5)
		27(54)	61.61±7.12		Mild OA	20.1(6.4)
		20(44)	65.23±7.72		Moderate OA	18.0(4.7)
		11(34)	66.40±9.93		Severe OA	17.7(5.4)
(Brage et al., 1994)	Genucom Knee Analysis System	Unknown	65	12.2	Controls	11.3(3.0)
					Mild OA	15.0(4.8)
					Moderate OA	10.9(3.9)
					Severe OA	10.4(3.6)
(Miyazaki & Uchida, 2012)	Custom System (X-Ray at End Range)	22(100)	71.8±8.3	22.1	Controls (Pre-Exercise)	6.98(1.77)
		20(100)	73.8±9.2		Mild OA (Pre-Exercise)	6.18(1.78)
		26(100)	74.1±7.9		Severe OA (Pre-Exercise)	5.99(2.81
		22(100)	71.8±8.3		Controls (Post-Exercise)	8.17(2.18)
		20(100)	73.8±9.2		Mild OA (Post-Exercise)	8.85(2.00)
		26(100)	74.1±7.9		Severe OA (Post-Exercise)	8.55(3.44)

* Measures recorded at 0° of knee flexion.

JSN – Joint Space Narrowing grade. Grade values between 0-3 with increasing severity.

OP – Osteophyte development grade. Grade values between 0-3 with increasing severity.

OA – Osteoarthritic group.

K/L – Kellgren and Lawrence System Grading of Osteoarthritis. Grade values between 1-4 with increasing severity.

Appendix B

Table B.1 Frontal plane knee joint laxity studies across the literature using the TELOS VV stress radiograph with a load of 150N and 20° of knee flexion. Shown is the population studied, age (mean years and standard deviation), number of females studied (number of females and the percentage of the total cohort studied), and medial or lateral compartment frontal plane laxity (mean millimetres and standard deviation).

Author	**Sex Female (N,%)**	**Age (Years)**	**Population**	**Laxity (mm)**
(Lewek et al., 2004)	6(50)	49.5(6.1)	Controls Medial	3.2(1.0)
			Controls Lateral	4.3(1.3)
	6(50)	50.3(7.4)	OA-M Medial	5.1(1.5)
			OA-M Lateral	3.6(1.6)
(Lewek et al., 2005)	7(36.8)	49.3(5.8)	Controls Medial	3.3(0.9)
			Controls Lateral	4.1(1.5)
	7(33.3)	49.3(7.0)	OA-M Medial	5.0(1.7)
			OA-M Lateral	3.4(1.7)
(Rudolph et al., 2007)	7(46.7)	49.2	Middle Age Controls Medial	3.12(0.95)
			Middle Age Controls Lateral	4.20(1.27)
	10(71.4)	68.8	Older Age Controls Medial	3.05(0.76)
			Older Age Controls Latea	3.62(1.34)
	7(46.7)	49.2	OA-M Medial	4.77(1.72)
			OA-M Lateral	3.56(1.65)
(Schmitt & Rudolph, 2007)	13(50)	58.5	Controls Medial	2.76
			Controls Lateral	3.52
	14(50)	60.4	OA-M Medial	4.23
			OA-M Lateral	2.77
(Schmitt et al., 2008)	5(50)	64.5	Stable OA Medial	4.31(1.16)
			Stable OA Lateral	3.08(1.42)
	4(40)	64.7	Unstable OA Medial	4.54(2.28)
			Unstable OA Lateral	2.55(1.28)
(Kumar et al., 2013)	6(50)	59.5(10.4)	Controls Medial	3.3
			Controls Lateral	4.7
	8(50)	65.2(15.7)	OA-M Medial	5.5
			OA-M Lateral	3.4

OA-M Medial – Medial compartment laxity along the frontal plane of medial compartmental osteoarthritic patients.
OA-M Lateral – Lateral compartment laxity along the frontal plane of medial compartmental osteoarthritic patients.
Controls Medial – Medial compartment laxity along the frontal plane of control participants.
Controls Lateral – Lateral compartment laxity along the frontal plane of control participants.

Appendix C

Table C.1 The medial and lateral compartmental laxity for each participant (mean degrees). Group laxities (mean degrees and standard deviation) is show for each knee status and sex for each compartment. Medial and lateral compartmental origins (mean and standard deviation in degrees) are also shown for each participant.

