DISSERTATION FROM THE
NORWEGIAN SCHOOL OF
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Nicholas N. DePhillipo

Meniscal Ramp Lesions:

Anatomy, Biomechanics, and Clinical Outcomes

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Acknowledgements

Thank you to the Lord for giving me this opportunity of life. This dissertation is dedicated to my parents, Maria and John DePhillipo, whom have always supported me with each and every life endeavor. Thank you for your guidance, encouragement, and love throughout this journey. I know it is not always easy for me being so far away from home but somehow you continue to push me towards my life goals. You may not realize it, but YOU are the reason I decided to further my education. You both are the hardest-working, most kind and generous individuals; but what makes you even more special is your combined efforts to maintain this family despite whatever stands in your way. Thank you for the inspiration and gift of life.

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List of Papers

This dissertation is based on the following papers, which are referred to in the text by their Roman numerals:

I. Incidence and Detection of Meniscal Ramp Lesions in Anterior Cruciate Ligament Reconstruction Patients. **DePhillipo NN**, Cinque ME**,** Chahla J, Geeslin AG, Engebretsen L, LaPrade RF. *Am J Sports Med*. 2017 Aug;45(10):2233-2237.

II. Quantitative and Qualitative Assessment of the Posterior Medial Meniscus Anatomy: Defining Meniscal Ramp Lesions. **DePhillipo NN**, Moatshe G, Chahla J, Aman ZS, Storaci HW, Morris ER, Robbins CM, Engebretsen L, LaPrade RF. *Am J Sports Med*. 2019 Feb; 47(2):372-378.

III. Effect of Meniscocapsular and Meniscotibial Lesions in ACL-Deficient and ACL-Reconstructed Knees: A Biomechanical Study. **DePhillipo NN**, Moatshe G, Brady A, Chahla J, Aman ZS, Dornan GJ, Nakama GY, Engebretsen L, LaPrade RF. *Am J Sports Med*. 2018 Aug;46(10):2422-2431.

IV. Current Trends Among U.S. Surgeons in the Identification, Treatment, and Time of Repair for Medial Meniscal Ramp Lesions at Time of ACL Surgery. **DePhillipo NN**, Engebretsen L, LaPrade RF. *Orth J Sports Med*. 2019 Feb 22;7(2).

V. Clinical Characteristics and Outcomes Following Primary ACL Reconstruction and Meniscal Ramp Repair. **DePhillipo NN**, Dornan GJ, Dekker TJ, Aman ZS, Engebretsen L, LaPrade RF. *Knee Surg & Sports Traum.* Under review.

Summary

Introduction

Anterior cruciate ligament (ACL) tears are the most common researched pathology in all of sports medicine. Researchers and clinicians have dedicated their careers to investigating the treatment of ACL tears and why ACL reconstructions fail. The medial meniscus is a known secondary stabilizer to the ACL and recent clinical studies have reported that meniscal deficiency is the most significant factor to predict ACL reconstruction graft failure. Meniscal ramp lesions, originally defined as peripheral tears of the posterior horn of the medial meniscus, have been reported to occur in roughly a quarter of all patients who suffer an ACL tear and have become increasingly recognized in the field of sports medicine over the past decade. However, controversy exists regarding identification and treatment of these lesions and a consensus has yet to be made on their exact biomechanical role in ACL deficient and ACL reconstructed knees.

Methods

This dissertation is based on five separate research projects. In the first project (Paper I), we retrospectively evaluated preoperative diagnostic imaging of patients with meniscal ramp lesions, confirmed via gold standard arthroscopic assessment, to investigate the incidence of ramp lesions in patients with ACL tears. We also sought to report the current sensitivity of preoperative magnetic resonance imaging (MRI) for the detection of ramp lesions. The second project (Paper II) utilized 14 human cadaveric knees in order to quantitatively and qualitatively describe the anatomy of the posterior horn of

the medial meniscus and posteromedial capsule anatomy pertaining to the location of a ramp lesion. Additionally, a histological analysis was conducted on pertinent meniscal and capsular tissue in order to analyze the cellular structure of the meniscocapsular and meniscotibial attachments of the medial meniscus. The third project (Paper III) investigated the biomechanical effects of meniscocapsular and meniscotibial based lesions of the posterior horn of the medial meniscus in ACL-deficient and ACL-reconstructed knees. This project utilized 12 matched pairs of cadaveric knees which were tested in a 6 degree of freedom robotic system. The fourth project (Paper IV) evaluated current trends among United States surgeons in the identification, treatment, and repair strategies for meniscal ramp lesions at the time of ACL surgery. This project utilized an electronic research survey and was distributed in a blinded fashion to the 91 directors of orthopaedic sports medicine fellowship training programs in the United States. The fifth project (Paper V) retrospectively evaluated clinical characteristics and outcomes in patients who underwent ACL reconstruction with medial meniscal ramp repair (n=50) and were compared to a matched cohort of isolated ACL reconstruction patients (n=50).

Main Results

In a consecutive series of 301 ACL reconstructions, 50 patients were diagnosed with a medial meniscal ramp lesion at the time of surgery (16.6% incidence) (Paper I). The sensitivity of MRI for ramp lesions was 48% based on the preoperative MRI report. A posteromedial tibial bone bruise was found to be a secondary sign of a ramp lesion in

72% of patients. In paper II, the posterior meniscocapsular attachment to the medial meniscus had a mean length of 20.2 mm and attached at a mean depth of 36.4% of the total posterior meniscal height, providing quantitative evidence of why ramp lesions may be hidden during arthroscopic evaluation. Histological analysis validated a shared attachment point of the meniscocapsular and meniscotibial attachments. In paper III, both meniscocapsular and meniscotibial tears significantly increased knee anterior tibial translation, internal and external rotation, and the pivot shift in ACL-deficient knees ($p<0.05$). The pivot shift was not restored with an isolated ACL reconstruction but was restored with a combined ACL reconstruction and meniscal ramp repair ($p<0.05$). In paper IV, the majority of sports medicine fellowship directors (n=31, 86%) reported routinely checking for a meniscal ramp lesion via inspection of the posteromedial meniscocapsular junction during an ACL reconstruction. The most common repair technique reported was all-inside (n=24, 66.7%) followed by an inside-out repair technique (n=8, 22.2%). Three (8%) surgeons reported that they do not repair meniscal ramp lesions. In paper V, there were 851 primary ACLR patients identified; 158 (18.6%) had medial meniscal ramp lesions confirmed at arthroscopy. The most common clinical characteristics in patients with ramp lesions were chronic ACL tears (68.4%), contact mechanism (88%), concomitant lateral meniscus tears (63.2%), and concomitant lateral meniscus posterior root tears (22.2%). Fifty of 58 patients who were identified with 2-year follow-up with combined ACLR and ramp lesions were matched to 50 isolated ACLR patients. Both groups reported significant improvements in subjective outcomes from preoperatively to postoperatively ($p < 0.001$). There were no significant differences in postoperative outcomes between combined ACLR with ramp repair and isolated ACLR ($p > 0.05$). Meniscal ramp patients had increased preoperative knee laxity demonstrated by grade 3 Lachman (44% vs. 6%) and pivot shift (38% vs. 12%) testing compared to isolated ACLR patients (p=0.005).

Conclusions

The results of this dissertation suggest that meniscal ramp lesions have a relatively low diagnostic sensitivity preoperatively and a careful intraoperative evaluation is required to identify all potential ramp lesions at the time of ACL surgery. These findings provide the anatomic foundation for an improved understanding of the meniscocapsular and meniscotibial attachments of the posterior medial meniscus which may help provide a more precise definition of a meniscal ramp lesion. The biomechanical analysis indicated that meniscal ramp lesions should be repaired at the time of ACL reconstruction to avoid continued knee instability (anterior tibial translation) and to eliminate the pivot-shift phenomenon. Additionally, patients reported improved clinical outcomes following ACL reconstruction and inside-out meniscal ramp repair with equivalence to isolated ACL reconstruction. These findings should prove useful for current orthopaedic surgeons to advance their practice and potentially decrease the rate of ACL graft reconstruction failure.

Abbreviations

- ACL Anterior cruciate ligament
- ACL-D Anterior cruciate ligament deficiency
- ACL-R Anterior cruciate ligament reconstruction
- ATT Anterior tibial translation
- BMC Bone marrow aspirate concentrate
- BTB Bone-patellar tendon-bone
- CI Confidence interval
- FCL Fibular collateral ligament
- H&E Hematoxylin and eosin
- IRB Institutional review board
- LFC Lateral femoral condyle
- LTP Lateral tibial plateau
- MCA Meniscocapsular attachment
- MFC Medial femoral condyle
- MM Medial meniscus
- MRI Magnetic resonance imaging
- MTA Meniscotibial attachment
- MTP Medial tibial plateau
- MVP Marrow venting procedure
- PCL Posterior cruciate ligament
- PHMM Posterior horn medial meniscus
- PLC Posterolateral corner
- POL Posterior oblique ligament
- PRP Platelet-rich plasma
- R-R Red-red
- R-W Red-white
- SD Standard deviation
- sMCL Superficial medial collateral ligament
- W-W White-white

Introduction

Increased attention has been directed toward the identification and treatment of concomitant knee injuries associated with anterior cruciate ligament (ACL) tears to best restore knee biomechanics and function. Data from ACL registries report that between 47% and 61% of ACL tears have concomitant meniscal tears(Ahlden, Samuelsson et al. 2012, Granan, Inacio et al. 2012), with the most-common intra-articular lesion involving the posterior horn of the medial meniscus (PHMM)(Noyes, Chen et al. 2011). Meniscocapsular tears of the PHMM are of specific interest because of the reported difficult visualization of the posteromedial "blind spot" when operating via traditional anteromedial and anterolateral portals.(Strobel 2013) These meniscocapsular lesions have recently been termed "ramp lesions",(Sonnery-Cottet, Conteduca et al. 2014) and their incidence has been reported in 16 to 24% of all knees with ACL tears (**Figure 1**).(Bollen 2010, Liu, Feng et al. 2011)

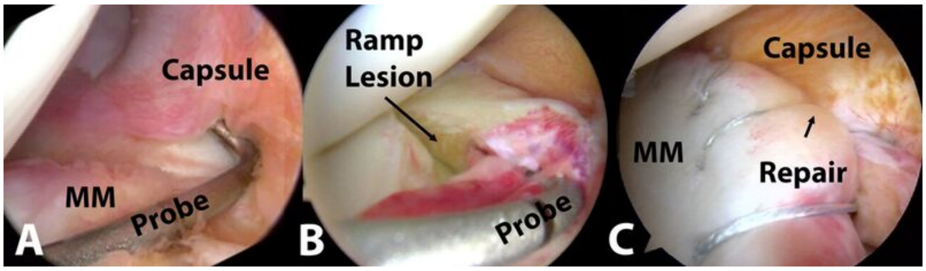


Figure 1. Intraoperative identification of a left knee medial meniscal (MM) ramp lesion. (A) Normal meniscocapsular junction with no evidence of ramp lesion. (B) Meniscal ramp lesion identified at time of arthroscopy (viewed through the intercondylar notch). (C) Restoration of meniscocapsular stability with ramp lesion repair via inside-out vertical mattress technique.

Preoperative magnetic resonance imaging (MRI) has been reported to have a low sensitivity for detecting meniscal ramp lesions.(Edgar C , Bollen 2010) Previous studies suggest that an accessory posteromedial portal may be required in order to reliably identify ramp lesions by arthroscopic probing.(Ahn, Kim et al. 2004, Sonnery-Cottet, Conteduca et al. 2014, Thaunat, Jan et al. 2016) Due to the limited utility of MRI to identify ramp lesions and the difficulty in identifying ramp lesions through standard arthroscopic portals, it has been reported that there is a high potential for these lesions to go undiagnosed and subsequently untreated.(Sonnery-Cottet, Conteduca et al. 2014, Peltier, Lording et al. 2015)

The medial meniscus has been reported to play a key role in stabilization for chronic ACL-deficient knees.(Shoemaker and Markolf 1986, Bonnin, Carret et al. 1996) The PHMM has been identified as a secondary restraint to anterior tibial translation.(Peltier, Lording et al. 2015) Due to increases in joint contact forces and subsequent early-onset of osteoarthritis after meniscectomy(Hoser, Fink et al. 2001, Stein, Mehling et al. 2010), there is increased interest throughout the past decade in meniscal preservation. Today, most authors favor meniscal repair over meniscectomy in light of the aforementioned consequences. However, discrepancy exists regarding treatment of meniscal ramp lesions, because some advocate for repair(Ahn, Wang et al. 2004, Li, Chen et al. 2015), while others suggest no treatment is necessary(Pujol and Beaufils 2009, Duchman, Westermann et al. 2015).

Currently, the available literature describing the biomechanical consequences of ramp lesions is limited. It is not clear whether these lesions affect joint kinematics and loading in the medial compartment of the knee similar to ACL deficiency(Gardner, Noyes et al. 2015, Noyes, Jetter et al. 2015) or posterior root lesions and complete radial tears of the medial meniscus(LaPrade, Jansson et al. 2014). However, recent biomechanical data suggest these lesions may result in increased anterior tibial displacement and increase strain on both the native ACL and ACL reconstructed graft.(Edgar C , Peltier, Lording et al. 2015, Stephen, Halewood et al. 2016) Due to the vital role of the medial meniscus as a secondary stabilizer, especially in the ACL-deficient knee, further research is needed on the clinical relevance of meniscal ramp lesions and their effect on knee joint kinematics.

Discrepancies regarding ramp lesion identification and treatment are highly dependent upon what constitutes a meniscal ramp lesion. Many of the current diagnostic, imaging, and biomechanical studies vary in the exact definition of a ramp lesion. The variation partly stems from geographical differences in the identification of these injuries and a lack of comprehensive anatomical research.(Granan, Inacio et al. 2012) The following section will present an overview of the current evidence regarding meniscal ramp lesions, from basic anatomy to treatment strategies, and their clinical relevance in sports medicine.

Background

What Is A Meniscal Ramp Lesion?

There is no consensus on the exact definition of a meniscal ramp lesion. A meniscal "ramp" lesion was first described by Hamberg et al.(Hamberg, Gillquist et al. 1983) in 1983 who reported on the disruption of the meniscocapsular attachment of the posterior meniscus during open surgical repair. With the innovation of the arthroscope, diagnosis of meniscal lesions became more evident. In 1984, Woods and Chapman reported on the arthroscopic prevalence of complete posterior meniscocapsular tears in both the medial (21.4%) and lateral (7.3%) menisci in ACL-deficient knees.(Woods and Chapman 1984) In response to this new perspective, Dr. Jack C. Hughston, M.D., predicted the importance yet complexity and skill required in arthroscopic diagnosis for these meniscal tears in an editorial:

> "The arthroscope is a great adjunct to the diagnosis of posterior capsule ligament tears of the menisci, especially when associated with anterior cruciate ligament tears. These are the type cases I feel fall into the category of anterior cruciate deficient knees because the meniscal tears were not recognized at initial arthrotomy. Still, I believe the arthroscopic diagnosis of many of these requires talent. However, I believe it is incorrect for the authors to state that arthroscopic examination is necessary for complete diagnosis in anterior cruciate ligament injuries. The physical examination and the clinical grading requires talent as well as the arthroscopy. I have no objection to their routine arthroscopy when an anterior cruciate ligament tear is suspected and I think it is a good way to diagnose the important associated meniscal tears; however, it is too dogmatic to state that arthroscopy is *necessary*."
>
> -**Jack C. Hughston, MD:** Editor of *The American Journal of Sports Medicine* (1984)

In 1988, Strobel(Strobel 1988) characterized a particular type of meniscal injury associated with ACL rupture involving the peripheral attachment of the PHMM and termed them “ramp” lesions due to their arthroscopic appearance of a downward slope or ramp. This injury was reported to be a meniscocapsular separation at the PHMM associated with ACL tears, but was of special interest due to its potential hidden location within the posterior septum, especially when the knee is near full extension. Since its original description, different anatomical locations have been proposed as the site of a ramp injury. The definition has been expanded in the literature as a longitudinal tear of the peripheral attachment of the PHMM at the meniscocapsular junction, with a length of 2.5 cm.(Liu, Feng et al. 2011) Since this description, others have suggested that a ramp lesion also involves the meniscotibial attachment of the posterior medial meniscus and also vertical tears of the posterior medial meniscus itself, rather than only involving tears at the posterior meniscocapsular junction.(Ahn, Bae et al. 2011, Peltier, Lording et al. 2015)

The name ‘ramp’ derives from its arthroscopic appearance of a downwards ‘ramp’ when viewing the meniscocapsular junction posteromedially. This area of the posterior medial knee has become of special interest because there is a potential fold in the capsule as it attaches posteriorly to the medial meniscus, and thus forms a “blind spot” during arthroscopic surgery.(Sonnery-Cottet, Conteduca et al. 2014) These ramp tears may be often under-recognized because they can hide from the surgeons point of view when viewing anteriorly or if the surgeon fails to assess this zone with the capsule under tension (retracting the capsule posteriorly with the use of a probe) (**Figure 2**).

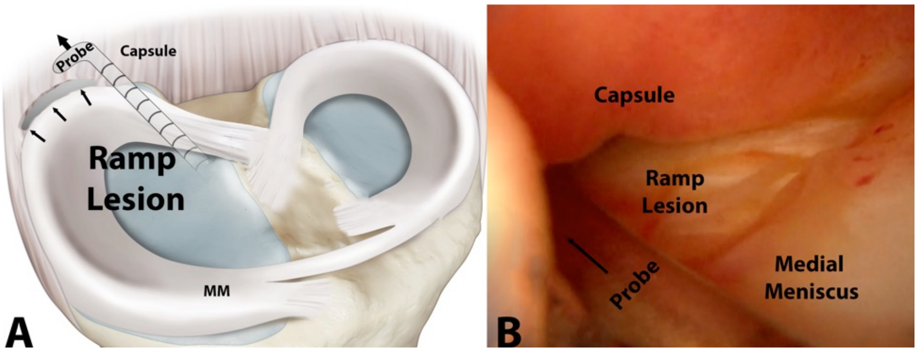


Figure 2. A) Illustration of a medial meniscocapsular separation, termed 'ramp' lesion. B) Arthroscopic view of medial meniscal ramp lesion with probe separating posterior medial meniscus from the posterior medial capsule.

Thaunat et al.(Thaunat, Fayard et al. 2016) proposed a classification system for meniscal ramp lesions in 2016. This system was the first to allow for a comprehensive assessment of ramp lesions arthroscopically according to subjective, expert opinion. These authors described five meniscal ramp tear types: 1) meniscocapsular lesion, 2) partial superior lesions of the posterior medial meniscus, 3) partial inferior ("hidden") lesions of the posterior medial meniscus with meniscotibial ligament disruption, 4) complete tear at the red-red zone of the posterior aspect of the medial meniscus with meniscotibial ligament disruption, and 5) double (vertical) tear of the posterior medial meniscus with meniscotibial ligament disruption (**Figure 3**).(Thaunat, Fayard et al. 2016)

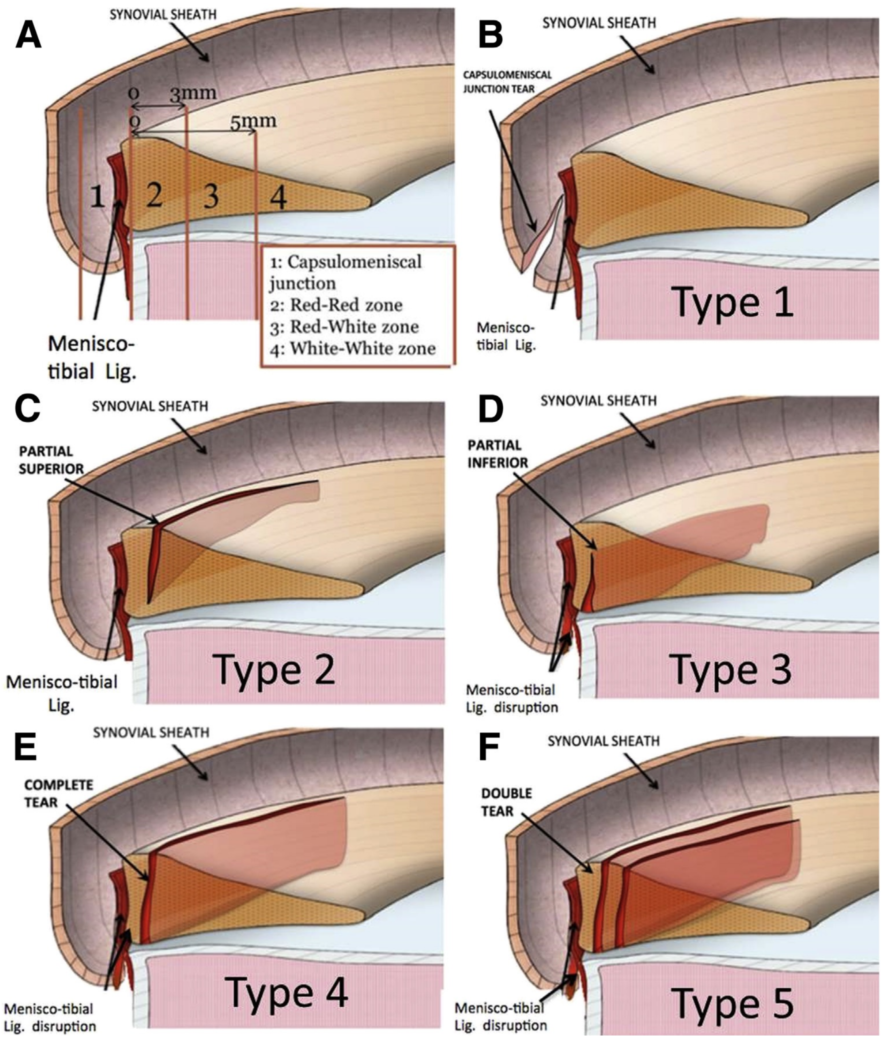


Figure 3. Schematic of proposed classification system for medial meniscal ramp lesions from Thaunat et al. (*Arthroscopy Techniques*, 2016).

Despite its detailed structure for describing meniscal ramp lesions, there is limited anatomical evidence to support this classification system and to date it lacks clinical validation.(Thaunat, Fayard et al. 2016) Furthermore, the prevalence of each type of meniscal ramp lesion is unknown and has yet to be described with this classification system, which limits its clinical utility. While this classification system does incorporate tears of both the meniscocapsular and meniscotibial attachments of the PHMM, there is a lack of quantitative description of the posteromedial anatomy to correlate with such tear patterns.

Anatomy

The menisci are comprised of a dense extracellular matrix which is composed of primarily water (72%) and collagen (22%).(Herwig, Egner et al. 1984, Makris, Hadidi et al. 2011) Collagen is the main fibrillar component of the menisci and varies in amount depending on region within the meniscus. Collagens are primarily responsible for the tensile strength of the menisci, contributing up to 75% of the dry weight of the extracellular matrix.(Herwig, Egner et al. 1984, Makris, Hadidi et al. 2011) The collagen fibers are heavily cross-linked and are ideal for transferring vertical compressive load into "hoop stresses".(Voloshin and Wosk 1983)

Previously, authors have divided the menisci into three segments (anterior horn, body, and posterior horn), while others divide it into five zones that are distinguishable on an anatomical basis (anterior root [zone 1], anteromedial zone [zone 2], medial zone [zone 3], posterior zone [zone 4], and the posterior root [zone 5]).(Strobel 1988, Smigielski, Becker et al. 2015) Pertaining to vascularity, the menisci can be divided into three zones: red-red, red-white, and white-white, designated from the outer periphery to the inner margin, respectively (**Figure 4**).(Arnoczky and Warren 1982) In the red zone, type I collagen is predominant (80% composition by dry weight), with other collagen variants (e.g., type II, III, IV, VI, and XVIII) present in less than 1%.(Herwig, Egner et al. 1984, Makris, Hadidi et al. 2011) In the white zone, collagen (70% by dry weight) is composed of only two types of collagen—types II (60%) and I (40%).(Cheung 1987) These zones are often used for classifying the location of meniscal lesions according to its proposed blood supply and for decision-making treatment options (e.g. meniscus repair vs. meniscectomy).(Barber-Westin and Noyes 2014)

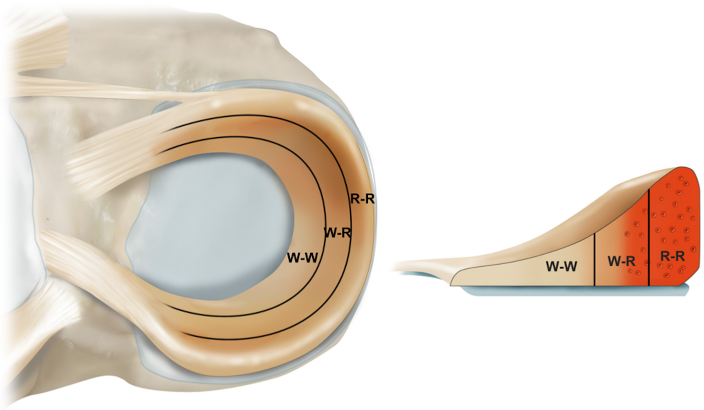


Figure 4. Illustration demonstrating the classic three zones of the meniscus according to its reported vascularity. W-W: white-white; W-R: white-red; R-R: red-red.