		Medial Compartment Laxity (°)	**Medial Compartment Origin (°)**	**Lateral Compartment Laxity (°)**	**Lateral Compartment Origin (°)**
	ACL Reconstructed				
Female	**1**	4.76	14.61(0.68)	2.50	14.55(0.66)
	2	1.98	0.87(0.56)	3.11	0.16(0.24)
	3	3.26	-8.42(0.17)	2.84	-8.99(0.49)
	4	3.71	1.67(0.13)	2.94	1.50(0.14)
	5	7.43	-0.81(0.32)	6.39	-0.11(0.46)
	6	5.82	0.54(0.19)	5.95	-0.15(0.65)
	Mean (SD)	4.49(1.95)		3.96(1.73)	
Male	**1**	6.58	-1.68(0.87)	5.46	-1.74(1.08)
	2	3.65	14.12(0.49)	3.08	14.01(0.24)
	3	4.72	0.7(0.39)	2.31	0.21(0.48)
	4	4.75	2.68(0.13)	3.69	3.30(0.09)
	5	6.24	5.34(0.39)	3.85	5.32(0.30)
	6	3.16	5.84(0.16)	2.42	6.08(0.09)
	Mean (SD)	4.85(1.36)		3.47(1.16)	
	ACL Reconstructed Contralateral				
Female	**1**	5.33	-0.59(0.97)	3.19	-0.57(1.42)
	2	4.34	-11.69(0.23)	3.10	-10.98(0.62)
	3	3.32	9.37(0.74)	3.13	8.88(0.34)
	4	5.58	-4.66(1.0)	4.23	-4.67(0.93)
	5	5.98	-2.42(0.44)	4.85	-2.56(0.14)
	6	4.77	-1.09(0.49)	3.49	-0.28(0.11)
	Mean (SD)	4.89(0.96)		3.66(0.72)	
Male	**1**	6.75	-8.84(0.19)	3.17	-8.66(0.23)
	2	2.79	-11.64(0.08)	2.55	-11.47(0.06)
	3	6.22	4.92(0.99)	3.91	3.72(1.02)
	4	2.63	1.71(0.21)	2.18	1.54(0.17)
	5	5.24	-9.45(0.32)	2.81	-8.74(0.18)
	6	1.96	-8.95(0.60)	1.32	-8.73(0.06)
	Mean (SD)	4.26(2.05)		2.66(0.88)	
	Controls				
Female	**1**	5.40	11.57(0.21)	6.17	10.77(0.16)
	2	5.68	-12.38(0.85)	5.78	-12.47(0.61)
	3	3.97	-3.96(0.50)	3.25	-3.52(0.49)
	4	8.03	6.26(0.17)	8.45	6.87(0.78)
	5	3.36	2.90(0.14)	3.45	2.86(0.37)
	6	7.91	-15.40(0.39)	4.76	-15.49(0.16)
	Mean (SD)	5.72(1.94)		5.31(1.94)	
Male	**1**	4.90	6.71(0.51)	2.70	6.85(0.50)
	2	6.91	7.71(0.72)	3.95	7.72(0.25)
	3	5.63	-5.76(0.35)	3.95	-6.37(0.29)
	4	5.91	0.71(0.23)	5.78	0.68(0.18)
	5	2.95	-1.50(0.49)	2.55	-1.67(0.38)
	6	3.02	-1.30(0.15)	3.06	-1.58(0.32)
	Mean (SD)	4.89(1.61)		3.66(1.20)	

Table C.2 The p-values for the laxities of the medial and lateral compartment between across knee status and sexes. A two-way mixed model ANOVA was used to compare ACL reconstructed and Contralateral knees, whereas a two-way ANOVA was used to compare between ACL reconstructed knees and control knees, and ACL reconstructed contralateral knees and control knees.

Status	**Knee Status (p-value)**	**Sex (p-value)**	**Knee Status x Sex Interaction**
Medial Compartment			
ACL Reconstructed & Contralateral	0.820	0.255	0.882
ACL Reconstructed & Controls	0.380	0.737	0.406
Contralateral & Controls	0.305	0.304	0.876
Lateral Compartment			
ACL Reconstructed & Contralateral	0.195	0.529	0.211
ACL Reconstructed & Controls	0.233	0.107	0.370
Contralateral & Controls	0.019[A]	0.019[B]	0.547

[A] Statistically significant difference across knee status of lateral compartments of the contralateral knees and control knees.

[B] Statistically significant difference across sex of lateral compartments of the contralateral and control knees.

Appendix D

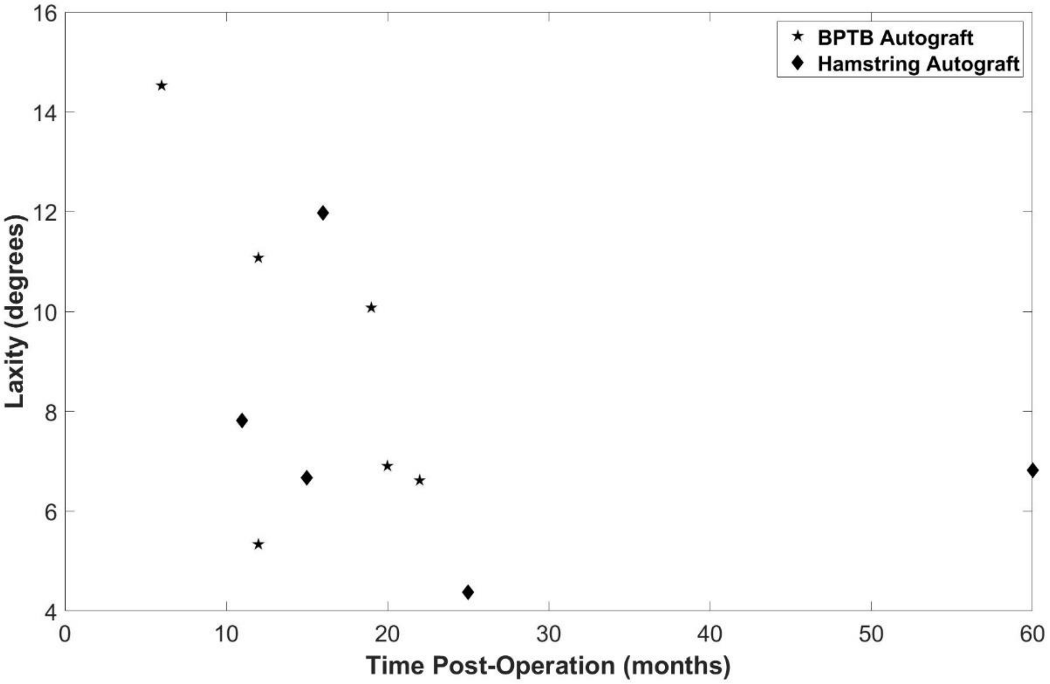

Figure D.1 The time post surgical reconstruction and the frontal plane laxity of each ACL reconstructed participant's knee, separated between the type of autograft used in their surgical reconstruction of bone-patellar tendon-bone (BPTB) or hamstring.

Appendix E

Using a 95% confidence interval with a critical value of 1.96, control sample mean of 9.5°, standard deviation of 2.9° and sample size of 12, ACL reconstructed sample mean of 8.2°, standard deviation of 3.0°, and sample size of 12, and power of 80% (value 0.8416), the following sample size calculation can be made (Bhalerao & Kadam, 2010).

Cohen's *d* effect size (Δ) $= \frac{x_1 - x_2}{s}$

$$= \frac{x_1 - x_2}{\sqrt{\frac{(n_1-1)s_1^2+(n_2-1)s_2^2}{n_1+n_2}}}$$

$$= \frac{9.5-8.2}{\sqrt{\frac{(12-1)2.9^2+(12-1)3.0^2}{12+12}}}$$

$$= 0.4602$$

Where:
x_1 is population 1 mean
x_2 is population 2 mean
s is the standard deviation of the data

Sample Size (N) $= \frac{2(Z_a+Z_{1-B})^2\sigma^{2,}}{\Delta^2}$

$$= \frac{2(1.96+0.8416)^2 2.3^2}{0.4602^2}$$

$$= 393$$

Where:
Z_a is critical value
$Z_{1\text{-}B}$ is power
σ is standard deviation
Δ is Cohen's *d* effect size