The medial meniscus is a semilunar fibrocartilage structure that covers approximately 50% of the medial tibial plateau.(Clark and Ogden 1983) It is broader posteriorly, measuring approximately 11 mm in width, and becoming narrower anteriorly toward its anterior meniscal root attachment.(Clark and Ogden 1983, Smigielski, Becker et al. 2015) The menisci enable effective articulation between the femoral condyle and the tibial plateau in their respective compartment; however, there are differences in the gross anatomy between the medial and lateral menisci that have clinical implications. First, the medial compartment consists of a convex femoral condyle and a concave tibial plateau which is thought to contribute to increased inherent bony stability which relates to an increased potential for musculoskeletal healing. In contrast, the lateral compartment consists of a convex femoral condyle and convex tibial plateau; the incongruency between joint surfaces laterally contributes to its inherent instability.(Clark and Ogden 1983, Laprade, Wentorf et al. 2006, Sanchez, Sugalski et al. 2006)

Second, the medial meniscus is larger and has a reduced mobility in comparison to the lateral meniscus, which makes it susceptible to injury during pivoting, rotation, and deep knee flexion movements.(Shoemaker and Markolf 1986, Bonnin, Carret et al. 1996) Third, the medial meniscus has a direct attachment to the medial collateral ligament (MCL), whereas the lateral meniscus does not have a direct attachment to the fibular collateral ligament (FCL).(LaPrade and Hamilton 1997, LaPrade, Ly et al. 2003, LaPrade, Engebretsen et al. 2007) However, the posterior horn of the lateral meniscus does have an attachment to the posterior cruciate ligament (PCL) and medial femoral condyle through the meniscofemoral ligaments (i.e. ligaments of Wrisberg and Humphrey).(Messner and Gao 1998)

Fourth, the posterior horn of the medial meniscus is firmly attached to the posterior capsule entirely; conversely, the lateral meniscus has a void in between its capsular attachment. This void is known as the popliteal hiatus and allows for the passage of the popliteus tendon, which transitions from an intra-articular to extra-articular structure and attaches to the anterior fifth of the popliteal sulcus on the femur.(LaPrade, Ly et al. 2003) As a result, there are differences in the lengths of the capsular attachments of the medial and lateral menisci as well as differences in meniscal mobility during arthroscopic evaluation. Consequently, there are anatomic variations between the medial and lateral menisci that relate directly to meniscal injury mechanisms, intra-operative inspection and diagnosis, and healing potential.

The anterior and posterior roots anchor the meniscus to the tibial plateau, and the body of the meniscus is attached to the adjacent joint capsule and to the tibia by the meniscotibial ligaments.(Johannsen, Civitarese et al. 2012, LaPrade, Ellman et al. 2014, Smigielski, Becker et al. 2015) Previous authors have quantified the anatomy of the meniscal root attachments, which provide clinically relevant measurements to be used during surgical evaluation and treatment of meniscal root tears. Specifically, it has been reported that the average area of the posterior meniscal root attachments are 30.4 mm^2 and 39.2 mm^2 for the medial and lateral meniscus, respectively.(Johannsen, Civitarese et al. 2012) The most applicable and surgically relevant landmarks for identifying the medial meniscus root center are the apex of the medial tibial eminence which is 9.6 mm anterior from the center of the medial root, and the most proximal attachment of the PCL is directly 8.2 mm posterior from the medial posterior root center. Laterally, the anatomy and distances are different. For example, the lateral posterior root center is 1.5 mm posterior and 4.2 mm medial to the apex of the lateral tibial eminence, and most proximal attachment of the PCL is directly 12.7 mm posterior from the lateral posterior root center.(Johannsen, Civitarese et al. 2012)

While these descriptions for meniscal root anatomy are extremely helpful, the literature is lacking any sort of quantifiable data regarding the location and presence of meniscal ramp lesions. Specifically, there are limited quantifiable descriptions on the meniscocapsular and meniscotibial attachments of the PHMM and a lack of description to surgically relevant anatomy. Thus, an improved understanding of the anatomy of the PHMM attachments may improve (1) the understanding of its importance in tears localized at the PHMM and (2) the anatomic approach to their treatment.

Epidemiology & Incidence

Anterior cruciate ligament tears are one of the most common traumatic injuries among physically active individuals. Fifty percent of ACL tears occur in patients between the ages of 15 and 25 years old and one in 18 ACL rupture patients experience an ACL injury to the contralateral limb.(Centers for Disease and Prevention 2006, Shelbourne, Gray et al. 2009) It has been estimated that female athletes have a four to eight fold increased risk of tearing their ACL compared to their male counterparts of equivalent age and sport.(Arendt and Dick 1995, Myklebust, Maehlum et al. 1998, Agel, Arendt et al. 2005) The most common sports associated with ACL tears are soccer, basketball, volleyball, and handball.(Hewett, Lindenfeld et al. 1999, Heidt, Sweeterman et al. 2000, Myklebust, Engebretsen et al. 2003, Mandelbaum, Silvers et al. 2005) Approximately 70-80% of ACL tears involve noncontact mechanisms of injury during a jump-landing, change of direction, or pivoting maneuver.(Noyes, Matthews et al. 1983, Noyes, Mooar et al. 1983, Boden, Dean et al. 2000, Fauno and Wulff Jakobsen 2006) These mechanisms of injury are considered internal risk factors that are modifiable and as a result, ACL tear prevention programs are predicated on the evaluation and intervention of these biomechanical movement patterns that occur at the time of injury.

Since the inception of Title IX of The Educational Assistance Act in 1972 in the United States, the number of female athletes at the high school level has increased more than 11 times, whereas the number of male athletes participating in sports has increased only 3%.(2002) In 2001, the total number of ACL injuries among female athletes was estimated to be 38,000 annually in the United States alone.(Toth and Cordasco 2001) In 2010, the estimated total number of ACL injuries was approximately 350,000 annually in the United States.(Cimino, Volk et al. 2010, Wojtys and Brower 2010) These data support the theory of increased ACL injuries following the passage of the Title IX Act due to the higher prevalence and risk of ACL tears among female athletes. Due to the increased interest in sports participation, coupled with increased ACL injury rates, injury surveillance programs have been established in order to monitor ACL injured athletes in hopes to identify trends that researchers can use to implement injury prevention programs.(Florenes, Bere et al. 2009, Bere and Bahr 2014) These injury surveillance programs also provide insight to the consequences of ACL injuries and post-traumatic function of athletes.

The ACL plays an integral role in knee stability and function, especially in athletes who participate in cutting and pivoting sports. The physical consequences of ACL tears have been well documented and include physical disability, inability to decelerate, cut or pivot while running, as well as associated pain and swelling with activities.(Lohmander, Ostenberg et al. 2004, von Porat, Roos et al. 2004, Cimino, Volk et al. 2010) In addition, an athlete ≤ 25 years of age who sustains a primary ACL tear has a reported 24-29% increased risk for sustaining a subsequent ACL tear if they return back to sport.(Webster, Feller et al. 2014) Most athletes require ACL reconstruction in order to improve their physical dysfunction; however, there are a number of detrimental consequences associated with sustaining an ACL tear regardless of treatment.(Lohmander and Roos 1994, von Porat, Roos et al. 2004, Shelbourne and Gray 2009, Shelbourne, Gray et al. 2009, Grindem, Eitzen et al. 2014) Lohmander et al.(Lohmander, Englund et al. 2007) conducted a literature review for the purpose of identifying the long-term consequences of injuries to the ACL and menisci. This analysis revealed that approximately 70% of young athletes who suffered an ACL injury developed moderate pre-mature knee osteoarthritis within 10 to 15 years.(Lohmander, Englund et al. 2007) At 10 to 20 years after the diagnosis, on average, 50% of those with a diagnosed ACL or meniscus tear developed osteoarthritis with associated pain, severely affected quality of life, and functional impairment; what authors referred to as "the young patient with an old knee".(Lohmander, Englund et al. 2007) To date, there is a lack of evidence to support a protective role of repair or reconstruction surgery of the ACL against post-traumatic osteoarthritis (PTOA) development.(Tsoukas, Fotopoulos et al. 2016, Lin, Wang et al. 2017) In a systematic review, authors reported significant positive associations between follow-up time and the increased prevalence of PTOA after ACL reconstruction.(Cinque, Dornan et al. 2018) Specifically, the model-estimated proportion of PTOA at 5, 10, and 20 years after ACL reconstruction was 11.3%, 20.6%, and 51.6%, respectively. Additionally, increased chronicity of ACL tear before surgery (i.e. delayed ACLR) and increased age were significantly positively correlated with the development of PTOA.(Cinque, Dornan et al. 2018) Thus, a need exists for improvement in the appropriate management of such consequential and debilitating knee injuries.

Concomitant intra-articular lesions are commonly seen in patients sustaining ACL tears. Approximately 43% of all ACL-injured patients have been reported to have an associated meniscal tear, with lateral meniscal tears having a slightly higher incidence than medial meniscus tears (56% vs. 44%, respectively) in knees with acute ACL tears.(Borchers, Kaeding et al. 2011, Bisson, Kluczynski et al. 2013) However, in the setting of chronic ACL deficiency (> 6 weeks), medial meniscus tears are more common.(Keene, Bickerstaff et al. 1993) The reduced mobility of the medial meniscus makes it susceptible to injuries, especially in deep flexion and with rotational trauma in the ACL-deficient knee when the loading is increased in the posterior horn of the medial meniscus.(Becker, Wirz et al. 2005)

The menisci function together with the cartilage and thus are extremely important for successful outcome following ACLR. It has been well established that meniscal preservation is extremely important for the longevity of the knee joint, with increasing rates of post-traumatic osteoarthritis with meniscal resection.(Lohmander, Englund et al. 2007, Group, Wright et al. 2010, Lin, Wang et al. 2017) In addition, the menisci also play a role in providing secondary stability to the knee; specifically, the posterior horn of the medial meniscus, which is a secondary stabilizer for anterior tibial translation in the ACL-deficient knee.(Shoemaker and Markolf 1986, Papageorgiou, Gil et al. 2001) Recent data indicate that medial meniscal pathology is one of the most the significantly correlated factors associated with increased risk of revision ACLR.(Trojani, Sbihi et al. 2011, Webster, Feller et al. 2018) Current evidence suggests the potential for decreasing ACLR graft failure rates with successful repair of unstable medial meniscal ramp lesions.(Ahn, Bae et al. 2011, Stephen, Halewood et al. 2016, Edgar, Kumar et al. 2018) However, it is important to understand how often ramp lesions occur in the general population of patients who sustain ACL tears in order to evaluate the overall potential effect of ramp repair strategies.

The reported incidence of meniscal ramp lesions has increased over time as these injuries have become more recognized both preoperatively on MRI and intraoperatively at the time of ACL surgery. In 2010, Bollen(Bollen 2010) reported a meniscal ramp incidence of 9.3% (n=17) in a prospective assessment of 183 consecutive ACLR over a 14-month period. Di Vico et al.(Di Vico, Di Donato et al. 2017) reported a rate of 9.6% in a series of 115 patients who underwent ACLR. Edgar et al.(Edgar, Kumar et al. 2018) reported on 337 patients who underwent primary ACLR over a 5-year period and identified ramp lesions in 44 patients, for an overall incidence of 13.1%. Liu et al.(Liu, Feng et al. 2011) reported an incidence of 16.6% in a larger cross-sectional study involving 868 consecutive ACLR patients. Malatray et al.(Malatray, Raux et al. 2018) prospectively evaluated 56 pediatric and adolescent patients (mean age 14.0 ± 1.3 years) and found that 23% had a meniscal ramp lesion at the time of ACL surgery. Plymale et al.(Plymale, Fleisig et al. 2014) reported a 12.3% incidence in tears at the meniscocapsular junction in patients who underwent primary ACL reconstruction; however, ramp lesion incidence increased to 23.6% in revision ACL reconstruction patients. Similarly, Seil et al.(Seil, Mouton et al. 2018) reported an incidence of 24% in 224 patients who underwent either primary or revision ACLR. Most recently, Sonnery-Cottet et al.(Sonnery-Cottet, Praz et al. 2018) reported an incidence of 23.9% in 3214 patients at the time of ACLR (primary and revision). Variations in meniscal ramp incidence may be related to the patient populations involved and geographic locations in which the research is performed (e.g. Asia, Europe, United States).

Despite the broad range of the reported incidence of ramp tears in the ACL-deficient knee, it is important to understand the injury mechanisms (noncontact vs. contact) and clinical characteristics of ACL injured patients because this may differ with varying patient populations. These variations may be directly related to the diagnostic techniques used. Specifically, relying on preoperative MRI vs. arthroscopic evaluation and the use of different surgical techniques to evaluate the location for a potential ramp lesion may affect the ability to accurately diagnose a ramp tear.

Diagnosis

Imaging

Magnetic resonance imaging is a reliable diagnostic modality for most intra and extra-articular pathologies of the knee. However, researchers have previously demonstrated the inability of MRI scans to detect associated injuries with ACL tears, such as FCL tears or injuries to the posterolateral corner of the knee.(Geeslin and LaPrade 2010, Kane, DePhillipo et al. 2018) Similarly, while MRI is reliable for most meniscal pathologies, studies have reported a low sensitivity of MRI and interpreting radiologists to specifically detect ramp lesions.(Bollen 2010, Liu, Feng et al. 2011) The inconsistency in the definition of a meniscal ramp lesion may also contribute to the difficulty in diagnosing these tears on MRI. Geeslin et al.(Geeslin and LaPrade 2010) reported that medial compartment bone bruises, most commonly of the anteromedial femoral condyle, were frequently found on MRI scans in patients with isolated and combined posterolateral corner knee injuries. Defining the incidence and location of bone bruise patterns on MRI can aid in the understanding of the mechanism of injury for ramp lesions as well as serve as an indirect sign for injury, thus improving the overall rate of preoperative diagnosis.

The most common reported finding on MRI for diagnosing a meniscal ramp lesion is the presence of a thin, vertical line of fluid at the meniscocapsular junction of the PHMM, visualized best on the fat-saturated images of the sagittal view.(Hash 2013, Hatayama, Terauchi et al. 2018) However, previous authors have reported the identification of meniscal ramp lesions on the images in the coronal view.(De Maeseneer, Shahabpour et al. 2002) Specifically, authors report the presence of perimeniscal fluid above the medial meniscus at the level of the superficial MCL. The proposed mechanism for this is that the meniscus is torn elsewhere, resulting in fluid leakage which becomes trapped between the MCL and the medial meniscus on the coronal view.(De Maeseneer, Shahabpour et al. 2002)

Edgar et al.(Edgar, Kumar et al. 2018) reported the suspicion of a meniscal ramp lesion via MRI in 33 of 43 patients with ramp lesions, yielding a sensitivity of 77% for meniscal ramp detection on MRI. Similarly, Arner et al.(Arner, Herbst et al. 2017) reported on 13 patients with ramp lesions and found an inconsistent diagnosis rate of 54% to 84%, however a very high specificity on MRI (92% to 98%). In contrast, Bollen(Bollen 2010) reported that 0 of 11 arthroscopically confirmed ramp lesions were detected on preoperative MRI. Subsequently, Bollen(Bollen 2010) proposed that because MRI is performed with the patient supine and the knee near full extension, the meniscocapsular separation is most likely reduced during imaging, leading to a large number of false negatives. This is similar to how a reduced bucket-handle tear may not be detected on MRI.(Bollen 2010) Hirtler et al.(Hirtler, Unger et al. 2015) also reported a low detection of isolated meniscocapsular separations preoperatively on MRI, because 16% of lesions were accurately diagnosed and 84% were missed compared to intraoperative evaluation. Additionally, in comparison to other meniscal tears, the sensitivity for preoperative diagnosis for ramp lesions has reported to be significantly lower than that for meniscal body tears (71% vs. 94%, respectively; p=0.01).(Hatayama, Terauchi et al. 2018) The authors indicated that the sensitivity of a higher MRI magnet strength (i.e. 3 Tesla MRI) was superior to that of a lesser MRI magnet strength (i.e. 1.5 Tesla MRI) (83% vs. 67%, respectively).(Hatayama, Terauchi et al. 2018)

Considering the relatively low diagnostic utility of MRI for ramp tears, establishing secondary signs of meniscal ramp lesions on preoperative MRI may lead to an increased suspicion and preoperative diagnosis for planning surgical procedures, similarly to those previously established for posterolateral corner injuries.(Geeslin and LaPrade 2010) Additionally, combining the MRI evaluation with pertinent clinical characteristics of injured patients may help improve the preoperative diagnostic accuracy of meniscal ramp lesions at the time of ACL reconstruction.

Clinical Characteristics

The first large case series reporting the incidence and clinical characteristics for patients with combined ACL and meniscal ramp tears was conducted by Liu et al.(Liu, Feng et al. 2011) Of 144 patients with arthroscopically confirmed ramp lesions, 78% were males and 22% were females with a mean age of 24.7 years. They reported significant differences in age between patients with meniscal ramp lesions and without ramp lesions. Specifically, an age < 30 years old was associated with a higher incidence of ramp lesions ($p < .05$). Although the mechanism of injury was not specifically reported, the majority of patients with ramp lesions had chronic injuries with an average 27.2 months between the time from injury and surgery. Additionally, a concomitant lateral meniscus tear was present in 22% (n=32) of cases with a medial meniscal ramp lesion.(Liu, Feng et al. 2011)

Di Vico et al.(Di Vico, Di Donato et al. 2017) reported a significant correlation between time from injury to surgery and the presence of a meniscal ramp lesion in 115 primary ACLR patients. Specifically, the prevalence of ramp lesions increased in patients who were treated surgically during the first 6 months following injury (14%); this is in comparison to a 2% prevalence for patients who reported greater than 6 months' time from injury to surgery. This suggests the potential for these meniscal lesions to heal on their own without repair.(Liu, Zhang et al. 2017) However, this study is limited by its relatively small sample size with analysis of only 11 patients who had meniscal ramp lesions.(Di Vico, Di Donato et al. 2017)

In contrast, Sonnery-Cottet et al.(Sonnery-Cottet, Praz et al. 2018) reported on the largest sample size to date for meniscal ramp lesion incidence and clinical characteristics, including 3214 primary and revision ACL reconstruction patients. The authors presented their findings on 769 patients with meniscal ramp lesions and noted a higher prevalence of meniscal ramp lesions for: males (79%, n=610) compared to females (21%, n=159), chronic injuries (56%, n=432) compared to acute injuries (44%; n=337), and a contact mechanism of injury (69%; n=528) compared to a noncontact injury (31%; n=241). Multivariate regression indicated that age ≤ 30 years of age significantly predicted the likelihood of a combined ACL tear with meniscal ramp lesion compared to an ACL tear with no meniscal ramp lesion ($p < .05$). Preoperatively, a higher grade of anterior knee instability was found with ramp lesions compared to no evidence of ramp lesions; specifically, > 6 mm of increased side-to-side ATT documented on KT-1000. Additionally, the regression model indicated that prevalence of meniscal ramp lesions were significantly associated with the presence of concomitant lateral meniscus tears and revision ACL reconstruction ($p < .05$).(Sonnery-Cottet, Praz et al. 2018)

In a prospective study, Seil et al.(Seil, Mouton et al. 2018) evaluated injury characteristics for 224 patients who underwent primary or revision ACL reconstruction. The authors reported that patients were three times more likely to have a ramp lesion if a contact mechanism occurred at the time of injury. Additionally, patients were nine times more likely to have a ramp lesion with a complete ACL tear compared to a partial ACL tear.(Seil, Mouton et al. 2018) The previous studies reporting on the identification of preoperative risk factors for meniscal ramp lesions allow for an increased awareness and potential for improved rates of intraoperative diagnosis at the time of ACLR.

Intraoperative

The gold standard for diagnosing meniscal ramp lesions is arthroscopy.(Bollen 2010, Liu, Feng et al. 2011, Sonnery-Cottet, Conteduca et al. 2014) Due to the potential hidden nature of ramp lesions, different techniques have been proposed to evaluate the location of ramp lesions during arthroscopy. The modified Gillquist view (trans-notch) allows for the arthroscope to be advanced between the posterior cruciate ligament and medial femoral condyle, allowing direct access to the posteromedial meniscocapsular junction and visualization of potential ramp lesions.(Gillquist, Hagberg et al. 1979) Gillquist et al.(Gillquist, Hagberg et al. 1979) first described this arthroscopic view in 1979 which was developed due to previous reports of missed diagnoses during arthroscopy, including injuries to the posterior horn of the medial meniscus, meniscotibial ligament, PCL, and MCL(Gillquist and Hagberg 1976, Gillquist, Hagberg et al. 1977). The traditional technique describes testing of the meniscocapsular attachments and posteromedial ligaments by rotating the leg with the knee in flexion.(O'Connor 1974, Gillquist, Hagberg et al. 1979) The modified technique reports manipulation of the capsule via an arthroscopic probe which is used to push away the capsule in order to inspect the meniscocapsular junction for potential hidden ramp lesions. The benefit of using this view, as opposed to the direct anterior approach, is that it affords the surgeon direct visualization of the medial edge of the PCL, medial meniscus root attachment, and meniscocapsular junction of PHMM. Additionally, no other incisions are needed with the Gillquist approach which is an inherent strength for intraoperative assessment.

In contrast, previous authors have advocated for the use of an accessory posteromedial portal to help guide an accurate diagnosis, visualization, and repair of ramp lesions.(Sonnery-Cottet, Conteduca et al. 2014, Peltier, Lording et al. 2015, Thaunat, Jan et al. 2016) For this approach, a small incision is made posterior to the MCL and posterior oblique ligament, anterior to the medial head of the gastrocnemius, and superior to the semimembranosus. An accessory posteromedial portal can be used for both visualization and working instruments for inspection and repair.(Li, Chen et al. 2015) However, often times an additional incision is needed on the lateral side of the knee (transportal) in order to access the meniscocapsular junction appropriately for repair.(Seil, Mouton et al. 2018) The reported disadvantages of this approach are that it requires multiple portals and the repair and inspection are limited to the meniscocapsular junction only, because the surgeon has limited access for meniscotibial-sided tears due to the portals being superior to the meniscus.(Malatray, Raux et al. 2018) An inherent advantage of this approach is placing the arthroscope in the posteromedial portal directly which can potentially improve the rate of unseen ramp lesions during arthroscopy. In a study evaluating the diagnostic accuracy of adding a posteromedial portal for the evaluation of ramp lesions, Sonnery-Cottet et al.(Sonnery-Cottet, Conteduca et al. 2014) reported a high rate (17%) of missed meniscocapsular tears before the addition of a posteromedial portal. It is important to recognize that surgical technique is often predicated on one's previous learning experience, because surgeons tend to practice what they know. Therefore, understanding the current trends of orthopaedic surgeons, especially those at academic and teaching hospitals, may allow for a better understanding of the reported incidence of ramp lesions and lead to improved diagnostic strategies for the classification of meniscal ramp tears.

Biomechanics

The menisci have a number of reported functions within the knee, including load transmission and distribution of forces, joint lubrication, cartilage nutrition, proprioception, and acting as secondary stabilizing structures.(Messner and Gao 1998) The biomechanical functions of the menisci are to withstand compressive, tensile, and shear forces (**Figure 5**).(Messner and Gao 1998) The medial meniscus has been reported to have an essential role in stabilizing the knee in chronic ACL-deficient knees.(Terry and Hughston 1985) Biomechanical studies have demonstrated the importance of the menisci for the longevity of the knee joint and the interdependence between the medial meniscus and the ACL.(Papageorgiou, Gil et al. 2001, Padalecki, Jansson et al. 2014, Steineman, LaPrade et al. 2017)

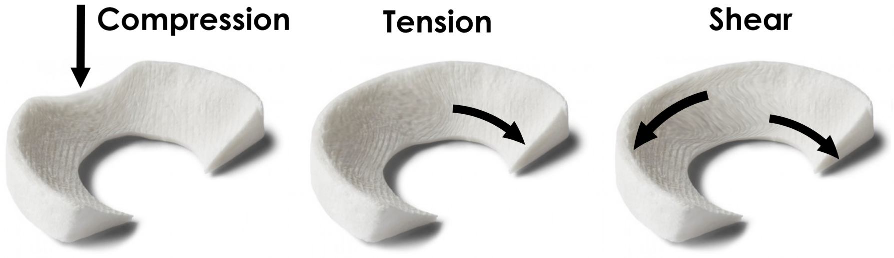


Figure 5. Biomechanical properties of the human meniscus.

Muriuki et al.(Muriuki, Tuason et al. 2011) described changes in tibiofemoral contact pressures after vertical tears of the PHMM as compared with radial split tears. The authors concluded that vertical tears of the PHMM increased contact pressure and reduced contact area in the medial and lateral compartments, with no differences as compared with a total medial meniscectomy.(Muriuki, Tuason et al. 2011) Similarly, Dugas et al.(Dugas, Barrett et al. 2015) evaluated the contact mechanics following meniscocapsular separation in 10 cadaveric specimens. The authors created a meniscal ramp lesion via a 1.5 cm incision in the posteromedial capsule. Results indicated no significant differences between intact, meniscocapsular tear, or repair states ($p > .05$); however, there was an observable trend towards increased tibiofemoral contact pressure and contact area after creation of the meniscocapsular tear. The authors theorized that although the changes in contact mechanics were small, these changes could potentially induce degenerative changes at the articular cartilage surface over prolonged periods of standing, walking, or physical activity in the unrepaired state.(Dugas, Barrett et al. 2015)

In 2001, Papageorgiou et al.(Papageorgiou, Gil et al. 2001) demonstrated the biomechanical interdependence between the ACL-reconstructed graft and the medial meniscus. They reported increased forces of up to 54% in the ACL-reconstructed graft after a medial meniscectomy, further advocating the potential for increased ACL reconstruction graft failure with medial meniscal deficiency.(Papageorgiou, Gil et al. 2001) Recent data suggest that medial meniscocapsular tears, when left untreated, predispose the ACL-reconstructed knee to increased anterior tibial translation (ATT) and potential increased strain in the ACL-reconstructed graft which correlated to ACL reconstruction graft failure.(Edgar, Kumar et al. 2018)

Despite the evidence surrounding the medial meniscus and its supportive role in anterior knee stability, there is continued controversy whether meniscal ramp lesions specifically affect knee kinematics in ACL-reconstructed knees. Table 1 reports the maximal residual differences in anterior tibial translation and knee rotation among prior biomechanical studies assessing the effects of meniscal ramp lesions. When comparing the degree in which knee translation is increased, it is important to evaluate the normal amounts of movement in ACL-intact and ACL-deficient knees. For example, previous research has shown that a side-to-side difference of 3 mm with a maximal manual force device (KT-1000 arthometer) is indicative of a completely torn ACL.(Tyler, McHugh et al. 1999, Ganko, Engebretsen et al. 2000) Therefore, the reported increases of between 1 mm to 5 mm in anterior tibial translation with the presence of meniscal ramp lesions in the controlled laboratory setting may indeed have clinical implications.

Table 1. Maximal increases in knee kinematics among biomechanical studies assessing meniscal ramp lesions in ACL-deficient knees compared to intact state.

Study	ATT (mm)	IR (deg)	ER (deg)
Ahn et al. 2011	5.2	2.8	NR
Stephen et al. 2016	3.0	NR	2.5
Peltier et al. 2015	3.5	2.8	1.7
Edgar et al. 2018*	1.2	NR	NR

ATT: anterior tibial translation; IR: internal rotation; ER: external rotation; NR: not reported.
*Did not cut ACL during testing

The biomechanical functions of the PHMM attachments are essential because recent investigations have reported that meniscal deficiency is the most significant clinical factor to predict ACL reconstruction graft failure.(Parkinson, Robb et al. 2017) For meniscal ramp lesions, both of the connecting meniscocapsular and meniscotibial structures have been reported to affect knee kinematics in two different biomechanical models.(Peltier, Lording et al. 2015, Stephen, Halewood et al. 2016) However, an understanding of the separate biomechanical effects of tears to the meniscocapsular attachment (MCA) and the meniscotibial attachment (MTA) of the PHMM in ACL-deficient and ACL-reconstructed knees is still lacking. To date, research regarding the biomechanical effectiveness of meniscal ramp repair is limited and it has been reported on an all-inside repair technique(Stephen, Halewood et al. 2016); however, an inside-out repair has yet to be studied biomechanically for ramp lesions.

Treatment Strategies

Current surgical treatment strategies for meniscal tears include repair, meniscectomy, and trephination. The designated treatment is dependent upon the location of the tear, tear pattern, stability of the tear, and quality of the meniscal tissue. For meniscal ramp lesions, there is controversy regarding surgical treatment options due to the vascular zone of the meniscus in which a ramp lesion is reported to occur.

Meniscal Healing

The meniscus has been reported to be a relatively avascular structure with a limited peripheral blood supply. Branches of the popliteal artery are the major blood vessels that nourish the menisci with extensions from a perimeniscal capillary plexus that enters each meniscus and has a richer contribution in the anterior and posterior horns.(Petersen and Tillmann 1995, Gray 1999, Makris, Hadidi et al. 2011) Specifically, the vascularity of the menisci is primarily derived from the superior and inferior medial and lateral genicular arteries and the middle genicular artery.(Arnoczky and Warren 1982) The inferior medial genicular artery supplies the peripheral 20-30% of the medial meniscus, while the inferior lateral genicular artery supplies the peripheral 10-25% of the lateral meniscus.(Arnoczky and Warren 1982) A synovial fringe that extends approximately 3 mm over the surface of each meniscus adds further to the peripheral vascularity. The central 70-75% of both menisci have been reported to receive nutrition via diffusion only. Consequently, there is significant discrepancy in the vascularity of the menisci, with the peripheral tissue ('red-red' and 'red-white' zones) more vascular than the central zones ('white-white' zone) (**Figure 6**).(Arnoczky and Warren 1982) The vascularity of the menisci has also been reported to diminish and become more peripheral with age.(Petersen and Tillmann 1995) Therefore, the healing potential of the meniscus depends largely on the location of the lesion and the age of the patient. Because of its high vascularity, peripheral meniscal tears (closest to the meniscocapsular junction) have the greatest potential for healing.

Figure 6. Histologic cross-section of the medial meniscus demonstrating the vascularization of the meniscus according to its 3 zones (adapted from Arnoczky and Warren, *Am J Sports Med,* 1982). PCP: perimeniscal capillary complex; RR: red-red; RW: red-white; WW: white-white; F: femur; T: tibia.

Clinically, tears in the white-white zone have classically been treated with debridement and meniscectomy, rather than repair, given the lower likelihood of successful healing of a repair in avascular tissue.(Grant, Wilde et al. 2012) In contrast, meniscal tears in the red-red and red-white zones are typically treated with repairs due to the increased vascularity in these regions (dependent also on tissue quality and tear type).(Helms 2002, Johnson and Weiss 2012, Barber-Westin and Noyes 2014) Some authors advocate for the surgical repair of all meniscal ramp lesions at the time of ACLR, based on the potential increased risk of persistent instability and reconstruction graft failure when not treated.(Stephen, Halewood et al. 2016, Thaunat, Jan et al. 2016) However, given the vascularization of the capsule and the red-red vascular zone of the meniscus, some clinical studies have reported on the potential for these tears to heal without surgical treatment.(Duchman, Westermann et al. 2015, Liu, Zhang et al. 2017)

Liu et al.(Liu, Zhang et al. 2017) prospectively evaluated 91 consecutive patients who had complete ACL tears and concomitant stable ramp lesions (defined as nondisplaced tears < 1.5 cm in length). Patients were randomly allocated to either surgical repair via all-inside technique (study group) or trephination only (control group). At 2 year follow-up, the authors reported no significant differences ($p > .05$) between study and control group according to subjective outcomes scores and knee stability on physical examination.(Liu, Zhang et al. 2017) Additionally, there were no significant differences regarding the healing status of the ramp lesions assessed with postoperative MRI between the two groups ($p = 0.543$). These results indicate that a trephination alone may be capable of stimulating a cellular environment necessary for generating healing of meniscocapsular-based tears without suture repair.(Liu, Zhang et al. 2017)

Similarly, Yang et al.(Yang, Guan et al. 2017) retrospectively analyzed 68 patients who underwent ACL reconstruction with hamstring autograft who had arthroscopic confirmation of a meniscal ramp tear. Patients were either treated with 1) an arthroscopic refreshing of the injured ramp area or 2) all-inside ramp repair with an all-inside meniscal repair device (Fast-Fix). Inclusion criteria consisted of ramp lesions that were considered stable, with a maximal ramp tear width of 1 to 2 cm. Results demonstrated no significant differences in patient-reported outcomes or objective measures of knee range-of-motion at 12 and 24 months postoperatively ($p < .05$). Therefore, the authors concluded that this alternative treatment option of meniscal refreshing may be worth investigating due to the reported minimalistic approach for all-inside ramp repair for stable meniscal ramp lesions.(Yang, Guan et al. 2017)

Repair Techniques

There are two main reported techniques for repairing meniscal ramp lesions: 1) all-inside and 2) inside-out repair. Previous studies have reported satisfactory clinical outcomes at a minimum 2-year follow-up after combined ACLR and all-inside ramp repair.(Thaunat, Jan et al. 2016, Keyhani, Ahn et al. 2017, Sonnery-Cottet, Praz et al. 2018) Sonnery-Cottet et al.(Sonnery-Cottet, Praz et al. 2018) reported an 11% overall meniscal repair failure rate in patients who underwent combined ACL reconstruction and all-inside ramp repair via an accessory posteromedial portal. The proposed advantages for all-inside repair include no additional incisions with the use of a single posteromedial portal, improved visualization of the PHMM when utilizing an accessory posteromedial portal, and quicker surgical repair time. However, a potential disadvantage of all-inside repair via an accessory posteromedial portal is the inability to access tears involving the meniscotibial attachment or undersurface tears of the PHMM. Other disadvantages include the capacity to use fewer sutures for repair, risk of saphenous nerve and vein injury with a posteromedial portal, and deployment of a surgical implant into the meniscus with hybrid repair devices.(Thaunat, Fayard et al. 2016) Deployment of a surgical implant into the meniscus can be a major problem as this can cause further tearing of the meniscus and/or potentially cause iatrogenic cartilage damage during or after deployment of the implant.(Heilpern, Stephen et al. 2018)

Inside-out meniscal repair techniques have been reported to increase the strength of the repair construct by utilizing an increased number of sutures.(Chahla, Serra Cruz et al. 2016) Although technically demanding, the versatility for suture placement combined with anatomic repair of the meniscus to the posterior capsule affords an inside-out repair advantageous compared to all-inside devices (**Figure 7)**. Disadvantages of inside-out repair techniques include the need for additional incisions, risk of neurovascular injuries with the surgical approach, and the extended surgical time for the meniscus repair.(Chahla, Serra Cruz et al. 2016, Joshi, Usman et al. 2016, Chahla, Dean et al. 2017, DePhillipo, Cinque et al. 2017) With the relatively high failure rate (11%) following all-inside meniscal ramp repair(Sonnery-Cottet, Praz et al. 2018), future clinical studies are necessary to assess patient outcomes following inside-out ramp repair techniques. To date, no study has evaluated clinical outcomes following ACL reconstruction with inside-out meniscal ramp repair compared to patients with isolated ACL reconstruction.

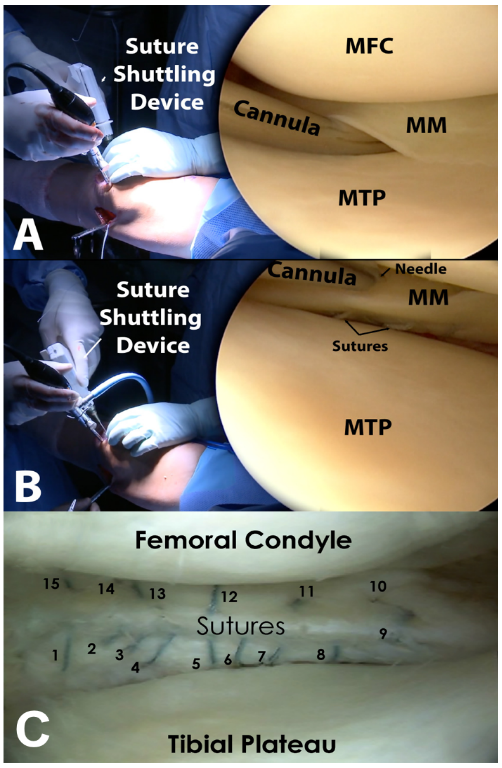


Figure 7. Inside-out meniscal repair technique. Use of suture shuttling device for suture placement within A) inferior meniscus and posterior capsule and B) superior meniscus and posterior capsule. C) Example of use of multiple sutures for increasing repair construct during vertical mattress inside-out repair technique. MFC: medial femoral condyle, MTP: medial tibial plateau, MM: medial meniscus.

Timing of Surgery

Controversy exists regarding early versus delayed surgery in patients who sustain complete ACL tears.(Deabate, Previtali et al. 2019) Previous studies have demonstrated that ACL reconstruction is not necessary for all patients, as a subset of ACL tear patients can cope with this knee injury and regain adequate function.(Kostogiannis, Ageberg et al. 2007, Grindem, Eitzen et al. 2014, Thoma, Grindem et al. 2019) While nonoperative management may be recommended initially, those who fail conservative treatment and ultimately delay ACL reconstruction may have increased risks for developing cartilage and meniscal lesions.(Church and Keating 2005, Mehl, Otto et al. 2019, Stone, Perrone et al. 2019) Kennedy et al.(Kennedy, Jackson et al. 2010) evaluated 300 ACL reconstruction patients and found that there was a significantly higher risk of developing a medial meniscus tear in patients with delayed surgery ≥ 1 year from time of injury (odds ratio: 7.99, p = .004). Similarly, Papastergiou et al.(Papastergiou, Koukoulias et al. 2007) found an increased incidence of overall meniscal tears (medial and lateral) when ACL surgery was delayed beyond 3 months. Another reported risk in delayed surgery that has been reported is the development of secondary meniscal tears, with significant increased rates of meniscal tears with delays > 6 months from time of injury.(Hagmeijer, Hevesi et al. 2019)

These results correspond with previous biomechanical data that showed when the ACL is torn, the *in-situ* forces in the medial meniscus increase by 100%.(Papageorgiou, Gil et al. 2001, Bhatia, LaPrade et al. 2014) Therefore, a delay in ACL reconstruction may increase the rate of medial meniscal ramp lesions.(Liu, Feng et al. 2011) Furthermore, an undiagnosed ramp lesion may place a patient at risk for recurrent ACL injury.(Robb, Kempshall et al. 2015) However, to date, the ideal timing for ACL surgery has yet to be determined.

Aims of the Dissertation

The overall aims of this doctoral thesis were to evaluate meniscal ramp lesions regarding the diagnosis, anatomy, biomechanics, current surgical trends, and clinical outcomes. Specifically, we were able to address a number of questions, including:

1) What is the incidence of meniscal ramp lesions in ACL tear patients and how often are ramp lesions diagnosed correctly on MRI preoperatively? (*Paper I*)
2) Can the anatomy of the medial meniscus and its surgically relevant attachments be quantitatively and qualitatively defined consistently? (*Paper II*)
3) Do meniscal ramp lesions affect knee joint kinematics in ACL-deficient and ACL-reconstructed knees and is an anatomic meniscal ramp repair biomechanically effective? (*Paper III*)
4) What are the current U.S. trends in orthopaedic surgery regarding arthroscopic identification and treatment of meniscal ramp lesions at the time of ACL surgery? (*Paper IV*)
5) Do patients report satisfactory outcomes after undergoing ACL reconstruction and meniscal ramp repair compared to ACL reconstruction in isolation? (*Paper V*)

Materials & Methods

<u>*Paper I (Diagnosis)*</u>

Study Design

A prospectively collected patient outcomes database was retrospectively queried to identify ACL reconstruction patients. Query of the database identified 301 patients who underwent primary or revision ACL reconstruction and had a confirmed medial meniscus tear between April 2010 and July 2016 by a single surgeon. Inclusion criteria were defined as patients with a confirmed ACL tear and medial meniscus tear. Exclusion criteria were defined as patients who had a concomitant medial meniscal root tear on their ipsilateral knee or multi-ligament knee injuries. All patients were clinically examined preoperatively and underwent standardized preoperative imaging evaluation with plain radiographs and an MRI.

Imaging Evaluation

The arthroscopic procedures were reviewed to determine the presence of a ramp lesion and concomitant pathologies. A "ramp lesion" was defined as a tear of the peripheral attachment of the posterior horn of the medial meniscus at the meniscocapsular junction. In patients identified to have a ramp lesion, the preoperative MRI report was reviewed to determine whether a ramp lesion was diagnosed by the interpreting musculoskeletal radiologist, and the sensitivity was calculated. Additionally, two independent orthopaedic surgeons evaluated the preoperative MRI to assess for potential associated injury patterns. The most common magnet strength for MRI was

3.0 T (n=40) followed by a 1.5 T magnet (n=10). All patients that had a 3.0 T MRI were scanned at our institution, with the remaining 1.5 T scans reviewed from outside imaging facilities. Evaluation for meniscal ramp lesions was best visualized on proton-density fat saturated T2-weighted images utilizing the sagittal view.

Surgical Technique

Standard anteromedial and anterolateral portals were made for routine arthroscopy; no additional portals were required to assess for the presence of meniscal ramp lesions. Viewing from the anterolateral portal, the arthroscope was advanced through the intercondylar notch with the knee in 30 degrees of flexion for inspection of the posterior horn of the medial meniscus. A probe was directed over the superior aspect of the posterior horn of the medial meniscus to allow for inspection of the junction between the meniscus and capsule to identify whether a ramp lesion was present. The probe was used to retract the posteromedial capsule away from the posteromedial meniscocapsular attachment to assess for any tears, and a ramp lesion was diagnosed if a tear or separation was present. An accessory posteromedial portal was not required to completely visualize the posterior meniscocapsular attachment.

Paper II (Anatomy)

Specimen Preparation

Fourteen non-paired, fresh-frozen male cadaveric knee specimens (mean age: 61.0 years; range: 54-66 years) with no evidence of prior injury, previous surgery, osteoarthritis, meniscus pathology, or ligament pathology were used for this study. The cadaveric specimens utilized in this study were donated to a tissue bank for the purpose of medical research and then purchased by our institution. All specimens were stored at -20˚ C and thawed at room temperature 24 hours prior to preparation. Before testing, each specimen underwent an arthrotomy to confirm the absence of intraarticular pathology.

In preparation for potting, the tibial, fibular, and femoral diaphyses were cut 20 cm from the joint line. Sharp dissection to bone was performed, and all soft tissues were removed 10 cm distal and proximal to the joint line and the fibula was fixed to the tibia in its anatomic position. The superficial medial collateral ligament, posterior capsule, semimembranosus tendon, and entire posteromedial corner structures were left intact. The femurs were then sectioned down the midline, in the sagittal plane to allow for direct visualization of the meniscus anatomy and corresponding tibial attachments while preserving the femoral attachments. The tibia and fibula were potted in a cylindrical mold filled with poly methyl methacrylate (PMMA; Fricke Dental International Inc., Streamwood, IL).

Anatomic Measurements

The tibia was rigidly clamped to prevent any movement during testing. A coordinate measuring device with a manufacturer reported repeatability of 0.025 mm (Romer Absolute Arm, Hexagon Metrology, North Kingstown, RI) was used to record points in 3-dimensional space using Rhino 5 software (McNeel North America, Seattle, WA). Point coordinates were imported into Python software (The Python Software Foundation, https://www.python.org) and measurements were calculated using a custom software script. The 3-dimensional anatomic distances and lengths were calculated and broken down into directional components using the knee's main axes: anterior-posterior, medial-lateral, and proximal-distal. The proximal-distal direction was defined using the tibial axis. The medial-lateral direction was defined using the most medial and lateral points of the tibial plateaus. The anterior-posterior axis was defined as being perpendicular to the coronal plane, calculated from the proximal-distal and medial-lateral axes defined above. The same investigator performed all measurements to decrease interobserver variability. A second board-certified orthopaedic surgeon was present during all testing for landmark confirmation.

The total meniscus length was calculated by summing the distance between discrete points taken along the periphery of the entire length of the curved medial meniscus from the posterior root to the anterior root attachments. Utilizing the geometric data and 3-dimensional points, curved distances and percentages of meniscal attachments were calculated and referenced according to where they attached along the total curved meniscus length (from posterior to anterior). The length of the PHMM was measured along the central portion of the meniscus using 5 data points. Parallel to these measurements, the corresponding length of the posterior medial capsular attachment was measured using 5 data points along the periphery of the posterior medial meniscus between its lateral extent and the lateral aspect of the posterior oblique ligament (POL). For the meniscotibial attachment to the medial meniscus, the length of the entire structure was measured using 3 data points. Surgically relevant arthroscopic and open landmarks were identified and measured in relation to their attachments on the medial meniscus. Surgically relevant landmarks included the meniscofemoral and meniscotibial attachments of the POL, the meniscofemoral and meniscotibial attachments of the deep medial collateral ligament (dMCL), the anteromedial meniscocapsular attachment, the centers of the anterior and posterior meniscal root attachments, center of the ACL tibial attachment, center of the posterior cruciate ligament (PCL) tibial attachment, center of the shiny white fibers of the posterior meniscal root tibial attachment, and the capsular attachment of the direct arm of the semimembranosus tendon. In addition, digital calipers were used to measure meniscal width (anterior horn, mid-body, posterior horn), meniscal height (posterior horn), and the length and width of the medial tibial plateau.

Histological Analysis

A sample of 10 non-paired, fresh-frozen male cadaveric knee specimens (mean age 58.3 years; range, 45-70 years), separate from the specimens used for anatomical measurements, were used for the histological analysis. Tissue specific to the meniscocapsular and the meniscotibial attachments of the PHMM was gathered via open dissection of the posterior medial meniscus anatomy. All tissues were fixed in 10% neutral buffered formalin at room temperature for 72 hours, rinsed in phosphate buffered saline (PBS), and stored in PBS at 4˚C before paraffin processing. The tissues were then paraffin processed by hand. Specifically, samples were dehydrated from 75% ethanol (EtOH), through 100% EtOH, cleared with three changes of xylene, and paraffin infiltrated with three changes of paraffin wax at 60˚C while shaking the samples. Tissues were embedded in paraffin, solidified in cassettes on ice, and sectioned at 6 µm widths. Prior to staining, slides were dried in a 60˚C oven for two hours, deparaffinized with two changes of xylene, and rehydrated to water. Hematoxylin and eosin (H&E) staining was then conducted to determine the orientation of the meniscocapsular and meniscotibial attachments of the posterior medial meniscus. All images were taken using a Nikon Eclipse Ni-U upright microscope (Nikon, Edgewood, New York, USA).

Paper III (Biomechanics)

Specimen Preparation

Twelve matched pairs (n = 24) of fresh-frozen, male cadaveric knee specimens (mean age: 61.0 years; range: 54-66 years) with no evidence of prior injury, previous surgery, osteoarthritis, meniscus pathology, or ligament pathology were used for this study. Institutional review board approval was not required because deidentified cadaveric specimens are exempt from review at our institution. The cadaveric specimens utilized in this study were donated to a tissue bank for the purpose of medical research and then purchased by our institution. All specimens were stored at -20º C and thawed at room temperature 24 hours prior to preparation. Before testing, each specimen underwent a diagnostic arthroscopy to confirm the absence of intra-articular pathology. The posterior horn of the medial meniscus was visualized through a standard anterolateral portal and an accessory posteromedial portal.

In preparation for potting, the tibial, fibular, and femoral diaphyses were cut 20 cm from the joint line. Sharp dissection to bone was performed, and all soft tissues were removed 10 cm distal and proximal to the joint line and the fibula was fixed to the tibia in its anatomic position. The tibia, fibula, and femur were potted in a cylindrical mold filled with poly methyl methacrylate (PMMA; Fricke Dental International Inc., Streamwood, IL). During specimen preparation for each knee, range of motion (flexion-extension and internal-external rotation) was actively tested to detect and reduce the potential effect of joint stiffness and rigidity.

Robotic Testing Setup

Each knee was held in an inverted orientation, with the potted distal end secured in a custom-made fixture mounted onto a universal force/torque sensor (Delta F/T Transducer, ATI Industrial Automation, Apex, North Carolina) attached to the end effector of a 6-degrees-of-freedom robotic arm (Kuka KR-60-3, Kuka Robotics, Augsburg, Germany). The potted femur was then rigidly fixed onto a stationary pedestal (**Figure 8**). Next, the stylus tip of a portable measuring arm (Romer Absolute Arm, Hexagon Metrology; manufacturer-reported point repeatability of 0.025 mm) was used to define the knee joint coordinate system by collecting points at the medial- and lateral-most aspects of the tibial plateau, the medial and lateral femoral epicondyles, and along the tibial diaphysis.(Grood and Suntay 1983, Wu and Cavanagh 1995) The coordinate system defined the knee joint center of rotation and the anterior-posterior, medial-lateral, and superior-inferior axes. Prior to testing, each knee was robotically subjected to a full passive path motion (0° to 120° of flexion) with minimal forces and torques on all axes.

The native passive path of the knee in neutral rotation was recorded from full extension to 120° in 1° increments with minimized forces (<5 N) and torques (<0.5 Nm) in the remaining 5 degrees of freedom. A 10 N compressive load was applied along the axis of the tibial shaft to ensure tibiofemoral contact throughout testing. This robotic testing setup has been previously described and validated for knee joint kinematic testing.(Goldsmith, Jansson et al. 2013, Goldsmith, Smith et al. 2014) The average time of testing for one specimen was approximately 4 hours.

Figure 8. Schematic representation of the robotic setup with the inverted knee mounted in the robotic testing system.

Biomechanical Testing

The intact state was tested first in all knees, followed by the ACL cut state. The knees of each pair were then randomly assigned to either cutting the A) meniscotibial attachment first, or B) meniscocapsular attachment first, following ACL sectioning. For knees that underwent meniscotibial attachment sectioning first, the meniscocapsular attachment was sectioned next, and for those that underwent meniscocapsular sectioning first, the meniscotibial attachment was sectioned next, such that all knees had both the meniscotibial and meniscocapsular attachments sectioned. The ACL was then reconstructed in all knees, followed by repair of the meniscocapsular (MCA) and meniscotibial (MTA) attachments. The following states were tested 1) intact (n=24), 2) ACL-deficient (n=24), 3) ACL deficient with a meniscocapsular lesion (n=12), 4) ACL deficient with a meniscotibial lesion (n=12), 5) ACL deficient with both meniscocapsular and meniscotibial lesions (n=24), 6) ACLR with both meniscocapsular and meniscotibial lesions (n=16), 7) ACLR with repair of both meniscocapsular and meniscotibial lesions (n=16). After testing the first 8 specimens, all specimens underwent a post-test arthrotomy to assess the success of the outside-in repair technique utilized. In all 8 specimens the repairs were found to have failed and the repair technique was switched to an inside-out repair in the robot. Post-testing arthrotomy of all remaining specimens (n=16) demonstrated a successful repair of the meniscocapsular and meniscotibial lesion. The post-repair testing of the initial 8 specimens was not included in the final analysis (ACLR, MCA repair, MTA repair) (**Figure 9**).

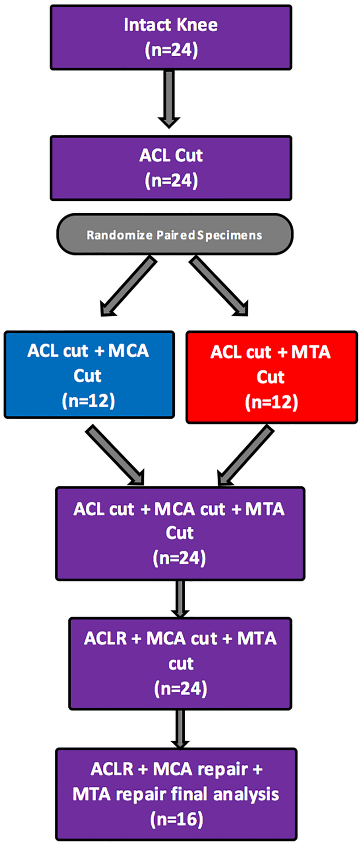


Figure 9. Flowchart depicting the order of biomechanical testing states for all specimens per randomization. ACL: anterior cruciate ligament; ACLR: anterior cruciate ligament reconstruction; MCA: meniscocapsular attachment; MTA: meniscotibial attachment.

The knees were subjected to the following testing conditions: anterior tibial load of 88 N, internal and external rotation torques of 5 N-m, and a simulated pivot shift test of 10 N valgus force coupled with 5 N-m internal rotation torque as previously described.(Engebretsen, Wijdicks et al. 2012) Anterior tibial translation was tested at 30° and 90°, simulated pivot shift test at 15° and 30°, and internal/external rotation at 0° to 90° with 15° increments. For each state, anterior tibial displacement, internal rotation, and external rotation were compared to the intact state for all testing conditions.

Surgical Technique

An anatomic single-bundle ACL reconstruction was performed in all specimens as previously described.(Goldsmith, Jansson et al. 2013) The ACL was reconstructed utilizing a bone-patellar tendon-bone allograft with 10 mm bone blocks. To create a meniscocapsular attachment (MCA) lesion, the knee was flexed to 90° and a scalpel was then inserted through the posteromedial portal and a tear was made in the meniscocapsular junction, extending 2.5 cm medially from the medial meniscus root attachment. The meniscocapsular lesion was repaired utilizing an arthroscopic assisted inside-out technique using 4-6 meniscal sutures (#2 FiberWire, Arthrex, Inc., Naples, FL) with the knee in the robot at 90° of flexion (**Figure 10**).

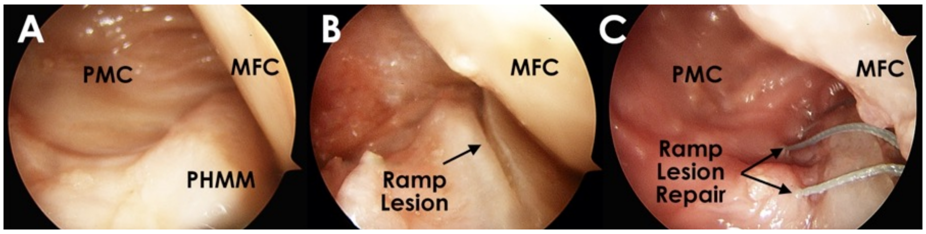


Figure 10. Arthroscopic image of a meniscocapsular lesion. A) Intact meniscocapsular junction with camera inserted through the intercondylar notch. B) Utilizing an accessory posteromedial portal, a scalpel was inserted and used to recreate a meniscocapsular tear. C) Inside-out meniscal repair with sutures placed in a vertical mattress fashion, first through the posterior horn of the medial meniscus and second through the posteromedial capsule. MFC: medial femoral condyle; PHMM: posterior horn medial meniscus; PMC: posteromedial capsule.

To simulate the meniscotibial attachment (MTA) lesion, a longitudinal posterior approach was performed; a dissection between the gastrocnemius muscle heads was performed. The posterior capsule, oblique popliteal ligament, champagne glass drop-off and the semimembranosus tendon were visualized. A horizontal incision was made through the distal capsule, medial to the posterior cruciate ligament (PCL) tibial facet, and 1.5 cm distal to the joint line. The meniscotibial attachment was detached with a scalpel from this point to the level of the semimembranosus tibial attachment on the tibia. The meniscotibial lesion was repaired with the knee in full extension using two suture anchors (SwiveLock®, Arthrex Inc. Naples, FL)) placed in the proximal aspect of the medial tibial plateau, reinforced with two #2 FiberWire sutures to restore the meniscotibial attachment (**Figure 11**). All meniscus lesions, repairs, and ACL reconstructions were performed by two board certified orthopaedic surgeons with experience in arthroscopy and meniscus surgery. The same two board certified surgeons have performed several knee biomechanical studies and anatomy studies.

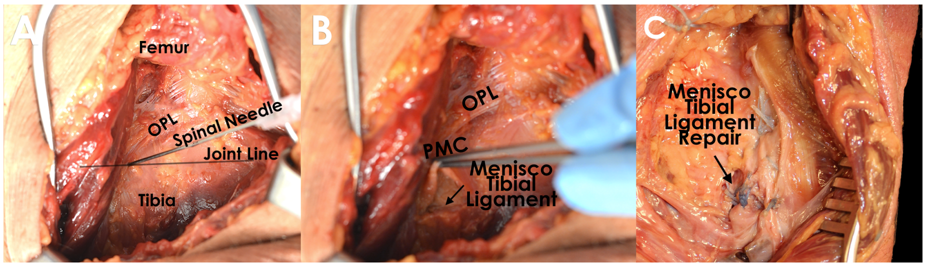


Figure 11. Open image of a meniscotibial lesion. A) Open posterior dissection with intact meniscotibial ligament and pertinent landmarks. B) To identify the meniscotibial ligament, an 18-gauge spinal needle was inserted into the posteromedial joint line, and an incision was made approximately 1 cm medial to the PCL tibial facet, and 1.5 cm from the joint line. A scalpel was then inserted directly inferior to the meniscus and a cut was made on the fibers attaching the meniscus to the tibia to recreate a meniscotibial ligament tear. C) Open posterior repair of the meniscotibial attachment with the knee in full extension using two suture anchors (SwiveLock®, Arthrex Inc. Naples, FL) placed in the proximal aspect of the medial tibial plateau. PCL: posterior cruciate ligament, OPL: oblique posterior ligament, PMC: posteromedial capsule.

Statistical Analysis

For this study, statistical power was considered in the context of detectable effect size (Cohen's d) given a fixed study design and sample size. Assuming an overall alpha level of 0.05 with Bonferroni correction for 8 comparisons and two-tailed testing, repeated measures comparisons of group means involving 12, 16 and 24 specimens were sufficient to detect effect sizes of d=1.29, d=1.06 and d=0.82 with 80% statistical power, respectively. Data was analyzed after subtracting each specimen's intact values. For the repair and the reconstruction states, only the specimens that underwent repair were compared to their intact and sectioned states, thus excluding the specimens that did not undergo repair. Because all measurement variables were reasonably normally distributed and the comparisons included different sample sizes, paired t-tests were used to make all comparisons among knee conditions. Holm's method was used to control the familywise type-1 error rate to 0.05 within each experiment and flexion angle combination, and Holm-adjusted p-values were presented. Adjusted p-values less than 0.05 were deemed statistically significant.

Paper IV (Survey)

Questionnaire Development

A questionnaire was electronically sent in a blinded fashion to 91 directors of orthopaedic sports medicine fellowship training programs in the United States (**Table 2**). Participants' email addresses were obtained through the American Orthopaedic Society for Sports Medicine directory of current fellowship program directors. A cover letter that accompanied the questionnaire stated the purpose of the questionnaire and ensured anonymity. All survey participants had the opportunity to decline the questionnaire. Inclusion criteria included only those surgeons who currently performed ACL reconstruction surgery. Exclusion criteria were those surgeons who did not perform ACL reconstruction or who chose to opt out of the survey. The survey was sent out and responses were collected from January 2018 to July 2018. We developed the questionnaire according to previous trends in the literature regarding meniscal ramp lesions and by expert opinion and knowledge from years of clinical practice. This study was deemed exempt from approval by an institutional review board.

Statistical Analysis

Data was prospectively collected via an online questionnaire survey tool. Data were extracted from the online survey database and summarized. Standard descriptive statistics were performed.

Table 2. The survey questionnaire. Questions assessed the surgeon's expertise in preoperative diagnosis, intraoperative identification, and treatment strategies of medial meniscus ramp lesions at the time of ACL surgery.

Q1: Do you identify the posteromedial meniscocapsular junction (i.e. location of "ramp" lesions) routinely at the time of ACL surgery? If yes, please specify how you locate these lesions during arthroscopy: A. No B. Anterior View C. Modified Gillquist view, by placing the scope through the intercondylar notch medial to the PCL D. Accessory posteromedial portal
Q2: What repair technique do you use for meniscal ramp lesions at the time of ACL surgery? • Inside-out technique • All-inside technique • I do not repair meniscal ramp lesions • Other (please specify)
Q3: What clinical information do you use to diagnosis a medial meniscus ramp lesion during preoperative planning? Please select all that apply:

• MRI: High intensity signal between posterior horn of medial meniscus and posteromedial capsule • MRI: Posteromedial tibial bone bruise pattern • Exam: Grade III Lachman's test • Exam: Grade III pivot shift (during exam under anesthesia) • Exam: Positive/gross anterior drawer test • I do not preoperatively diagnosis meniscal ramp lesions • Other (please specify)
Q4: What criteria do you use to make a decision regarding meniscal repair vs. no treatment for medial meniscal ramp lesions? Please select all that apply: • Extent of tear (i.e. partial vs. complete) • Meniscal stability (i.e. gross anterior displacement of medial meniscus upon probing) • Size of tear (> or < 2.5cm in length) • Involvement of meniscotibial ligament • Other (please specify)
Q5: Do you notice a subjective difference in the reduction of the amount of knee instability following a ramp repair (anterior tibial translation or pivot shift) before completing your ACL reconstruction (i.e. Lachman reduces from a '3' to a '2')? A. Yes B. No C. Do not assess knee stability after meniscus repair during surgery
Q6: When did you begin to recognize meniscal ramp lesions during your career? A. 1 year ago B. 2-4 years ago C. 5-6 years ago D. > 7 years ago
Q7: What is the average time it takes you to repair a medial meniscus ramp lesion during surgery? A. < 15 minutes B. 15-30 minutes C. 30-45 minutes D. > 60 minutes
Q8: What is your prescribed weight bearing status following an ACL reconstruction and medial meniscus ramp repair? A. Weightbearing as tolerated with crutches x 2-4 weeks B. Nonweight bearing x 4 weeks C. Nonweight bearing x 6 weeks D. Partial weight bearing x 2-4 weeks E. Other (please specify)
Q9: What is your prescribed return to play timeline following a primary ACL reconstruction and medial meniscus ramp repair? A. 5-6 months B. 6-7 months C. 7-8 months D. 9+ months
Q10: How often is preoperative MRI accurate in diagnosing medial meniscus ramp tears? A. Never (0%) B. Rarely (0-25%)

C. Sometimes (25-50%)
D. Often (50-75%)
E. Always (100%)

<u>*Paper V (Outcomes)*</u>

Study Design

This study was approved following review from an institutional review board. Demographic data and clinical outcome scores were collected on all primary ACL reconstruction patients that were performed by a single board-certified orthopaedic surgeon. Inclusion criteria included patients who underwent combined primary ACLR with bone-patellar tendon-bone (BPTB) autograft and medial meniscus ramp repair for an unstable medial meniscus ramp lesion from April 2010 to January 2017 with a minimum 2-year follow-up. Patients with a combined ACLR and medial meniscus ramp repair were matched in a 1-to-1 allocation according to age, gender, and activity-level, with patients who underwent primary isolated ACLR. Exclusion criteria included patients who underwent multi-ligament knee reconstruction, previous meniscus surgery, displayed concomitant lateral meniscus tears, meniscal root tears, meniscal radial tears, concomitant cartilage procedures, concomitant osteotomy procedures, concomitant fractures, bilateral ACLR, revision ACLR, and ACLR with allograft or hamstring tendon.

Surgical Technique

All included patients underwent anatomic, single-bundle, primary ACLR with BPTB autograft according to a previously described and biomechanically validated technique.(Ziegler, Pietrini et al. 2011, Goldsmith, Jansson et al. 2013, Chahla, Moatshe et al. 2017) All included patients with unstable meniscal ramp lesions underwent inside-out meniscal repair according to a previously described and biomechanically validated technique.(DePhillipo, Cinque et al. 2017, DePhillipo, Moatshe et al. 2018) A repairable meniscal ramp lesion was considered a complete tear located within the meniscocapsular and/or meniscotibial attachment of the posterior horn of the medial meniscus, that was unstable on probing. Ramp lesions were evaluated utilizing a modified Gillquist view by placing the arthroscope through the intercondylar notch medial to the posterior cruciate ligament and using a probe above the medial meniscus to push against the posteromedial capsular attachment (**Figure 12**).

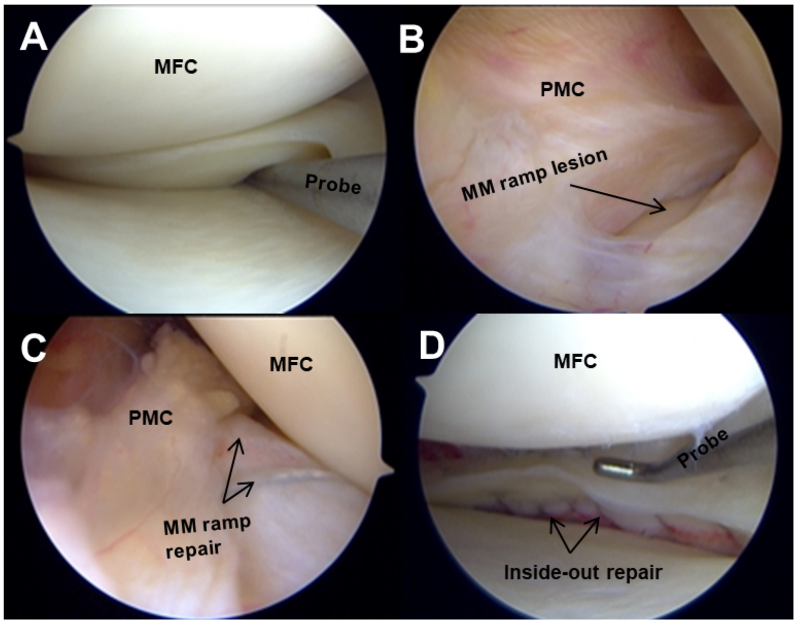


Figure 12. Arthroscopic photos of medial meniscus ramp repair utilizing an inside-out vertical mattress technique. A) Medial meniscal instability when viewing anteriorly as depicted by increased anterior meniscal translation upon probing. B) Modified Gillquist view showing complete disruption at the meniscocapsular junction, followed by C) re-approximation of the meniscocapsular attachment during suture placement through meniscus and posteromedial capsule. D) Completed inside-out meniscal ramp repair illustrating stability and double-row vertical mattress suture placement. MFC: medial femoral condyle, PMC: posteromedial capsule, MM: medial meniscus.

Postoperative Rehabilitation **Protocol**

The postoperative rehabilitation protocol was identical for patients who underwent combined ACLR with meniscal ramp repair and isolated ACLR. All patients were allowed to bear weight as tolerated upon discharge and were instructed to use crutches until they could ambulate without a limp. Physical therapy commenced within twenty-four hours after surgery to initiate early range-of-motion (ROM), muscle reactivation, and to control edema. Rehabilitation included straight leg raises in an immobilizer until there was no extension lag at which point patients were transitioned to a functional hinge knee brace (CTi, Ossur Americas, Foothill Ranch, CA). Patients were allowed to begin straight-ahead running exercises at 4 months, with restrictions on pivoting and twisting. Gradual return to play progression was initiated after 6 months following the successful completion of a functional sports test. Return to sports or activity was allowed when the patient achieved normal strength, stability, and knee ROM comparable to the contralateral side, at around 7 to 9 months postoperatively.

Patient-Reported Outcomes, Patient Satisfaction, and Complications

At a minimum 2 years following the index surgery, patients were administered an electronic subjective questionnaire, which included the following clinical outcome measures: Lysholm score, the Western Ontario & McMaster Universities Osteoarthritis Index (WOMAC) score, the Short Form-12 (SF-12) physical component summary (PCS), the Tegner Activity scale, the International Knee Documentation Committee (IKDC) score, and patient satisfaction with outcome. Patient satisfaction was measured on a 1 to 10 scale with 10 being very satisfied and 1 being very unsatisfied. Demographic characteristics were recorded including age, gender, body mass index (BMI), and sport/activity at time of ACL injury. Data regarding knee ROM and stability on physical exam (Lachman and pivot shift tests) were collected both preoperatively and at a minimum of 2 years postoperatively. Additionally, level of return to sport and preinjury activity level was collected and classified as 'lower than preinjury level', 'same level as preinjury level', or 'above preinjury level'. Meniscal repair failure was defined as any subsequent surgery that required revision meniscal repair. Complications were recorded, including reintervention surgery requiring partial meniscectomy, ACLR graft failure (ipsilateral and contralateral), deep vein thrombosis, or arthrofibrosis requiring a lysis of adhesions.

Statistical Analysis

For outcome variables comparing preoperative and postoperative scores, a paired t-test was utilized. Because ceiling or floor effects are common in the outcome scales we assessed, non-parametric, rank-based statistical methods were used for group comparisons of postoperative patient-reported outcomes. Specifically, because each ACLR with ramp tear patient was matched to an isolated ACLR patient, the Wilcoxon Signed Rank test was used for these postoperative group comparisons. Independent t-tests were used to compare age and BMI between groups. Comparisons of categorical data including gender, chronicity, knee stability on physical exam, complication rate, and return to preinjury level of activity were performed by use of Chi-square tests and Fisher Exact tests. All *p* values were two-tailed and an alpha level of less than 0.05 was considered significant.

Results

Paper I (Diagnosis)

Of 301 ACL reconstruction patients, 50 patients were diagnosed with meniscal ramp lesions at the time of surgery. The incidence of ramp lesions was 16.6%. The majority of patients with ramp lesions were males (66%), reported acute injuries (75%, <6 weeks from injury to surgery), and the most common mechanism of injury was pivoting or twisting (68%). The most common sports/activities associated with ACL and meniscal ramp lesions were skiing and soccer. Preoperatively, 48% of meniscal ramp lesions were correctly diagnosed on MRI by the interpreting radiologists. A secondary finding of a posteromedial tibial bone bruise on MRI was identified in 72% of all patients with concomitant medial meniscal ramp lesions (**Figure 13**).

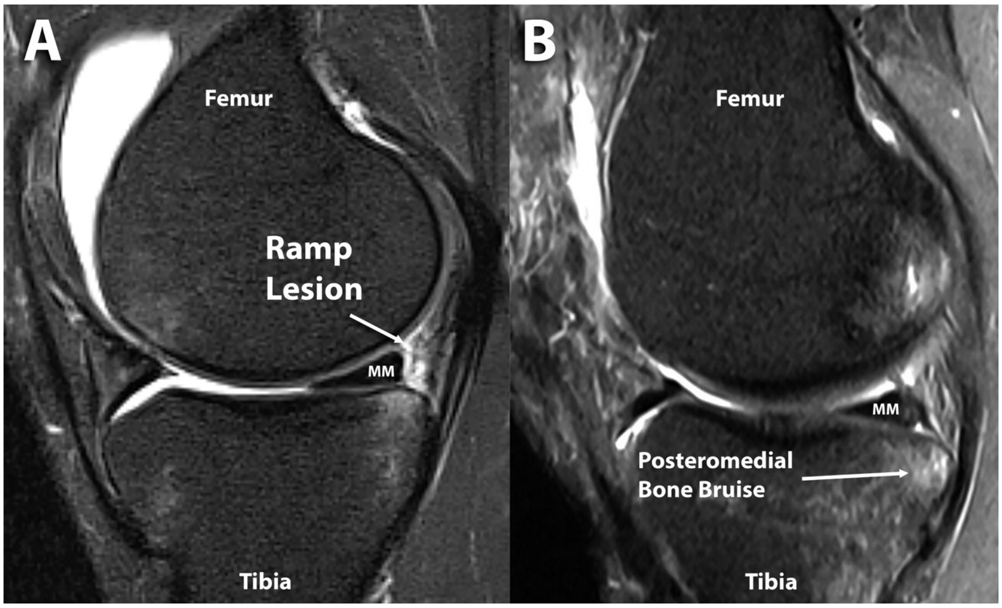


Figure 13. Preoperative MRI demonstrating meniscal ramp lesion and associated posteromedial tibial bone bruise pattern, best visualized on sagittal fat-saturated T2-weighted images. (A)

Meniscal ramp lesion indicated by an increase in signal intensity at the peripheral margin of the posterior horn of the medial meniscus at the meniscocapsular junction. (B) Posteromedial tibial bone bruise and posterior medial meniscus contusion present on preoperative MRI in a patient with a combined ACL tear and meniscal ramp lesion diagnosed at the time of arthroscopy (*Paper I*).

Paper II (Anatomy)

The mean length of the PHMM was 21.3 ± 2.0 mm, which was essentially confluent with the entire length of the posterior capsule (20.2 mm). The posterior medial capsule did not attach directly to the superior margin of the PHMM in all specimens; rather the capsule attached at a mean depth of 36.4% of the total PHMM height. This provides evidence for the potential hidden fold in the posterior meniscocapsular junction. The posterior meniscotibial ligament was present in all specimens and had a mean length of 14.0 ± 5.4 mm at its insertion on the posterior tibia. The meniscotibial ligament attachment merged with the posterior meniscocapsular attachment to form a common PHMM attachment at the most posterior point of the meniscocapsular junction in all specimens (**Figure 14**).

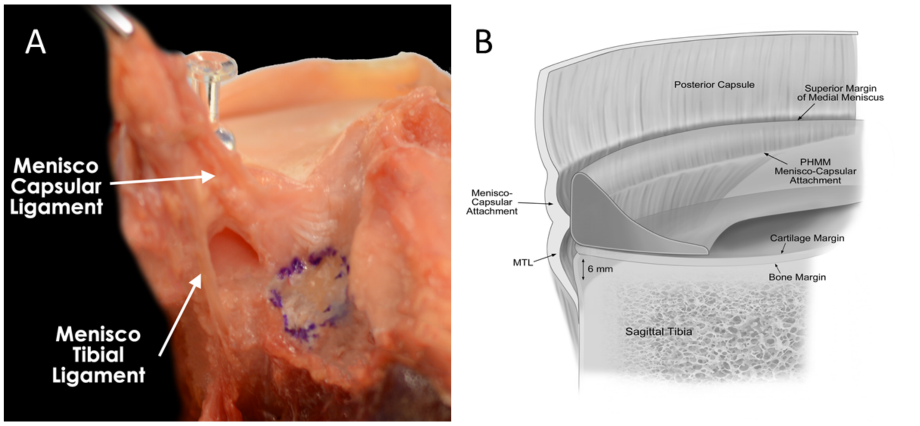


Figure 14. A) Sagittal view of a cadaveric dissection of the posterior horn medial meniscus (PHMM) anatomy, showcasing the meniscocapsular and meniscotibial ligament (MTL) attachments as they merged to form a common attachment. The posterior cruciate ligament (PCL) facet is outlined in methylene blue to illustrate the proximity of the PCL tibial attachment. B) Illustration of the PHMM and shared common attachment of both the meniscocapsular and MTL. The MTL attached 5.9 mm distal to the articular cartilage margin of the posterior medial tibial plateau (*Paper II*).

The POL attachment to the meniscus had a mean length of 8.2 ± 2.1 mm and was located directly between the posterior meniscocapsular attachment and the deep MCL attachment. The mean length of the deep MCL's attachment on the medial meniscus was 14.8 ± 3.2 mm and the center attachment point was approximately 50.5% of the total curved meniscal length. The semimembranosus tendon had a fascial attachment to the posterior inferior margin of the medial meniscus in 86% of specimens. The mean length of this semimembranosus-meniscal attachment was 9.2 ± 2.1 mm. Hematoxylin and eosin (H&E) staining demonstrated no differences in cellular structure, density, or fiber directionality between the meniscocapsular and meniscotibial attachments of the PHMM. Additionally, alcian blue staining demonstrated no differences in glycosaminoglycan expression between both meniscocapsular and meniscotibial attachments (**Figure 15**).

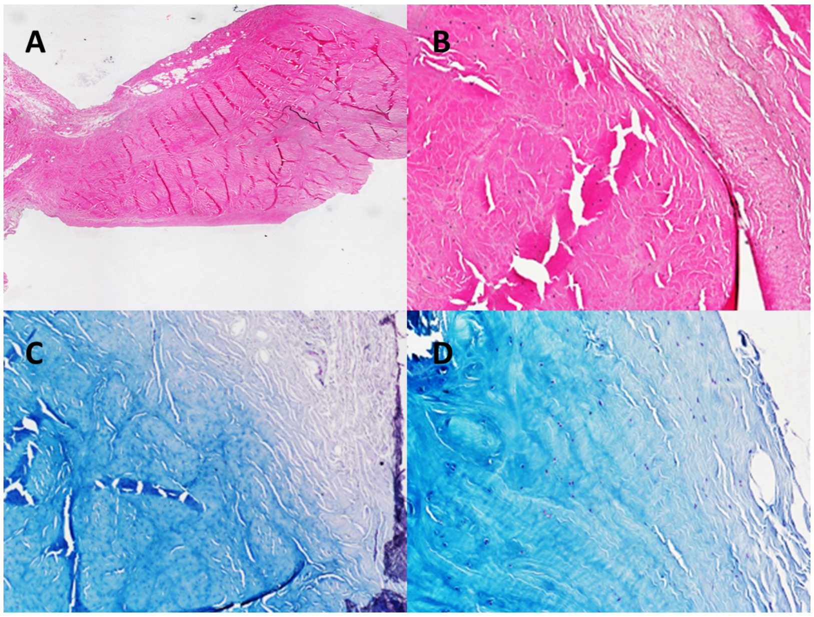


Figure 15. (A, B) Hematoxylin and eosin staining of the capsular and tibial attachments of the PHMM, demonstrating similar appearance of collagen type I and cell density with no observed differences between the attachments. (C, D) Glycosaminoglycan expression in meniscocapsular and meniscotibial attachments was visually similar, with a clear decrease in expression from high to low as the meniscus transitioned toward to the capsular and tibial attachments (anterior to posterior). (A, B) There is no difference in the fiber orientation between the meniscocapsular and meniscotibial attachments of the PHMM, while (C, D) these 2 structures are indistinguishable regarding their collagen composition as they converge and attach to the PHMM (*Paper II*). *Meniscocapsular attachment. #Meniscotibial attachment. PHMM, posterior horn medial meniscus.

<u>Paper III (Biomechanics)</u>

Cutting both the meniscocapsular and meniscotibial attachments of the PHMM significantly increased anterior tibial translation at both 30 ($p \leq .020$) and 90 degrees ($p <$ .005) in ACL-deficient knees. There were no differences in knee kinematics with a meniscocapsular-based tear compared to a meniscotibial-based tear, and the combination of both tears did not further contribute to increased knee kinematics.

Isolated ACL reconstruction did not restore internal rotation, external rotation, or pivot shift (*p* < .002) in the presence of unaddressed meniscal ramp lesions. Subsequently, combined ACL reconstruction with meniscal ramp repair (of both meniscocapsular and meniscotibial attachments) was necessary to restore the pivot shift relative to the intact state. Additionally, isolated meniscocapsular and meniscotibial lesions significantly increased internal rotation and external rotation at all flexion angles in ACL-reconstructed knees (*p* < .001). Combined meniscocapsular and meniscotibial repairs following ACL reconstruction restored rotation at 0 and 15 degrees; however, repair did not sufficiently restore internal rotation and external rotation at higher knee flexion angles (> 30 degrees) (**Figure 16**).

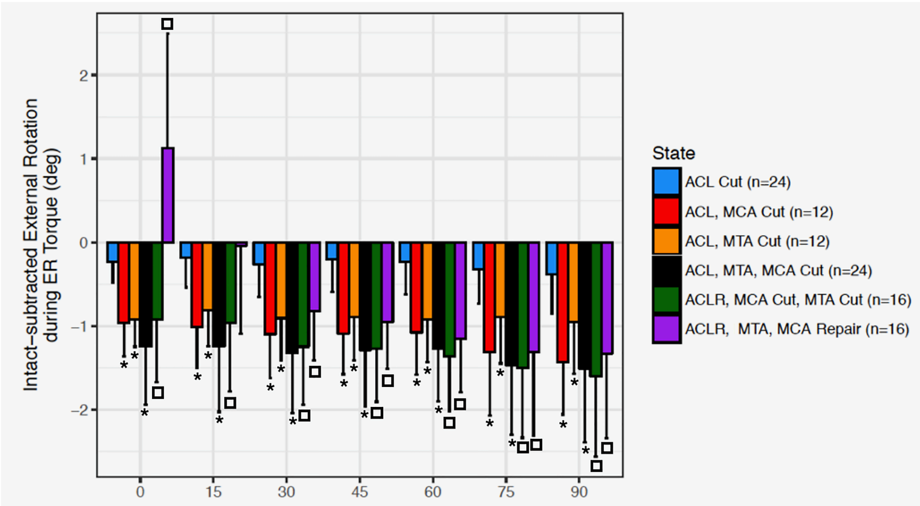


Figure 16. Changes in tibial external rotation during a 5 N-m internal rotation torque for the different states. ACL: anterior cruciate ligament, ACLR: anterior cruciate ligament reconstruction, MCA: meniscocapsular attachment, MTA: meniscotibial attachment.
*Indicates significantly different from ACL deficient state. The ACLR and the repair states were compared to the intact state, and 'small square' indicates significant difference compared to the intact state (*Paper III*).

Paper IV (Survey)

Overall, the response rate from fellowship directors surveyed was 50%. The results indicated that 86% of surgeons report routinely checking for meniscal ramp lesions at the time of ACL reconstruction. The majority of surgeons cited the preoperative physical exam findings as potential indicators for identifying meniscal ramp lesions in ACL-deficient knees. Specifically, a grade III Lachman test was reportedly used as an indicator for 22% of surgeons and a grade III pivot shift test for 25% of surgeons. The most common inspection strategy cited for evaluation of a meniscal ramp tear was the modified Gillquist view (67%); three (8%) surgeons reported the routine use of an accessory posteromedial portal during evaluation of a ramp lesion. The most common ramp repair technique was all-inside (67%) followed by inside-out (22%), while 8% of surgeon's reported that they do not repair meniscal ramp lesions when a tear is identified intraoperatively. The majority of surgeons (53%) require a self-reported time of 15 minutes or less for a meniscal ramp repair.

Sixty-one percent of surgeons reported the routine intraoperative assessment of anterior knee stability following ramp repair, prior to ACL reconstruction fixation. Thirty-three percent cited a subjective difference in improved knee stability with ramp repair while 28% reported that they do not notice a subjective difference with anterior knee stability prior to ACL reconstruction fixation. The most common return-to-play timeline following primary ACL reconstruction and meniscal ramp repair was 7 to 8 months

(36%), while 25% reported delayed return-to-play ≥ 9 months and 6% reported 5 to 6 months for return-to-play.

Paper V (Outcomes)

There were 1176 ACL reconstruction patients identified, with 851 (72.4%) primary ACL reconstruction patients and 325 (27.6%) revision ACL reconstruction patients. Of the 851 primary ACL reconstruction patients, 158 (18.6%) had medial meniscal ramp lesions confirmed at the time of arthroscopy. Meniscal ramp lesions had a slightly higher incidence in males (53%) compared to females (47%). The most common clinical characteristics identified in patients with ramp lesions were chronic injuries (≥ 6 weeks, 68%), contact mechanism of injury (88%), concomitant lateral meniscus tear (63%), and concomitant lateral meniscus posterior root tear (22%). Sixty-two percent (n=98) had an isolated ACL injury with a meniscal ramp lesion, while 38% (n=60) had an additional ligamentous knee injury.

Of the patients who met inclusion for subanalysis for meniscal ramp repair outcomes, there was an 86% retention with 8 patients lost to follow-up. Outcomes were subsequently reported for 50 patients who underwent combined primary ACL reconstruction with BPTB autograft and inside-out medial meniscal ramp repair. These patients were matched to a group of isolated ACLR patients which served as the control group. The average follow-up was 2.8 years (range, 2.0 to 8.0) and there were no significant differences in age (p = 0.667), gender (p = 1.00), BMI (p = 0.261), or chronicity of injury (p = 0.529) between patients in the repair group versus control group. At final follow-up, there were no significant differences between patients who underwent combined ACLR with meniscal ramp repair and isolated ACLR for subjective outcomes postoperatively ($p > 0.05$).

Patients who underwent meniscal ramp repair had evidence of increased knee laxity preoperatively as demonstrated by grade 3 Lachman (44% vs. 6%) and pivot shift (38% vs. 12%) tests compared to isolated ACLR patients ($p = 0.005$) (**Table 3**). The majority of patients in the ACLR with ramp repair group (84%) and isolated ACLR group (90%) returned to the same preinjury level of activity (**Table 4**). There were no significant differences in return to level of activity/sport between ACLR with meniscal ramp repair and isolated ACLR patients ($p = 0.658$). There were six (12%) reported complications in the ACLR with meniscal ramp repair group and four (8%) reported complications in the isolated ACLR group, with no significant difference between frequencies of complications ($p = 0.505$). The failure rate of inside-out repair was 4% at a mean 34 months postoperatively. In both groups, there were no ACL reconstruction graft failures at a mean 2.8 years postoperatively and one patient (2%) in the isolated ACLR group reported a contralateral ACL tear.

Table 3. Frequencies of anterior knee stability on physical exam as reported by subjective grading of Lachman and pivot shift maneuvers for patients with combined ACL reconstruction (ACLR) with medial meniscal ramp repair (n=50) and matched isolated ACL reconstruction patients (n=50). Results are reported as total number followed by percentages. Statistical differences in categorical data between preoperative and postoperative frequencies were computed via a chi-square test (*Paper V*).

Examination Test	**Isolated ACLR (n/%)**	**Combined ACLR and Ramp Repair (n/%)**	***P* Value**
Lachman (Preoperative)			
Grade 1	1 / 2%	0 / 0%	
Grade 2	46 / 92%	28 / 56%	
Grade 3	3 / 6%	22 / 44%	*<0.001
Lachman (Postoperative)			
Grade 0	44 / 88%	45 / 90%	
Grade 1	6 / 12%	5 / 10%	0.749
Pivot Shift (Preoperative)			
Grade 1	2 / 4%	0 / 0%	
Grade 2	42 / 84%	31 / 62%	
Grade 3	6 / 12%	19 / 38%	*0.005
Pivot Shift (Postoperative)			
Grade 0	50 / 100%	50 / 100%	1.00

*Statistical significance = $P < .05$. ACL, anterior cruciate ligament.

Table 4. Frequencies of level of return to activity/sport for patients with combined ACL reconstruction (ACLR) with medial meniscal ramp repair (n=50) and matched isolated ACL reconstruction patients (n=50). Results are reported as total number followed by percentages (*Paper V*).

Return to Activity / Sport Level	**Isolated ACLR (n/%)**	**Combined ACLR and Ramp Repair (n/%)**
Lower Level	4 / 8%	6 / 12%
Same Level	45 / 90%	42 / 84%
Higher Level	1 / 2%	2 / 4%

*Return to sport was characterized according to subjectively reported values and measured as a comparison to preinjury activity/sport level. ACL, anterior cruciate ligament.

Discussion

The most important findings of this thesis indicate improved strategies for the preoperative diagnosis of meniscal ramp lesions, report one of the first quantitative descriptions of the posteromedial meniscus anatomy, provides evidence of the biomechanical consequences of meniscal ramp lesions, and report good clinical outcomes following combined ACL reconstruction and inside-out meniscal ramp repair. Additionally, trends have been identified for the identification and treatment options for meniscal ramp lesions by the top academic sports medicine surgeons in the United States, which has provided insight to the overall nature of how orthopedic surgeons may treat ramp lesions. This detailed information may help guide both future research and clinical strategies for improving the diagnosis, treatment, and clinical outcomes following combined ACL reconstruction and meniscal ramp repair.

In the current work, the incidence of meniscal ramp lesions in concomitant ACL tears was found to be approximately 17% to 19% between the diagnosis and clinical outcome studies (*Papers I and V*). This is consistent with previous reports of meniscal ramp lesion incidence ranging from 10% to 30% across multiple continents (Asia, North America, Europe).(Bollen 2010, Liu, Feng et al. 2011, Di Vico, Di Donato et al. 2017, Hatayama, Terauchi et al. 2018, Malatray, Raux et al. 2018, Seil, Mouton et al. 2018, Sonnery-Cottet, Praz et al. 2018) A recent study found an increased prevalence of ramp lesions of 42% in ACL tear patients, with 20% (n=73) considered unstable and 22% (n=82) considered stable meniscal ramp tears.(Balazs, Greditzer et al. 2019) A secondary finding of a posteromedial bone bruise of the proximal tibia was found in 72% of patients with combined ACL tears and meniscal ramp lesions, which allowed for a 24% improvement in the sensitivity of an accurate diagnosis for ramp lesions on preoperative MRI (*Paper I*). Following this study, three other reports were published regarding the prevalence of bony edema of the posteromedial tibia associated with ramp lesions. Kumar et al.(Kumar, Spencer et al. 2018) reported similar findings, with 66.3% of patients with ACL and meniscal ramp lesions had a posteromedial tibial bone bruise on preoperative MRI. Balazs et al.(Balazs, Greditzer et al. 2019) reported that patients with ACL tears were significantly more likely to have a meniscal ramp lesion if they had bone marrow edema of the posteromedial tibia (OR: 3.0; $p < 0.0001$). In contrast, Hatayama et al.(Hatayama, Terauchi et al. 2018) observed a 38.5% prevalence of bony edema for medial meniscal ramp lesions, which was not significantly different than the prevalence of bony edema for medial meniscal body tears (40%) in their study. Therefore, the true prevalence of this secondary sign for meniscal ramp lesions is unknown and has also been correlated previously with the incidence of posterolateral corner injuries (e.g. FCL tears) due to a theorized varus force placed on the knee at time of injury.(Geeslin and LaPrade 2010) However, bony edema should not be overlooked when observed on preoperative MRI scans because it may clue clinicians to suspecting a medial meniscal ramp lesion or posterolateral corner injury.

Controversy exists regarding the means of arthroscopic identification of meniscal ramp lesions. All meniscal ramp lesions were diagnosed utilizing a modified Gillquist view in *Papers I and V*; thus, a posteromedial portal was not necessary. This was confirmed in

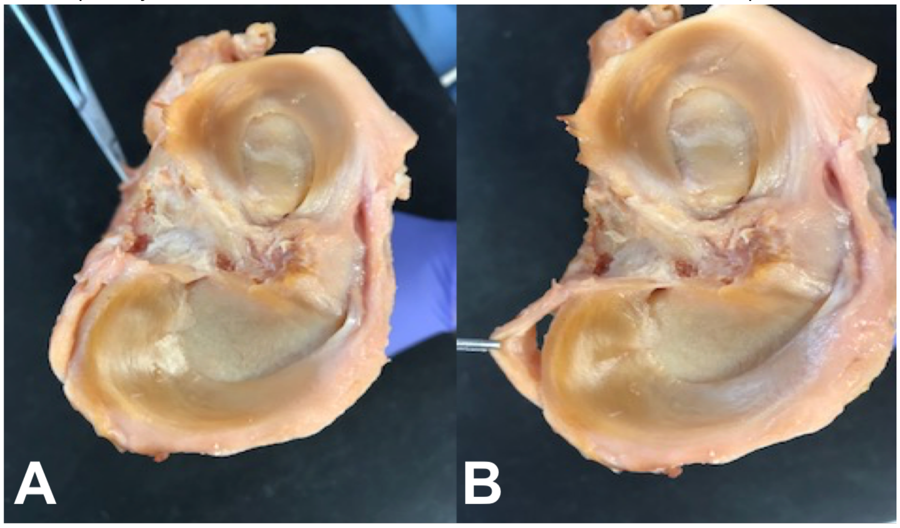
Paper IV, because 67% of U.S. based orthopaedic surgeons self-reported that the modified Gillquist view allows for a complete diagnosis of ramp lesions arthroscopically, while 8% of surgeons reported the use of posteromedial arthroscopic portal to diagnose a ramp tear. However, previous authors advocate for the use of a posteromedial portal as well as a trans-septal portal for both improving the diagnosis of potential hidden lesions, and to better access the ramp area for all-inside meniscal repair.(Peltier, Lording et al. 2015, Thaunat, Fayard et al. 2016, Thaunat, Jan et al. 2016, Keyhani, Ahn et al. 2017, Kim, Lee et al. 2018) Malatray et al.(Malatray, Raux et al. 2018) reported a ramp lesion incidence of 2% via direct anterior viewing; the diagnostic accuracy improved with a modified Gillquist view, with a 13% incidence of ramp lesions found during this arthroscopic view. Furthermore, these authors reported that there no additional ramp lesions found with the creation of a posteromedial portal.(Malatray, Raux et al. 2018) Therefore, it is recommended that surgeons do not rely on a direct anterior approach for diagnosing meniscal ramp lesions. Rather, the utilization of the modified Gillquist view (intercondylar view) allows for quick access and direct arthroscopic visualization of the posteromedial knee without creating additional incisions and can be performed routinely during an ACL reconstruction (*Papers I, IV, V*).(Bumberger, Koller et al. 2019)

Despite the increased awareness and relatively high reported incidence of meniscal ramp lesions, discrepancy exists regarding the exact definition of a ramp lesion. It has been hypothesized that not only one specific tear pattern is consistent with a ramp lesion, but rather there are multiple meniscal 'ramp-tear' variants. This has been eluded to previously by Thaunat and colleagues from France, with the reported classification system involving five different types of meniscal ramp lesions.(Thaunat, Fayard et al. 2016) Subsequently, one of the suggested theories involving the variation in the reported incidence for meniscal ramp lesions is centered around the inconsistency in definition. Two contributing factors associated with this point are 1) lack of quantitative anatomical descriptions for the posteromedial meniscus, and 2) differences in arthroscopic assessment for ramp lesions which have inherent cultural and geographic influences.

Previously, the lack of quantitative anatomy studies allowed researchers to formulate characterizations of meniscal ramp lesions based on observation and clinical experience. This data was not reported in epidemiological studies either, which further contributed to an increase in etiological and patient specific characteristics for meniscal ramp lesions with a void in an exact definition.(Chahla, Dean et al. 2016) When taking a close look at the literature overall, studies seemed to skip any gross anatomical analysis with regards to objective measures of the posteromedial meniscus anatomy.(Ahn, Bae et al. 2011, Liu, Feng et al. 2011, Thaunat, Fayard et al. 2016) Additionally, with some controversy reported among clinical studies evaluating patients with meniscal ramp lesions, there was an apparent need to go back and study the gross anatomy from both a qualitative and a quantitative perspective.(Bollen 2010, Mariani 2011, Muriuki, Tuason et al. 2011, Sonnery-Cottet, Conteduca et al. 2014, Arner, Herbst et al. 2017, DePhillipo, Cinque et al. 2017, Liu, Zhang et al. 2017)

In *Paper II*, the anatomy pertaining to the location of where meniscal ramp lesions occur was defined consistently with measurements to surgically relevant anatomic landmarks. This study was one of the first to provide quantifiable data for the anatomy of the posterior medial capsule, PHMM, posterior medial meniscotibial ligament, and meniscal attachments for the POL, deep MCL, and semimembranosus. We found that the posteromedial capsule does not attach directly to the PHMM, rather it attaches to approximately one-third of the distance below the superior margin of the medial meniscus (*Paper II*). This provides evidence for the previously theorized potential "hidden" nature of meniscal ramp lesions, specifically while the knee is near full extension.(Bollen 2010, Sonnery-Cottet, Conteduca et al. 2014) This anatomic nature of the posterior capsule has direct clinical implications. First, during an MRI scan with the patient supine and knee near full extension, the posterior capsule may remain taut against the PHMM, which can limit the amount of space or fluid that will collect in this area. This may provide direct evidence for the high rate of false negatives and low rate of detection for meniscal ramp lesions on MRI and further advocates for the essential of use of secondary signs for preoperative diagnosis on MRI (*Paper I*). Secondly, during arthroscopy, the surgeon may misinterpret the integrity of the posterior meniscocapsular attachment when viewing from the anterior view and/or the Gillquist (intercondylar notch) view due to the folding of the capsule onto the PHMM (**Figure 17**).(Sonnery-Cottet, Conteduca et al. 2014, Peltier, Lording et al. 2015) Thus, it is recommended that surgeons use a probe to retract or push the capsule away from the PHMM in order to directly visualize the folded capsule, which is where these potential hidden ramp lesions can be found.(DePhillipo, Cinque et al. 2017)

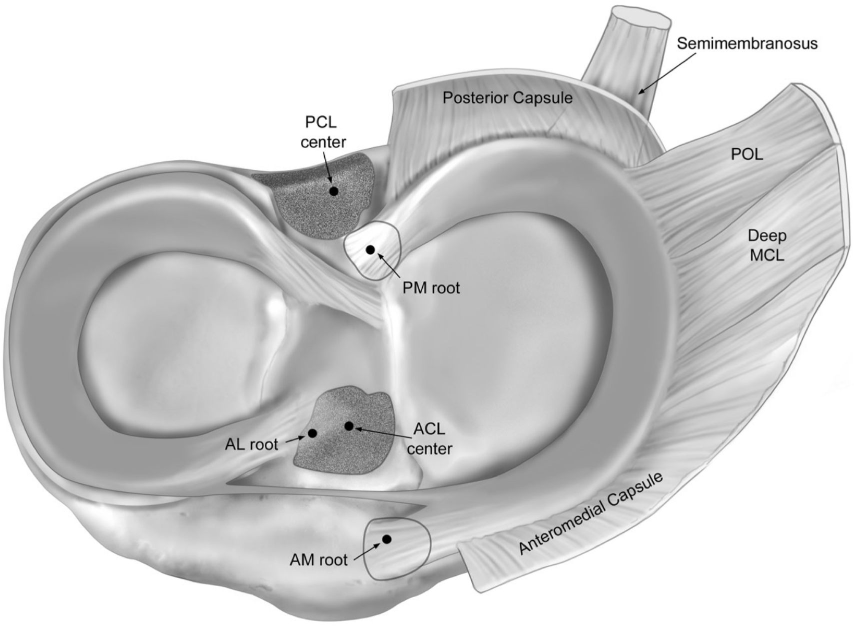
Figure 17. Example of hidden location for medial meniscal ramp lesions with knee in full extension. A) Cadaveric image of ramp tear with posteromedial capsule taut, and B) opening of meniscocapsular junction with instrument which allows clear visualization of ramp tear.



In comparison, the lateral meniscus has a more direct attachment to the posterolateral capsule, attaching approximately 11% below the superior margin of the posterior horn of the lateral meniscus.(Aman, DePhillipo et al. 2019) Also, the length of the posterior horn and capsule laterally are much shorter compared to medially (*Paper II*). These anatomical deviations between the posteromedial and posterolateral meniscal attachments partly explain why ramp lesions occur more frequently on the medial side and less on the lateral side of the knee. This may be intuitive to some clinicians or may have been previously presented with qualitative descriptions; however, both of these anatomic studies that were conducted in our laboratory were the first to provide objective, quantifiable evidence of the disparities between the lengths of the medial and lateral posterior horn and posterior capsule.(Aman, DePhillipo et al. 2019, DePhillipo, Moatshe et al. 2019)

With some of the early classifications of medial meniscal ramp lesions, authors had reported that a ramp tear was a pure posteromedial meniscocapsular separation with a length of 2.5 cm.(Strobel 1988, Liu, Feng et al. 2011) While the results of the anatomy measurements in *Paper II* did not necessarily change clinical practice directly, it allowed researchers and clinicians to have objective data for characterizing meniscal ramp lesions. *Paper II* showed that the average length of the posterior capsule was 2.0 cm, which corresponded with the entire length of the posterior horn (2.1 cm) (**Figure 18**). Thus, it was proposed that the definition for ramp lesions abandon an arbitrary length that lacks evidence-based correlation. Rather, meniscal instability and involvement of the meniscotibial ligament may be added to the classic 'meniscocapsular separation' for defining ramp lesions, as evidenced in *Papers II, III, and IV*. Additionally, *Paper II* provided objective measurements for future biomechanical studies, which allowed for precise sectioning of the posteromedial meniscocapsular and meniscotibial attachments of the medial meniscus in our biomechanics study (*Paper III*). This data further allows authors and researchers to communicate on the same level with each other and reference specific anatomical landmarks and surgically relevant measurements for defining meniscal ramp lesions on an international level.

Figure 18. A view illustration of the anatomic relationships of the posterior horn of the medial meniscus (PHMM), posterior capsule, posterior oblique ligament (POL), deep medial collateral ligament (MCL), and semimembranosus tendon. The posterior meniscocapsular attachment spanned the entire length of the PHMM and attached at an average depth of 36.4% of the total posterior meniscal height, supporting the potential for a ''hidden'' space for meniscal ramp lesions when the knee is near full extension. ACL, anterior cruciate ligament; AL, anterolateral; AM, anteromedial; PCL, posterior cruciate ligament; PM, posteromedial.



Another key finding in *Paper II* was the histological analysis which identified a shared attachment for the meniscocapsular and meniscotibial structures of the PHMM. Subsequently, it is theorized that both the meniscocapsular and meniscotibial attachments may function together as a single anatomical unit.(Terry and Hughston 1985) This theory is unconventional currently and in contrary to the previously proposed ramp tear classification system.(Thaunat, Fayard et al. 2016) However, despite the supported anatomical evidence of the H&E and alcian blue staining, this theory was further supported by the biomechanical data in *Paper III* which demonstrated that there was no increase in knee kinematics with sequential sectioning of the meniscocapsular attachment followed by the meniscotibial attachment (and vice versa).

These biomechanical findings suggest that although meniscal ramp lesions may occur in two separate locations, instead of only occurring at the meniscocapsular junction as previously described, a single ramp repair that allows fixation of either structure may be adequate to address lesions of both the meniscocapsular/tibial attachments and restore knee stability (*Papers II and III*). This theory is evident with previous biomechanical reports that demonstrated improved knee kinematics following all-inside ramp repair.(Ahn, Bae et al. 2011, Stephen, Halewood et al. 2016, Edgar, Kumar et al. 2018) Similarly, the results of *Paper III* demonstrated that a combined inside-out and open posterior repair were successful for restoring knee stability for meniscocapsular and meniscotibial-based ramp lesions, respectively. However, this dual repair did demonstrate knee over-constraint in full extension with knee external rotation. These results imply that when there are tears in both the meniscocapsular and the meniscotibial attachments of the PHMM simultaneously (as proposed by Thaunat et al.(Thaunat, Fayard et al. 2016), performing two separate repairs for both of these tears may not be warranted. Rather, an inside-out repair with a vertical mattress technique that captures both the meniscus and capsule, superiorly and inferiorly, may suffice as a stable ramp repair.(Johnson and Weiss 2012, Joshi, Usman et al. 2016, DePhillipo, Cinque et al. 2017) This theory was further supported in *Paper V*, which demonstrated improved subjective and objective outcomes following ACL reconstruction and meniscal ramp repair with solely an inside-out meniscus repair.

The results of the matched cohort subanalysis revealed no significant differences in subjective and objective outcomes between patients who underwent combined ACL reconstruction with an inside-out meniscal ramp repair compared to an isolated ACL reconstruction (p < .05) (*Paper V*). Similarly, authors have reported satisfactory outcomes following combined ACL reconstruction with an all-inside meniscal ramp repair.(Li, Chen et al. 2015, Thaunat, Jan et al. 2016, Keyhani, Ahn et al. 2017, Sonnery-Cottet, Praz et al. 2018) However, *Paper V* was one of the first outcomes studies to report an inside-out repair technique for ramp lesions, and the first to demonstrate equivalence to isolated ACL reconstruction via matched patient groups. These results support the clinical notion of repairing ramp lesions via an inside-out technique with a high reported success rate and a low likelihood of complications (*Paper V*).

Nonetheless, from a biomechanical perspective, there may be a role for all-inside ramp repair with a suture hook or lasso and without a hybrid implant. In *Paper III*, the dual repair of both the meniscocapsular and the meniscotibial attachments did not fully restore knee kinematics at higher angles of knee flexion. Therefore, future biomechanical studies may look to evaluate the most optimal knee fixation angles in order to restore native knee kinematics and evaluate biomechanical differences between all-inside and inside-out repair.

Given the posteromedial location of ramp lesions, the saphenous neurovascular bundle is (in theory) at an increased risk while creating the inside-out repair incision compared to the utilization of a single posteromedial portal.(Pace and Wahl 2010, Heilpern, Stephen et al. 2018) Because of the close proximity to the neurovascular bundle, placement of meniscal fixation devices, needle passing, or suture tying must be performed with caution.(Pace and Wahl 2010, DePhillipo, Cinque et al. 2017) Jan et al.(Jan, Sonnery-Cottet et al. 2016) reported a 1.8% incidence of postoperative saphenous nerve dysesthesia (with areas of dysesthesia along the medial leg ≥ 45 cm^2) specifically in patients following meniscal ramp repair via an accessory posteromedial portal (all-inside technique). There were no patients (0/50) who reported saphenous nerve distribution complications in *Paper V* with the use of an inside-out repair technique. However, it has been reported that there is an inherent learning curve and surgical skill associated with both of these repair techniques.(Jan, Sonnery-Cottet et al. 2016, DePhillipo, Cinque et al. 2017) Thus, it is recommended that surgeons directly visualize the posterior capsule in order to avoid iatrogenic injury to the saphenous neurovascular bundle during the surgical approach and repair (**Figure 19**).(Sonnery-Cottet, Conteduca et al. 2014, Thaunat, Jan et al. 2016, DePhillipo, Cinque et al. 2017)

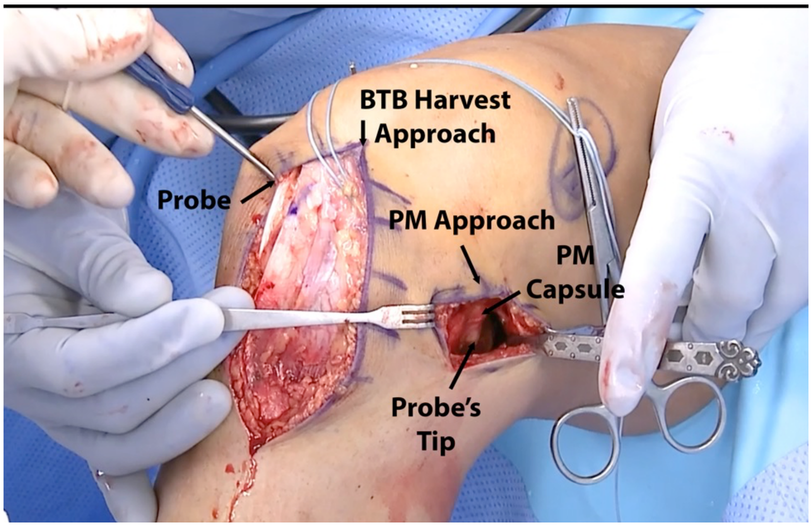


Figure 19. Surgical approach for combined ACL reconstruction with bone-patellar tendon-bone (BTB) autograft and medial meniscus ramp repair via inside-out repair technique. There were no reported saphenous neurovascular complications reported at 2-years follow-up in 50 patients with inside-out meniscus ramp repair.
PM: posteromedial.

The all-inside meniscal repair technique via a suture hook or lasso has demonstrated good results and has some advantages, including being less technically demanding, it has less neurovascular risk, and is probably the best option for surgeons who do not have knowledgeable assistants in surgery.(Sonnery-Cottet, Conteduca et al. 2014, Thaunat, Jan et al. 2016, Keyhani, Ahn et al. 2017) However, this technique is limited by the number of sutures that the surgeon can place in the repair, with an average of one to three sutures used for repair as previously reported with an all-inside technique via a posteromedial portal.(Sonnery-Cottet, Praz et al. 2018) This is in comparison to *Paper I*, which reported an average of 8.5 sutures used during inside-out meniscal ramp repair. While the inside-out technique is more technically demanding, this approach affords greater versatility in suture placement and allows the surgeon to pass a greater number of sutures, thereby creating a stronger repair.(Chahla, Serra Cruz et al. 2016, Joshi, Usman et al. 2016, DePhillipo, Cinque et al. 2017) The increased number of sutures utilized with this technique may in part explain the difference in meniscal repair failure rate compared to the all-inside technique (2-4% vs. 11-12.5%, respectively).(Heilpern, Stephen et al. 2018, Sonnery-Cottet, Praz et al. 2018)

Despite the reported use of an all-inside suture hook in practices located in Europe and Asia, the more commonly utilized technique for meniscal ramp lesions in the United States is the all-inside repair with hybrid device (*Paper IV*). Unlike the suture hook technique, the all-inside technique with a hybrid device carries the risk of anchor irritation, meniscal body tears from larger holes created by device insertion, and implant failure. In a systematic review, Westermann et al.(Westermann, Duchman et al. 2017) reported an overall 54% complication rate due to implant irritation and device migration following all-inside meniscal repair at the time of ACL reconstruction. There were two cases of saphenous nerve injury reported for the inside-out repair group and two cases for the all-inside repair group.(Westermann, Duchman et al. 2017) The overall reported clinical failure rates were 10% and 16% for inside-out and all-inside meniscal repair techniques, respectively.(Westermann, Duchman et al. 2017) Similarly, one previous biomechanical study reported a hybrid meniscal ramp repair failure rate of 12.5% using an all-inside FastFix 360 implant (Smith & Nephew, Andover, MA, USA).(Heilpern, Stephen et al. 2018) Despite the increased risks, one study has reported positive outcomes with this technique. Li et al.(Li, Chen et al. 2015) reported on 23 patients with meniscal ramp lesions treated with an all-inside repair via a standard anterior approach with two FastFix hybrid implants. The authors reported significant improvements in patient-reported outcomes at a mean follow-up of 14 months postoperatively; however, complications and failures were not specifically reported.(Li, Chen et al. 2015) Additionally, the 14 month follow-up reported in their study is shorter than the usual 24 month follow-up required in most peer-reviewed outcomes literature. Thus, the failure rate following all-inside repair via a hybrid device specifically for ramp lesions has yet to be determined in the literature.

Rates of secondary meniscal tears have been reported to occur in approximately 16% of patients who undergo primary ACL reconstruction.(Hagmeijer, Hevesi et al. 2019) Sonnery-Cottet et al.(Sonnery-Cottet, Praz et al. 2018) reported an 11% secondary partial meniscectomy rate following all-inside ramp repair via a suture hook technique with significantly improved patient reported outcomes as well as objective measures of knee stability from preoperatively to postoperatively at a mean follow-up of 45.6 months ($p < .05$). In comparison, the overall failure rate of inside-out ramp repair in *Paper V* was 4%, with 2% of patients requiring a secondary partial meniscectomy and the other 2% of patients requiring a revision meniscal ramp repair at a mean follow-up of 2.8 years postoperatively. This finding further supports the advantages of an inside-out meniscal repair technique, especially for large complex meniscal ramp lesions which require multiple sutures for a stable repair. Additionally, all patients had patellar tendon autografts with anatomic ACL reconstruction which may be responsible for the 0% rate of ACL reconstruction graft failure reported in *Paper V*. This was also the first study to report ramp repair outcomes with the patellar tendon autograft, because previous studies utilized hamstring tendon autografts for the ACL reconstruction.(Thaunat, Jan et al. 2016, Liu, Zhang et al. 2017, Yang, Guan et al. 2017, Sonnery-Cottet, Praz et al. 2018) Thus, the results of *Paper V* afford the recommendation of ACL reconstruction with patellar tendon autograft and inside-out meniscal ramp repair for patients who meet such indications, as there seems to be less risk of developing secondary meniscal tears, low complication rates, and equivalence to isolated ACL reconstruction regarding knee function.

Due to the complexity and tear pattern variability associated with meniscal ramp lesions, developing a standardized objective means for diagnosis of ramp tears appears to be limited. However, trends in patient characteristics have been previously reported with arthroscopically confirmed meniscal ramp lesions. Specifically, male sex, younger age (< 30 years old), a concomitant lateral meniscus tear, contact injury mechanism, increased medial meniscus slope, revision ACL reconstruction, and chronicity have been reported to be significantly associated with the presence of meniscal ramp lesions ($p < 0.05$).(Liu, Feng et al. 2011, Song, Liu et al. 2016, Di Vico, Di Donato et al. 2017, Seil, Mouton et al. 2018, Sonnery-Cottet, Praz et al. 2018, Balazs, Greditzer et al. 2019) This was confirmed in the clinical outcomes study (*Paper V*), because the majority of patients with ramp lesions were chronic injuries (≥ 6 weeks, 68%), reported a contact mechanism of injury (88%), and displayed a concomitant lateral meniscus tear (63%).

Two newly reported clinical associations that we found were concomitant lateral meniscus posterior root tears in 22% of ramp tear patients as well as reported ramp lesion prevalence in 38% of patients with multi-ligament knee injuries (*Paper V*). Previous biomechanical studies have identified that the lateral meniscus posterior root is a significant stabilizer for anterior tibial translation and knee internal rotation.(Shybut, Vega et al. 2015, Frank, Moatshe et al. 2017) These findings may help explain the increased knee instability on physical exam in *Paper V*, because 44% of patients had grade III Lachman's and 38% had grade III pivot shift tests with combined ACL and ramp tears; in comparison, 6% of patients with isolated ACL tears had a grade III Lachman's and 12% had grade III pivot shift tests. Similarly, authors have reported that 47% of patients with combined ACL and ramp tears had a significantly higher amount of dynamic rotational laxity, as expressed by grade III pivot shift testing, compared to patients with isolated ACL tears (25% grade III pivot shift; $p = 0.02$).(Mouton, Magosch et al. 2019) Additionally, our knee laxity results corroborate with the findings previously reported by Sonnery-Cottet et al.(Sonnery-Cottet, Praz et al. 2018), as 55% of patients in their study with combined ACL and ramp tears had > 6 mm of anterior knee laxity on physical exam. Therefore, clinicians ought to suspect either medial ramp tears and/or medial ramp with lateral root tears with the presence of grade III knee laxity preoperatively for patients with ACL tears.(Sonnery-Cottet, Praz et al. 2018, Mouton, Magosch et al. 2019)

The novel association of ramp lesions with multi-ligament knee injuries should promote awareness to orthopaedic surgeons to routinely perform an arthroscopic evaluation of the posteromedial knee routinely to evaluate the for a meniscal ramp lesion when treating multi-ligament knee injured patients (*Paper V*). Also, this data highlights the complexity associated with meniscal ramp lesions and their potential association with severe, traumatic mechanisms of injury. Ultimately, understanding the clinical characteristics associated with ACL tears and ramp lesions may help improve preoperative diagnosis and may be used for targeting injury prevention strategies.

Over the past two decades, sports medicine professionals have improved in the identification, treatment, and prevention of ACL injuries. Through injury surveillance and worldwide educational promotion of ACL injury prevention, sports have evolved with an improved awareness and suspicion for preventing ACL tears in both athletes and coaches. Educational awareness is key and is most likely the first step in initiating changes for injury prevention purposes in noncontact related ACL injuries.(Bahr and Holme 2003, Renstrom, Ljungqvist et al. 2008, Alentorn-Geli, Myer et al. 2009, Bahr 2016) Although individual neuromuscular training interventions may be effective in decreasing primary ACL injury rates(Myklebust, Engebretsen et al. 2003, Bonato, Benis et al. 2018), the context regarding meniscal ramp lesions in ACL tears pertains to re-injury risk reduction or preventing ACL reconstruction graft failure(DePhillipo, Moatshe et al. 2018, Edgar, Kumar et al. 2018).

The theory of preventing secondary ACL tears is extrapolated from the previously identified negative influence on knee kinematics (*Paper III*) and increased ACL reconstruction graft force with ramp lesions.(Ahn, Bae et al. 2011, Peltier, Lording et al. 2015, Stephen, Halewood et al. 2016, Edgar, Kumar et al. 2018) This theory is compounded with the additive and well-established role of the posterior medial meniscus being a secondary stabilizer to anterior tibial translation.(Shoemaker and Markolf 1986, Papageorgiou, Gil et al. 2001, Trojani, Sbihi et al. 2011) The interdependence of the ACL and medial meniscus is not a new concept(Papageorgiou, Gil et al. 2001, Trojani, Sbihi et al. 2011); however recent data have indicated that medial meniscal deficiency is the most significant factor affecting primary ACL reconstruction graft failure(Parkinson, Robb et al. 2017, Webster, Feller et al. 2018). Therefore, the recommendation of meniscal ramp repair from previous authors is further supported by the potential benefit of protecting the primary ACL reconstruction and preventing increased force placed on the ACL reconstruction graft.(Liu, Feng et al. 2011, Thaunat, Jan et al. 2016, Malatray, Raux et al. 2018, Seil, Mouton et al. 2018, Sonnery-Cottet, Praz et al. 2018) Similarly, the benefit of repairing meniscal ramp lesions is indicated from this compilation of evidence (*Papers I-V*), specifically with the increased knee kinematics with unaddressed meniscal ramp tears found in our biomechanical study (*Paper III*).

Another important concept in the paradigm of injury prevention is the association of meniscal ramp lesions with chronic injuries. In *Paper V*, we found a high prevalence of chronic injuries (68%) in patients with combined ACL and medial meniscal ramp tears. Similarly, the majority of previous studies evaluating clinical characteristics of patients with combined ACL tears and meniscal ramp lesions report a higher prevalence of chronic injuries, yet a specific timeframe for the development of ramp tears has not been established (*Papers I and V*).(Liu, Feng et al. 2011, Keyhani, Ahn et al. 2017, Edgar, Kumar et al. 2018, Sonnery-Cottet, Praz et al. 2018) However, one study did report incremental increases in the prevalence of ramp lesions with delayed surgery, specifically a 15% increase in ramp tear prevalence with delays of 12 to 24 months compared to 0 to 3 months.(Keyhani, Ahn et al. 2017) Additionally, rates of secondary meniscal tears have been reported to increase with delayed ACL reconstruction (33%) compared to patients who underwent surgery acutely (7%).(Hagmeijer, Hevesi et al. 2019)

Similarly, Zoller et al.(Zoller, Toy et al. 2017) demonstrated an increase in medial meniscus tears with delayed ACL surgery > 6 months (21% vs. 50%, $p < .001$). This was corroborated by Stone et al.(Stone, Perrone et al. 2019) who reported that a delay in ACL reconstruction > 1 year significantly increased the risk of developing medial meniscal tears in patients ≥ 40 years of age ($p = .002$). However, a recent study suggests that the timeline for developing irreparable meniscus tears may be much sooner, as a delay in ACL surgery > 8 weeks resulted in an increased likelihood of a medial meniscus tear that required partial meniscectomy (OR: 2.30; 95% CI: 1.04-5.12; $p = .04$).(Everhart, Kirven et al. 2019) Furthermore, a delay in ACL surgery > 5 months had an increased likelihood of medial compartment osteoarthritis (Outerbridge grade ≥ 3 or 4) ($p = .001$). Therefore, prompt diagnosis and early surgery may be recommended to prevent the development of ramp lesions in ACL tear patients or delay the progression of partial stable meniscal tears to complete unstable tears that subsequently need surgical repair.

Ethical Considerations

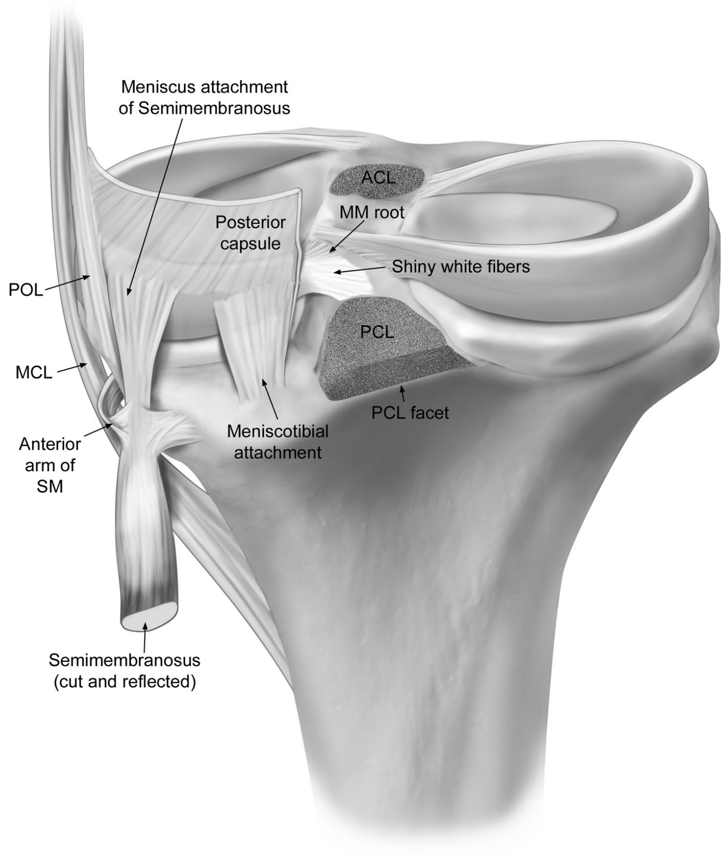
Through this systematic research process, the results of this doctoral thesis indicate the necessity to repair meniscal ramp lesions in the desire to restore knee stability and possibly prevent recurrent instability or secondary meniscal tears. However, there are some ethical concerns that must be considered. These ethical considerations include: societal bias, financial interests, global responsibility, and a positivistic paradigm that surrounds the global implementation of a specific clinical treatment strategy (i.e. inside-out meniscus repair).(Committes 2014)

There is potential bias towards recommending treatment options that may differ between countries and societies. The results of this doctoral work have different real-world implications among countries, partly due to different healthcare systems and societal viewpoints. This presents an ethical conflict because the implementation of inside-out meniscal repair can carry increased surgical fees, increased surgical time, and increased risk for complications with additional surgical procedures. Despite the enthusiasm for advancing science and medicine, the minimalistic approach (e.g. no repair for ramp lesions) has been popularized in modern society and holds true in today's research methods within the academic field of sports medicine.(McNamee 2007) The conflict of a more 'invasive treatment' versus a 'minimalistic approach' is an important concept to consider with the potential global adaptability of the current research. From a clinical standpoint, for example, a decreased rate of ACL reconstruction graft failure as much as 5% would be significant for all sports-related populations who sustain ACL tears. One could argue that this approach could be justified as utilitarian ethics are considered.(McNamee 2007) However, there are inherent differences among individual surgeons and the recommendation of inside-out meniscal repair from a single surgeon's practice may not result in the same outcomes in a different surgeons practice. Furthermore, all patients are different and should be treated independently with individualized recommendations and treatment protocols. Thus, as the doctoral student, it is my global responsibility to not only disseminate the results of this dissertation and communicate new knowledge, but it is also my duty as a researcher to realize the potential negative effects of global adoption. Therefore, it is recommended that the clinician consider all possible treatment options available in order to best protect the integrity of the knee joint for their patients.

Future Perspectives

A concept that is still not well understood is the exact mechanism of injury for meniscal ramp lesions. Much is known regarding the complex intrinsic injury mechanisms for noncontact related ACL tears, including altered knee movement patterns during pivoting, twisting, or jump-landing (e.g. increased knee abduction angle).(Boden, Dean et al. 2000, Bahr and Holme 2003, Hewett, Myer et al. 2005, Fauno and Wulff Jakobsen 2006) Stephen et al.(Stephen, Halewood et al. 2016) proposed two possible explanations regarding the etiology of meniscal ramp lesions in ACL injured knees: 1) the contraction of the semimembranosus at its insertion to the posteromedial meniscus; or 2) medial contrecoup injury after subluxation of the lateral tibial plateau and subsequent reduction of the tibia. The results of the anatomy study (*Paper II*) helped to provide supportive evidence for theory 1 by showing the direct meniscal-semimembranosus attachment (**Figure 20**); yet this explanation still remains inconclusive due to the lack of biomechanical testing for dynamic musculotendinous structures. Despite the high reported incidence of noncontact related mechanisms (e.g. 70%) associated with ACL tears(Boden, Dean et al. 2000, Fauno and Wulff Jakobsen 2006, Gilchrist, Mandelbaum et al. 2008), the majority of epidemiological studies on ramp lesions (including *Paper V*) report contact mechanisms of injury in these patients(Liu, Feng et al. 2011, Thaunat, Jan et al. 2016, Seil, Mouton et al. 2018, Sonnery-Cottet, Praz et al. 2018). Thus, the contrecoup theory may be most relevant and may help explain the increased bony edema of the posteromedial tibia on MRI associated with ramp lesions. However, future studies are needed that involve biomotion analysis for patients with ACL and meniscal ramp tears in order to gain further insight on the exact etiology for ramp lesions.

Figure 20. Posterior medial anatomy with the posterior capsule reflected. This figure illustrates the intimate relationship of the static and dynamic structures of the posteromedial corner, including the semimembranosus tendon fascial expansion that attached directly to the posterior horn of the medial meniscus. ACL, anterior cruciate ligament; MCL, medial collateral ligament; MM, medial meniscus; PCL, posterior cruciate ligament; POL, posterior oblique ligament; SM, semimembranosus.



The prevalence of ACL tears and complex meniscal tears in younger patients may be attributed to the increase in sports participation and year-round athletics in today's youth.(Krych, Pitts et al. 2010, Malatray, Raux et al. 2018, Ekas, Laane et al. 2019) Early sport specialization (ESS), which refers to intense training year-round in a specific sport starting at a young age, has been proposed as a contributing cause of increased rates of traumatic and overuse injuries in youth athletes.(Hall, Barber Foss et al. 2015, Post, Trigsted et al. 2017, DePhillipo, Cinque et al. 2018) Malatray et al.(Malatray, Raux et al. 2018) reported a similar incidence (23%) of combined ACL and medial meniscal ramp tears in children and adolescents (median age 14 $\pm$ 1.3 years) compared to adults. Currently, the influence of ESS on traumatic knee injuries such as ACL and meniscal tears is unknown; however, considering the high prevalence of these injuries in youth athletes, future studies are needed to evaluate this potential relationship.(Moksnes, Engebretsen et al. 2013, Malatray, Raux et al. 2018, Ekas, Laane et al. 2019) Furthermore, considering the known deleterious effects associated with ACL and meniscal tears regarding physical dysfunction and post-traumatic osteoarthritis, developing improved treatment strategies for pediatric and adolescent patients warrants further investigation.(Lohmander, Ostenberg et al. 2004, Lohmander, Englund et al. 2007)

The improved outcomes observed in *Paper V* and other studies when the repair is performed concurrently with an ACL reconstruction have been hypothesized to be related to the biological augmentation of the meniscal repair from factors in the bone marrow released within the joint.(Hutchinson, Moran et al. 2014) A recent study reported that the concentration of vascular endothelial growth factor (VEGF) and its angiogenetic receptor vascular endothelial growth factor receptor 2 (VEGFR2) were significantly greater after ACL reconstruction than after partial meniscectomy.(Galliera, De Girolamo et al. 2011) These results indicate a more favorable meniscal healing environment when meniscal repairs are performed concurrently with an ACL reconstruction.(Krych, Pitts et al. 2010, Westermann, Duchman et al. 2017) When considering the encouraging outcomes and potential positive effects of biologic augmentation(Centeno, Pitts et al. 2014, Krych, Nawabi et al. 2016, Shapiro, Kazmerchak et al. 2017), previous authors have recommended augmentation such as the addition of platelet-rich plasma (PRP) or bone marrow aspirate concentrate (BMC) at the time of meniscal repair(Moatshe, Morris et al. 2017, Muckenhirn, Kruckeberg et al. 2017, Kaminski, Kulinski et al. 2018). However, a recent study suggests that the addition of PRP may only benefit patients with isolated meniscal tears for reducing repair failure risk, as there was no benefit of PRP for patients who underwent combined ACLR and meniscal repair ($p = 0.23$).(Everhart, Cavendish et al. 2019)

Another possible augmentation option would be the utilization of a bone marrow stimulation procedure which is performed by using a microfracture awl to create holes into the intercondylar notch, also called a marrow venting procedure (MVP).(Dean, Chahla et al. 2017) A MVP releases similar factors as when drilling into the bone during an ACL reconstruction and may be a viable option when treating ramp lesions not associated with ACL injury.(Mariani 2011, Hirtler, Unger et al. 2015, Tiftikci and Serbest 2017) This specific scenario may be appropriate in patients who have had a primary ACL reconstruction without meniscal repair and then developed a secondary meniscal tear following the index ACL reconstruction surgery.(Ekas, Laane et al. 2019, Hagmeijer, Hevesi et al. 2019) Additionally, MVP is a more cost-effective option and most certainly a more feasible option for those with limited resources or who may not have access to PRP or BMC.

Although this dissertation did not directly evaluate the nonoperative treatment of stable meniscal ramp lesions, previous studies have reported the potential for ramp lesions to heal with trephination alone.(Liu, Zhang et al. 2017, Yang, Guan et al. 2017) For stable ramp lesions, biologic augmentation coupled with trephination may be a viable treatment option for these patients. However, future studies should evaluate the cost-effectiveness of these conservative treatment options compared to meniscal repair and to determine that if meniscal ramp lesions do not heal, if the rate of ACL reconstruction graft tear increase.

The remaining questions regarding the most effective treatment options for meniscal ramp lesions are situated around long-term clinical outcomes. Although previous studies have demonstrated the negative influence of ramp lesions on knee kinematics and ACL reconstruction graft force (*Paper III*)(Peltier, Lording et al. 2015, Stephen, Halewood et al. 2016, Edgar, Kumar et al. 2018), only one current study has evaluated the changes in tibiofemoral contact mechanics with meniscal ramp lesions(Dugas, Barrett et al. 2015). Therefore, future studies are needed to assess the long-term effects of unaddressed meniscal ramp lesions regarding the development of post-traumatic osteoarthritis in ACL tear patients.

Conclusions

The collective results of this dissertation allow for the expansion of the definition of medial meniscal ramp lesions to include meniscocapsular-based tears and meniscotibial-based tears. Tear characterization should include meniscal stability and partial versus complete tearing descriptions; the length of meniscal tear should not be a necessary indication for treatment. The biomechanical data indicate that meniscal ramp lesions have potential negative implications on knee kinematics and the results suggest performing repair at the time of ACL reconstruction, with an inside-out technique exhibiting superiority over all-inside techniques (suture hook and hybrid device). Additionally, there does not appear to be an advantageous role for isolated meniscotibial ligament repair aside from the previously established inside-out or all-inside repair techniques, due to the shared common attachment of the meniscocapsular and meniscotibial structures.

Due to the complexity and variability associated with meniscal ramp lesions, developing a standardized objective means for diagnosis appears to be limited. However, trends in clinical characteristics reported in these patients may help improve the clinical suspicion for both preoperative and intraoperative assessment:

- Presence of bony edema in the posteromedial tibia on the preoperative MRI (*Paper I*)
- Involvement of the posteromedial meniscotibial ligament and increased meniscal translation during arthroscopic probing (*Papers II, IV*)

- Routine use of the modified Gillquist view during arthroscopic assessment of ACL tear patients (*Papers I, IV, V*)
- Presence of increased knee laxity on preoperative physical exam in ACL tear patients, such as grade III Lachman's and grade III pivot shift testing (*Papers III, IV and V*)
- Patients who report a contact mechanism of injury at time of ACL tear (*Paper V*)
- Patients with concomitant ACL and lateral meniscal tears, specifically tears at the posterior lateral meniscus root attachment (*Papers I, V*)
- When treating ACL tear-based multi-ligament knee injured patients (*Paper V*)

The clinical outcomes demonstrate satisfactory improvements in short-term follow-up via subjective and objective reported data following ACL reconstruction with concomitant medial meniscus ramp repair. Results indicate equivalence for combined ACL reconstruction with an inside-out meniscal ramp repair compared to isolated ACL reconstruction. Thus, the following are recommended:

- Anatomic ACL reconstruction with preference of patellar tendon autograft in young patients with medial meniscal tears. However, graft choice is decided ultimately by both the surgeon and the patient undergoing ACL reconstruction
- Inside-out repair technique for complete, unstable meniscal ramp lesions which may offer a stronger repair with lower rates of secondary meniscal tears and meniscal repair failure
- Early surgical treatment (< 6 weeks) for patients with ACL and ramp tears in order to possibly prevent or delay the progression of meniscal ramp lesions

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Appendix A

Paper I **– Diagnosis**

Incidence and Detection of Meniscal Ramp Lesions on Magnetic Resonance Imaging in Patients With Anterior Cruciate Ligament Reconstruction

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Investigation performed at The Steadman Clinic, Vail, Colorado, USA

Background: Meniscal ramp lesions have been reported to be present in 9% to 17% of patients undergoing anterior cruciate ligament (ACL) reconstruction. Detection at the time of arthroscopy can be accomplished based on clinical suspicion and careful evaluation. Preoperative assessment via magnetic resonance imaging (MRI) has been reported to have a low sensitivity in identifying meniscal ramp lesions.

Purpose: To investigate the incidence of meniscal ramp lesions in patients with ACL tears and the sensitivity of preoperative MRI for the detection of ramp lesions.

Study Design: Case series; Level of evidence, 4.

Methods: All patients who underwent ACL reconstruction by a single surgeon between 2010 and 2016 were included in this study, and patients with medial meniscal ramp lesions found at the time of arthroscopy were identified. The sensitivity of MRI compared with the gold standard of arthroscopic evaluation was determined by review of the preoperative MRI musculoskeletal radiologist report, mimicking the clinical scenario. The incidence was calculated based on arthroscopic findings, and the potential secondary signs of meniscal ramp tears were evaluated on MRI.

Results: In a consecutive series of 301 ACL reconstructions, 50 patients (33 male, 17 female) with a mean age of 29.6 years (range, 14-61 years) were diagnosed with a medial meniscal ramp lesion at arthroscopic evaluation (16.6% incidence). The sensitivity of MRI for ramp lesions was 48% based on the preoperative MRI report. A secondary finding of a posteromedial tibial bone bruise was identified on preoperative MRI in 36 of the 50 patients with ramp lesions in a retrospective MRI review by 2 orthopaedic surgeons.

Conclusion: Medial meniscal ramp lesions were present in approximately 17% of 301 patients undergoing ACL reconstruction, and less than one-half were diagnosed on the preoperative MRI. A posteromedial tibial bone bruise was found to be a secondary sign of a ramp lesion in 72% of patients. Increased awareness of this potentially combined injury pattern is necessary, and careful intraoperative evaluation is required to identify all meniscal ramp tears.

Keywords: knee; knee ligaments; meniscus

Increased attention has been directed toward the identification and treatment of concomitant knee injuries associated with anterior cruciate ligament (ACL) tears to best restore knee biomechanics and function. Studies have reported that 43% of patients with ACL tears have concomitant lateral or medial meniscal tears.[6] Meniscocapsular tears of the posterior horn of the medial meniscus are of specific interest because of the reported difficult visualization of the posteromedial "blind spot" when operating via traditional anteromedial and anterolateral portals.[11] These meniscocapsular lesions have recently been termed *ramp lesions*,[9] and their incidence has been reported to be 9% to 17% of all ACL tears.[2,7]

Ramp lesions are a tear of the peripheral attachment of the posterior horn of the medial meniscus at the meniscocapsular

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junction.[2,12] Investigation of these lesions is important because recent biomechanical data suggest these lesions can result in increased anterior tibial displacement and increased strain on both the native ACL and ACL-reconstructed graft.[4,8,10]

Much of the literature regarding ramp lesions has focused on repair techniques and outcomes after surgery.[3,8-10,12] However, a relative paucity of studies is available on the diagnosis of ramp lesions using preoperative magnetic resonance imaging (MRI) with arthroscopic correlation.[2] Given this gap in knowledge, the aim of this study was to report the incidence of ramp lesions in patients with ACL reconstruction, to determine the sensitivity of preoperative MRI for the detection of ramp lesions with comparison to the gold standard of arthroscopy, and to examine possible secondary signs of a ramp lesion on MRI.

METHODS

Study Design

A prospectively collected patient outcomes database was retrospectively queried. Query of the database identified 301 patients who underwent primary or revision ACL reconstruction by a single surgeon (R.F.L.) between April 2010 and July 2016 and had a confirmed medial meniscal tear. Inclusion criteria were defined as patients with a confirmed ACL tear and medial meniscal tear. Exclusion criteria were defined as patients who had a concomitant medial meniscal root tear on their ipsilateral knee. All patients were clinically examined preoperatively and underwent standardized preoperative imaging evaluation with plain radiographs and an MRI.

Imaging Evaluation

The arthroscopic procedures were reviewed to determine the presence of a ramp lesion and concomitant injuries. A ramp lesion was defined as a tear of the peripheral attachment of the posterior horn of the medial meniscus at the meniscocapsular junction. In patients identified to have a ramp lesion, the preoperative MRI report was reviewed to determine whether a ramp lesion was diagnosed by the interpreting musculoskeletal radiologist, and the sensitivity was calculated. Additionally, 2 independent orthopaedic surgeons (J.C., A.G.G.) evaluated the preoperative MRI to assess for potential associated injury patterns. The most common magnet strength for MRI was 3.0 T (n = 40) followed by 1.5 T (n = 10). All patients who had a 3.0-T MRI were scanned at our institution, and the remaining 1.5-T scans were reviewed from outside imaging facilities. Evaluation for meniscal ramp lesions was best visualized on proton-density, fat-saturated, T2-weighted images using the sagittal view.

Surgical Technique

Standard anteromedial and anterolateral portals were made for routine arthroscopy; no additional portals were required to assess for the presence of meniscal ramp lesions. Viewing from the anterolateral portal, the surgeon advanced the arthroscope through the intercondylar notch with the patient's knee in 30° of flexion for inspection of the posterior horn of the medial meniscus. A probe was directed over the superior aspect of the posterior horn of the medial meniscus to allow for inspection of the junction between the meniscus and capsule to identify whether a ramp lesion was present. The probe was used to retract the posteromedial capsule away from the posteromedial meniscocapsular attachment to assess for any tears, and a ramp lesion was diagnosed if a tear or separation was present. An accessory posteromedial portal was not required to completely visualize the posterior meniscocapsular attachment.

RESULTS

Of the 301 consecutive patients with ACL reconstruction who met the study criteria, 50 patients had diagnosed meniscal ramp lesions at the time of arthroscopy. Review of the preoperative MRI reports of these 50 patients revealed that 24 patients (48%) had a ramp lesion diagnosed preoperatively (Figure 1). Of the 24 patients with meniscal ramp lesion identified on preoperative MRI, 18 (75%) had acute tears and 6 (25%) had a chronic lesion (>6 weeks).

Review of the preoperative MRI revealed that a posteromedial tibial bone bruise was identified in 72.0% (n = 36) of the 50 patients with ramp lesion. Of the 50 patients, 31 (62%) had acute injuries and 19 (38%) had chronic injuries (>6 weeks). Patient demographics are presented in Table 1.

All patients reported an acute injury or reinjury before undergoing arthroscopy for ACL reconstruction and meniscal ramp repair. The majority of patients were injured during sport or athletic participation (Figure 2).

Mechanisms of injury included twisting (n = 34, 68.0%), jump-landing (n = 9, 18.0%), and falling on a flexed knee (n = 7, 14.0%). Of the 50 patients with ramp lesion, 16 patients (32.0%) underwent revision ACL reconstruction (Table 2) and 3 patients (6.0%) had prior medial meniscal repairs that had retorn.

The mean time (±SD) from injury to primary ACL reconstruction with ramp repair was 5.7 ± 9.7 weeks (n = 34, 68.0%). The mean time from reinjury to revision ACL reconstruction with ramp repair was 6.1 ± 8.2 months (n = 16, 32.0%). Thirty-nine of the 50 patients with ramp lesion (78.0%) had concomitant lateral meniscal tears at the time of arthroscopy; 28 of the 39 (72%) were repaired and 11 (28%) underwent partial meniscectomy for lateral meniscal tears (Table 3).

All ramp lesions were repaired with an inside-out vertical mattress technique. Ramp lesions in this series were repaired with an average of 8.5 ± 3.2 sutures (Figure 3).

DISCUSSION

The most important findings of this study were that MRI had a low sensitivity (48%) for the detection of medial meniscal ramp lesions and that the incidence of ramp

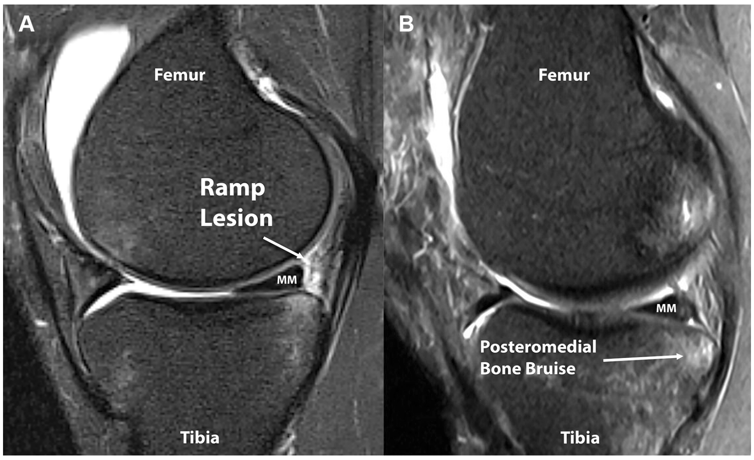

Figure 1. Preoperative magnetic resonance image (MRI) demonstrating meniscal ramp lesion and associated posteromedial tibial bone bruise pattern, best visualized on sagittal fat-saturated, T2-weighted images. (A) Meniscal ramp lesion, indicated by an increase in signal intensity at the peripheral margin of the posterior horn of the medial meniscus at the meniscocapsular junction. (B) Posteromedial tibial bone bruise and posterior medial meniscal contusion present on preoperative MRI in a patient with a combined anterior cruciate ligament tear and meniscal ramp lesion diagnosed at the time of arthroscopy. MM, medial meniscus.

TABLE 1
Characteristics of the 50 Patients With Medial Meniscal Ramp Lesions[a]

Clinical Characteristics	Total	Male	Female
Sex, n (%)		33 (66.0)	17 (34.0)
Age, y	29.6 ± 12.5	30.8 ± 13.4	27.1 ± 10.7
Body mass index, kg/m^2	24.1 ± 2.5	24.7 ± 2.6	23.0 ± 1.9
Time from injury to surgery, wk	14.7 ± 27.5	14.5 ± 29.4	15.0 ± 24.0

[a]Data are provided as mean ± SD unless otherwise noted.

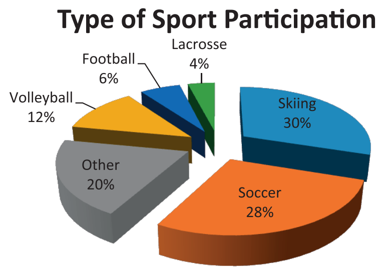

Figure 2. Type of sport or athletic activity reported at the time of injury for medial meniscal ramp lesions.

lesions in patients with concomitant ACL tears was 16.6%. A secondary finding of a posteromedial tibial bone bruise on MRI in 72% of all patients with a medial meniscal ramp lesion was identified. To our knowledge, this is one of the first studies to report MRI sensitivity for diagnosis of meniscal ramp lesions in patients who had ACL reconstruction and medial meniscal tear compared with the gold standard of arthroscopy.

On retrospective MRI review with comparison to arthroscopic detection of ramp lesions, a posteromedial tibial bone bruise on MRI was found to be an important secondary sign of a medial meniscal ramp lesion during arthroscopy. This finding is similar to the posteromedial bone bruise pattern previously reported in correlation with combined ACL and posterolateral corner (PLC) injuries[5]; however, only 2 patients in the present study sustained a PLC injury. Therefore, we propose that this secondary finding may not be specific for PLC injury. Due to the low sensitivity of MRI and difficult detection preoperatively,[4,7] a meniscal ramp lesion should be suspected in the presence of an ACL tear and a posteromedial tibial bone bruise with or without a PLC injury.

In 2010, Bollen[2] reported on a prospective evaluation of 183 consecutive patients undergoing ACL reconstruction and found a 9.3% incidence of meniscal ramp lesions at the time of arthroscopy. Preoperative MRI failed to identify the meniscocapsular tear in all patients with an available MRI; however, MRI was reviewed in only 11 of the 17 patients with ramp lesion (64.7%). Subsequently, Bollen proposed that because the MRI is performed with the knee near full extension, the meniscocapsular separation is most likely reduced during imaging, leading to a large number of false negatives.

Liu et al[7] reported a 16.6% incidence of meniscal ramp lesions at the time of arthroscopy in 868 patients undergoing ACL reconstruction. However, MRI findings were not compared with arthroscopic findings.[7] In a retrospective

TABLE 2
Previous Surgical Procedures, Graft Type, Time From Index Surgery, and Time From Reinjury to Revision ACLR and Meniscal Ramp Repair (n = 16)[a]

Study ID[b]	Previous Surgical Procedure (ACLR Graft Type)	Time From Index Surgery to Revision ACLR With Ramp Repair, mo	Time from Reinjury to Revision ACLR With Ramp Repair, mo
1	ACLR (HS auto)	7	5.6
3	ACLR (BPTB auto), medial meniscal repair	15	12.8
4	ACLR (BPTB auto)	180	1
5	1. ACLR (BPTB auto) 2. Revision ACLR (BPTB allo)	300	0.8
6	ACLR (iliotibial band auto)	36	30.4
7	ACLR (BPTB auto), lateral meniscal repair	14	3.7
15	ACLR (BPTB allo)	8	6.4
16	1. ACLR (HS auto) 2. Medial meniscal repair 3. Revision ACLR (tibialis anterior allo)	192	19.2
21	1. ACLR (BPTB auto), medial meniscal repair 2. Revision ACLR (BPTB allo) 3. Re-revision ACLR (BPTB allo), medial collateral ligament-R	58	6.4
23	ACLR (BPTB allo)	36	1
28	ACL repair	12	1.2
29	1. ACLR (quadriceps auto) 2. Revision ACLR (contralateral BPTB auto) 3. Partial meniscectomy	56	0.6
30	1. ACLR (BPTB allo) 2. Revision ACLR (HS auto)	21	4
31	1. ACLR (BPTB auto) 2. Revision ACLR (BPTB allo)	65	2
40	ACLR (BPTB allo)	58	1
49	ACLR (BPTB allo)	108	2

[a]Mean time from index surgery to revision ACL reconstruction was 6.0 ± 6.9 years. ACLR, anterior cruciate ligament reconstruction; allo, allograft; auto, autograft; BPTB, bone–patellar tendon–bone; HS, hamstring; MCLR, medial collateral ligament reconstruction.
[b]Deidentified study number for patients with ramp lesions.

TABLE 3
Concomitant Injuries Treated at Time of Surgery for Anterior Cruciate Ligament Reconstruction and Meniscal Ramp Lesion Repair (n = 50)[a]

Concomitant Injuries	No. of Injuries	Surgical Procedure, n
Lateral meniscal tear	39	Repair: 28 Meniscectomy: 11
FCL tear	7	FCLR: 7
MCL tear	7	MCLR: 7
PLC injury	2	PLCR: 2

[a]FCL, fibular collateral ligament; MCL, medial collateral ligament; PLC, posterolateral corner; R, reconstruction.

review, Edgar et al[4] reported on 337 patients who underwent primary ACL reconstruction over a 5-year period. Meniscal ramp lesions were found in 44 patients, for an overall incidence of 13.1%. Therefore, the present study, reporting a 16.6% incidence in patients undergoing ACL reconstruction, is in agreement with the previous literature.

Edgar et al[4] reported the suspicion of a meniscal ramp lesion via MRI in 33 of 43 patients with ramp lesion, yielding a sensitivity of 77% for meniscal ramp detection on MRI. In the present study, however, a sensitivity of only 48% for meniscal ramp lesions was reported on preoperative MRI. The poor sensitivity of MRI in identifying ramp lesions in our study could be attributed to the reduction of such a tear as the knee is extended during the imaging process.[2]

Previously reported clinical characteristics associated with ramp lesions include age, sex, and time from ACL injury to surgery. Liu et al[7] reported a higher prevalence in males than females, in patients younger than 30 years, and in patients who had ACL surgery within 24 months after ACL injury. Our findings are consistent with prior reported associated factors, because 66% of patients with meniscal ramp lesion were males and 34% were females. The mean age of patients with meniscal ramp lesion was 29.6 years and the mean time from new injury to ACL reconstruction and ramp repair was 3.6 months, supporting previously identified associated factors.

At the time of arthroscopy, all ramp lesions were identified without the use of an accessory posteromedial portal. Previous studies suggested that an accessory posteromedial portal was needed to reliably identify ramp lesions.[1,9,12] In contrast, the technique of the senior author (R.F.L.) presented herein evaluated for the presence of ramp lesions by displacing the posteromedial capsule away (posterior) from the meniscal tissue with a probe, thereby avoiding

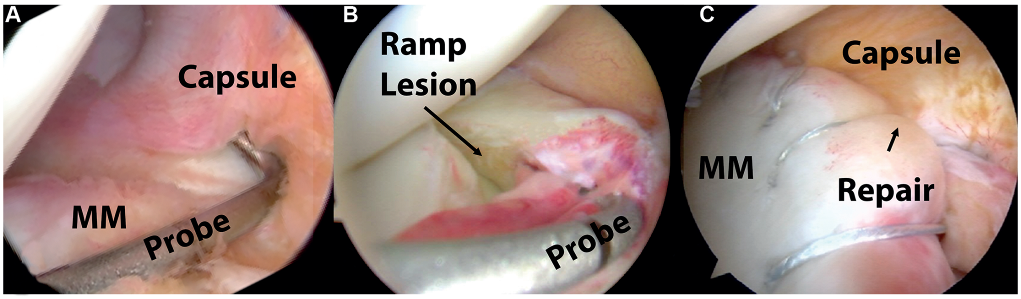

Figure 3. Intraoperative left knee meniscal ramp lesion. (A) Normal meniscocapsular junction with no evidence of ramp lesion. (B) Meniscal ramp lesion identified at time of arthroscopy (viewed through the intercondylar notch). (C) Restoration of meniscocapsular stability with ramp lesion repair via inside-out vertical mattress technique. MM, medial meniscus.

the creation of accessory portals and diminishing the overall morbidity and surgical time.

Some study limitations were identified for this study. Without evaluation of a noninjured population, we are unable to report the specificity of MRI for medial meniscal ramp lesions. Additionally, there was variability in the imaging center, MRI parameters, and interpreting radiologist; however, this variability replicates the clinical scenario and thus may improve the generalizability of our findings.

CONCLUSION

Medial meniscal ramp lesions were present in 17% of 301 patients undergoing ACL reconstruction, and less than one-half of these lesions were identified on preoperative MRI. A posteromedial tibial bone bruise was identified on preoperative MRI in 72% of all patients with a combined ACL tear and medial meniscal ramp lesion. Because MRI has been reported to have low sensitivity in identifying meniscal ramp lesions, clinicians should suspect a ramp lesion in the presence of a posteromedial tibial bone bruise on MRI in patients with an ACL tear. Increased awareness of this potentially combined injury pattern is necessary, and careful intraoperative evaluation is required to identify all lesions.

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Appendix B

Paper II **- Anatomy**

Quantitative and Qualitative Assessment of the Posterior Medial Meniscus Anatomy

Defining Meniscal Ramp Lesions

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Investigation performed at Steadman Philippon Research Institute, Vail, Colorado, USA

Background: Meniscal ramp lesions have been defined as a tear of the peripheral attachment of the posterior horn of the medial meniscus (PHMM) at the meniscocapsular junction or an injury to the meniscotibial attachment. Precise anatomic descriptions of these structures are limited in the current literature.

Purpose: To quantitatively and qualitatively describe the PHMM and posteromedial capsule anatomy pertaining to the location of a meniscal ramp lesion with reference to surgically relevant landmarks.

Study Design: Descriptive laboratory study.

Methods: Fourteen male nonpaired fresh-frozen cadavers were used. The locations of the posteromedial meniscocapsular and meniscotibial attachments were identified. Measurements to surgically relevant landmarks were performed with a coordinate measuring system. To further analyze the posteromedial meniscocapsular and meniscotibial attachments, hematoxylin and eosin and alcian blue staining were conducted on a separate sample of 10 nonpaired specimens.

Results: The posterior meniscocapsular attachment had a mean ± SD length of 20.2 ± 6.0 mm and attached posteroinferiorly to the PHMM at a mean depth of 36.4% of the total posterior meniscal height. The posterior meniscotibial ligament attached on the PHMM 16.5 mm posterior and 7.7 mm medial to the center of the posterior medial meniscal root attachment. The meniscotibial ligament tibial attachment was 5.9 ± 1.3 mm inferior to the articular cartilage margin of the posterior medial tibial plateau. The posterior meniscocapsular attachment converged with the meniscotibial ligament at the most posterior point of the meniscocapsular junction in all specimens. Histological staining of the meniscocapsular and meniscotibial ligament PHMM attachments showed similar structure, cell density, and fiber directionality, with no qualitative difference in the makeup of their collagen matrices across all specimens.

Conclusion: The anatomy of the area where a medial meniscal ramp tear occurs revealed that the 2 posterior meniscal attachments merged at a common attachment on the PHMM. Histological analysis validated a shared attachment point of the meniscocapsular and meniscotibial attachments of the PHMM.

Clinical Relevance: The findings of this study provide the anatomic foundation for an improved understanding of the meniscocapsular and meniscotibial attachments of the PHMM, which may help provide a more precise definition of a meniscal ramp lesion.

Keywords: knee; ramp lesion; medial meniscus; quantitative anatomy

Ramp lesions have been described as tears at the posterior meniscocapsular junction and/or tears of the posterior meniscotibial ligament,[19,20,24] and they have a reported incidence of 16% to 24% for all anterior cruciate ligament (ACL) tears.[8,15,18] Recent biomechanical studies reported discrepancies on the effect of untreated meniscal ramp lesions on knee kinematics of ACL-deficient and ACL-reconstructed knees.[10,17,21] Some authors advocate for the surgical repair of all meniscal ramp lesions at the time of ACL reconstruction, based on an increased risk of persistent instability and reconstruction graft failure when not treated.[2,9,23] However, given the vascularization of the capsule and the red-red zone of the meniscus,[3,4] some clinical studies reported the potential for these tears to heal without surgical treatment.[11,16]

There are limited data on the surgically relevant anatomy of the posterior horn of the medial meniscus (PHMM), and there is no consensus on the definition of ramp lesions. Thus, an improved understanding of the

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anatomy of the PHMM may improve (1) the understanding of its importance in tears localized at the PHMM and (2) the anatomic approach to their treatment. Therefore, the purpose of this study was to quantitatively and qualitatively describe the posterior medial meniscus and posteromedial capsule anatomy pertaining to the location of a meniscal ramp lesion with reference to surgically relevant landmarks. It was hypothesized that the meniscocapsular and meniscotibial attachments would have definable parameters concerning their anatomic attachments and consistent relationships to one another, as well as pertinent, surgically relevant landmarks with correlative histologic findings.

METHODS

Specimen Preparation

Fourteen nonpaired fresh-frozen male cadaveric knee specimens (mean age, 61.0 years; range, 54-66 years) with no evidence of prior injury, previous surgery, osteoarthritis, meniscal pathology, or ligament pathology were used for this study. The cadaveric specimens utilized in this study were donated to a tissue bank for the purpose of medical research and then purchased by our institution. All specimens were stored at −20°C and thawed at room temperature 24 hours before preparation. Before testing, each specimen underwent arthrotomy to confirm the absence of intra-articular pathology.

In preparation for potting, the tibial, fibular, and femoral diaphyses were cut 20 cm from the joint line. Sharp dissection to bone was performed; all soft tissues were removed 10 cm distal and proximal to the joint line; and the fibula was fixed to the tibia in its anatomic position. The superficial medial collateral ligament, posterior capsule, semimembranosus tendon, and entire posteromedial corner structures were left intact. The femurs were then sectioned down the midline in the sagittal plane to allow for direct visualization of the meniscal anatomy and corresponding tibial attachments while preserving the femoral attachments. The tibia and fibula were potted in a cylindrical mold filled with PMMA (Fricke Dental International Inc).

Anatomic Measurements

Setup and Measuring Device. The tibia was rigidly clamped to prevent any movement during testing. A coordinate measuring device with a manufacturer-reported repeatability of 0.025 mm (Romer Absolute Arm; Hexagon Metrology) was used to record points in 3-dimensional space with Rhino 5 software (McNeel North America). Point coordinates were imported into Python software (Python Software Foundation), and measurements were calculated with a custom software script. The 3-dimensional anatomic distances and lengths were calculated and broken down into directional components with the knee's main axes: anterior-posterior, medial-lateral, and proximal-distal. The proximal-distal direction was defined with the tibial axis. The medial-lateral direction was defined with the most medial and lateral points of the tibial plateaus. The anterior-posterior axis was defined as being perpendicular to the coronal plane, calculated from the proximal-distal and medial-lateral axes defined earlier. The same investigator (N.N.D.) performed all measurements to decrease interobserver variability. A board-certified orthopaedic surgeon (G.M.) was present during all testing for landmark confirmation.

Landmarks and Measurements. Total meniscal length was calculated by summing the distance between discrete points along the entire periphery of the curved medial meniscus, from the posterior root attachment to the anterior. Based on the geometric data and 3-dimensional points, curved distances and percentages of meniscal attachments were calculated and referenced according to where they attached along the curved meniscal length (posterior to anterior).

The length of the PHMM was measured along the central portion of the meniscus with 5 data points. Parallel to these measurements, the corresponding length of the posterior medial capsular attachment was measured with 5 data points along the periphery of the posterior medial meniscus between its lateral extent and the posterolateral aspect of the posterior oblique ligament (POL). For the meniscotibial attachment to the medial meniscus, the length of the entire structure was measured with 3 data points. Surgically relevant arthroscopic and open landmarks were identified and measured in relation to their attachments on the medial meniscus. Surgically relevant landmarks included the following: the meniscofemoral and meniscotibial attachments of the POL, the meniscofemoral and meniscotibial attachments of the deep medial collateral ligament (dMCL), the anteromedial meniscocapsular attachment, the centers of the anterior and posterior meniscal root attachments, the center of the ACL tibial attachment, the center of the posterior cruciate ligament tibial attachment, the center of the shiny white fibers of the posterior meniscal root tibial attachment, and the capsular attachment of the direct arm of the semimembranosus tendon. In addition, digital calipers were used to measure meniscal width (anterior horn, midbody, posterior horn), meniscal height (posterior

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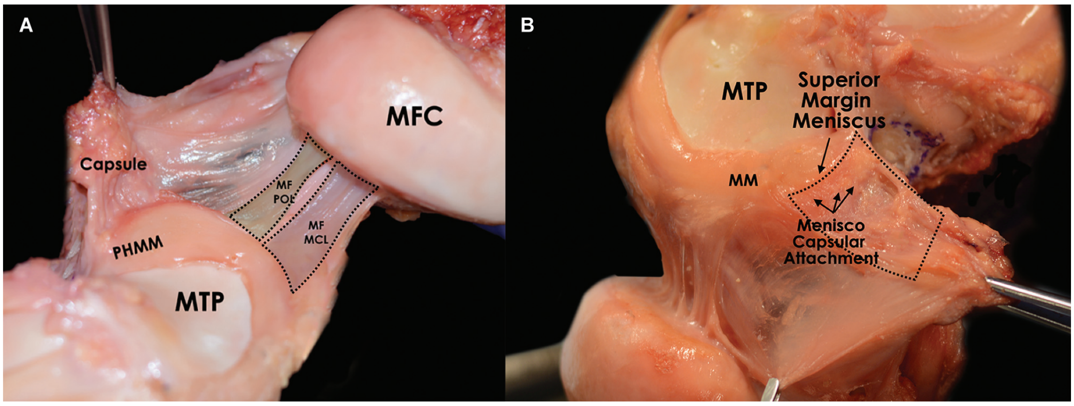

Figure 1. Right knee cadaveric dissection demonstrating (A) the relationship of the posterior medial capsule and meniscofemoral (MF) attachments of the POL and deep MCL to the posterior horn of the medial meniscus (PHMM) and (B) the posterior medial capsule attaching just below the superior margin of the medial meniscus (MM). MCL, medial collateral ligament; MFC, medial femoral condyle; MTP, medial tibial plateau; POL, posterior oblique ligament.

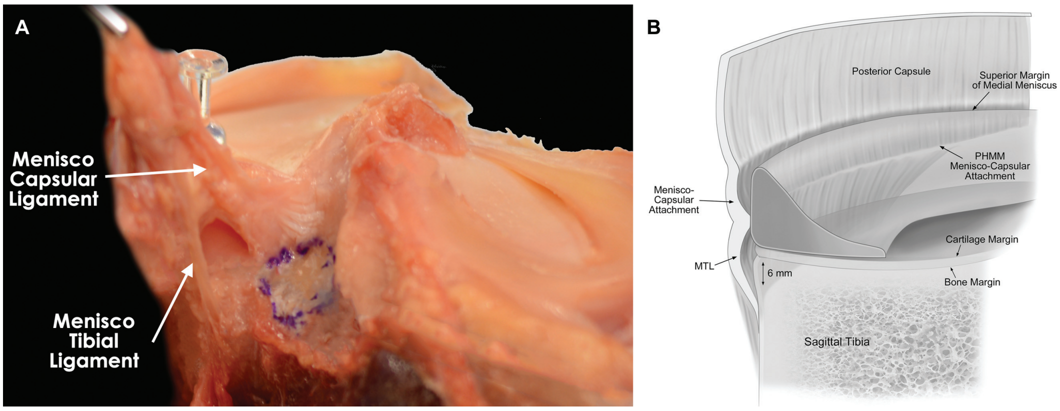

Figure 2. (A) Sagittal view of a cadaveric dissection of the posterior horn medial meniscus (PHMM) anatomy, showcasing the meniscocapsular and meniscotibial ligament (MTL) attachments as they merge to form a common attachment. The posterior cruciate ligament facet is outlined in methylene blue to illustrate the proximity of its tibial attachment. (B) Illustration of the PHMM and shared common attachment of the meniscocapsular ligament and MTL. The MTL attached 5.9 mm distal to the articular cartilage margin of the posterior medial tibial plateau.

horn), and the length and width of the medial tibial plateau. Standard descriptive statistics for all quantified measurements were performed and included the calculation of mean scores and SDs.

Histological Analysis

A sample of 10 nonpaired fresh-frozen male cadaveric knee specimens (mean age, 58.3 years; range, 45-70 years), separate from the specimens used for anatomic measurements, were used for the histological analysis. Tissue specific to the meniscocapsular and meniscotibial attachments of the PHMM was gathered via open dissection of the posterior medial meniscal anatomy by the same board-certified orthopaedic surgeon who confirmed the anatomic landmarks for the descriptive data analysis. All tissues were fixed in 10% neutral-buffered formalin at room temperature for 72 hours, rinsed in phosphate-buffered saline, and stored in phosphate-buffered saline at 4°C before paraffin processing. The tissues were then paraffin processed by hand. Specifically, samples were dehydrated from 75% ethanol, through 100% ethanol, cleared with 3 changes of xylene, and paraffin infiltrated with 3 changes of paraffin wax at 60°C while shaking. Tissues were embedded in

TABLE 1
Mean Dimensions of the Medial Meniscus and Medial Tibial Plateau (n = 14)[a]

Structure	Mean ± SD, mm
Medial meniscal width	
Anterior horn	7.6 ± 1.7
Midbody	9.3 ± 2.6
Posterior horn	12.6 ± 3.3
Height of posterior meniscal width	4.6 ± 1.5
Medial tibial plateau	
Length	49.1 ± 3.1
Width	35.1 ± 3.0

[a]The height of the medial meniscus was measured at the most posterior point along the posterior horn. The length and width of the medial tibial plateau were measured to include the articular cartilage margins.

paraffin, solidified in cassettes on ice, and sectioned at 6-μm widths. Before staining, slides were dried in a 60°C oven for 2 hours, deparaffinized with 2 changes of xylene, and rehydrated to water. Hematoxylin and eosin staining was then conducted to determine the orientation of the meniscocapsular and meniscotibial attachments of the posterior medial meniscus. All images were taken with a Nikon Eclipse Ni-U upright microscope. A histologist reviewed all histological specimens and directly interpreted the results regarding qualitative findings.

RESULTS

Posterior Meniscocapsular Attachment of the Medial Meniscus

The posterior meniscocapsular attachment had a mean ± SD length of 20.2 ± 6.0 mm (range, 11.3-33.2 mm) and did not attach directly to the superior margin of the PHMM. In all specimens, the posterior medial capsule attached inferior to the superior margin of the posterior medial meniscus at a mean depth of 36.4% of the total posterior meniscal height (Figure 1). The PHMM had a mean length of 21.3 ± 2.0 mm (range, 17.6-24.5 mm), essentially confluent with the entire length of the posterior capsule. The dimensions of the medial meniscus and medial tibial plateau are presented in Table 1.

Posterior Meniscotibial Ligament Attachment of the Medial Meniscus

The posterior meniscotibial ligament attachment to the PHMM had a mean length of 14.0 ± 5.4 mm (range, 6.4-27.4 mm) at its insertion on the posterior tibia (Table 2). This structure was identified in all specimens and coursed at an oblique angle from the posterior tibia to its insertion proximal to the inferior edge of the posterior medial meniscus. On average, the most lateral point of the meniscotibial ligament attachment on the posterior medial meniscus was 16.5 mm posterior (range, 12.9-25.6 mm) and 7.7 mm medial (range, 1.7-19.8 mm) to the center of the posterior medial meniscal root attachment. The meniscotibial tibial ligament attachment was located 5.9 ± 1.3 mm inferior (range, 3.7-8.0 mm) to the articular cartilage margin of the posterior medial tibial plateau. The meniscotibial ligament attachment merged with the posterior meniscocapsular attachment to form a common PHMM attachment at the most posterior point of the meniscocapsular junction in all specimens (Figure 2).

TABLE 2
Mean Length of the Meniscocapsular and Meniscotibial Attachments and the PHMM[a]

Structure	Mean ± SD, mm
Meniscocapsular attachment length	20.2 ± 6.0
Meniscotibial attachment length	14.0 ± 5.4
PHMM length	21.3 ± 2.0

[a]PHMM, posterior horn of the medial meniscus.

POL Attachment to the Medial Meniscus

The meniscal attachment of the POL was a direct expansion of the posteromedial capsule (ie, the POL capsular arm[14]) and was located directly between the posterior meniscocapsular attachment and the meniscofemoral dMCL attachment. There were 2 distinct POL structures: one attaching the meniscus to the femur and another attaching it to the tibia. The POL meniscofemoral attachment length was 8.2 ± 2.1 mm (range, 6.0-13.0 mm). The center of the meniscofemoral POL attachment was located 34.1 ± 6.7 mm medial (range, 26.6-48.7 mm) to the posterior medial meniscal root center, corresponding with a mean curved distance of 38.7% of the total meniscal length, from the posterior meniscal root to the anterior meniscal root. The POL meniscotibial attachment length was 9.0 ± 2.3 mm (range, 4.0-13.6 mm), and it inserted 6.7 ± 1.7 mm inferior (range, 3.4-10.1 mm) to the articular cartilage margin of the medial tibial plateau. On a curved distance, the POL meniscotibial attachment was 6.0 ± 3.6 mm anterior and 16.5 ± 4.5 mm medial to the center of the posterior meniscotibial ligament attachment (Figure 3).

dMCL Attachment to Medial Meniscus

The dMCL had a broad, firm attachment to the midbody of the medial meniscus in all specimens. The dMCL meniscofemoral attachment blended with the POL meniscofemoral attachment posteriorly and with the anteromedial capsule anteriorly. The mean length of the dMCL attachment on the medial meniscus was 14.8 ± 3.2 mm (range, 10.0-21.1 mm). The center of the meniscofemoral dMCL attachment was located 45.9 ± 7.0 mm medial to the posterior medial meniscal root center, corresponding with a mean curved distance of 50.5% of the total meniscal length. The meniscotibial attachment of the dMCL was a distinct and separate structure and had a mean length of 17.7 ± 3.4 mm (range, 12.8-24.4 mm), and it inserted 6.4 ± 1.9 mm inferior (range,

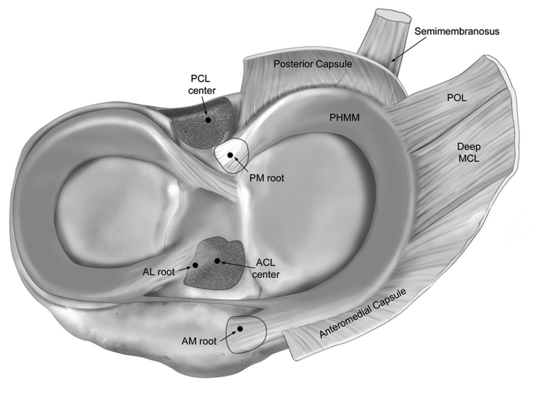

Figure 3. Axial view illustration of the anatomic relationships of the posterior horn of the medial meniscus (PHMM), posterior capsule, posterior oblique ligament (POL), deep medial collateral ligament (MCL), and semimembranosus tendon. The posterior meniscocapsular attachment spanned the entire length of the PHMM and attached at an average depth of 36.4% of the total posterior meniscal height, supporting the potential for a ''hidden'' space for meniscal ramp lesions when the knee is near full extension. ACL, anterior cruciate ligament; AL, anterolateral; AM, anteromedial; PCL, posterior cruciate ligament; PM, posteromedial.

3.6-11.1 mm) to the articular cartilage margin of the medial tibial plateau.

Semimembranosus Tendon

The semimembranosus tendon consisted of 2 main portions: the anterior arm and the direct arm. The semimembranosus tendon had a fascial attachment to the posterior inferior margin of the medial meniscus in 12 of 14 (86%) specimens (Figure 4). This semimembranosus-meniscal attachment branched from the anterior arm of the semimembranosus and was located between the posterior meniscotibial ligament and the meniscotibial POL attachments. The mean length of the fascial attachment of the semimembranosus to the meniscus was 9.2 $\pm$ 2.1 mm (range, 5.1-12.5 mm). The mean curved distance of the semimembranosus attachment was located at 34.0% of the total meniscal length from the posterior medial meniscal root center.

Histology

Hematoxylin and eosin staining of the PHMM demonstrated a well-defined collagen structure and cell distribution that was typical of meniscal structure. Conversely, the meniscocapsular and meniscotibial attachments both demonstrated long fibers organized linearly, which is characteristic of collagen type I–expressing fibroblasts that compose ligaments. Across all specimens, these attachments showed similar structure, cell density, and fiber directionality. No histological differences were observed, and the 2 attachments merged at a common attachment site on the PHMM (Figure 5).

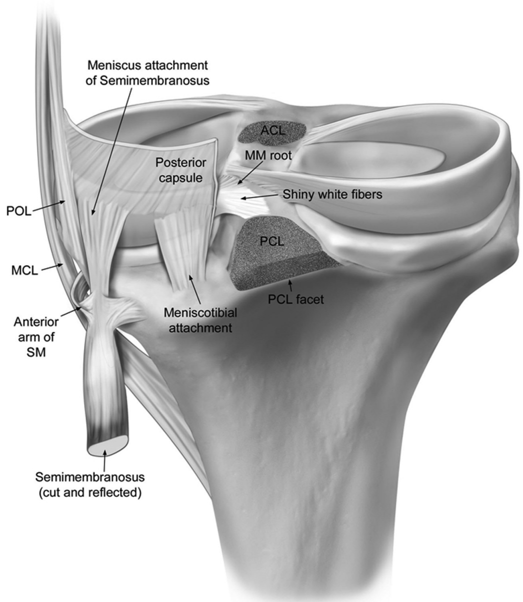

Figure 4. Posterior medial anatomy with the posterior capsule reflected. This figure illustrates the intimate relationship of the static and dynamic structures of the posteromedial corner, including the semimembranosus tendon fascial expansion that attached directly to the posterior horn of the medial meniscus. ACL, anterior cruciate ligament; MCL, medial collateral ligament; MM, medial meniscus; PCL, posterior cruciate ligament; POL, posterior oblique ligament; SM, semimembranosus.

Alcian blue staining of the specimens demonstrated a clear gradient of glycosaminoglycan presence, with high expression in the posterior medial meniscus and decreasing expression moving toward its meniscocapsular and meniscotibial attachments. Glycosaminoglycan expression in the meniscocapsular and meniscotibial attachments was similar and suggested no qualitative difference in the composition of their collagen matrices.

DISCUSSION

The main findings of the present study were that (1) there was a shared common attachment of the meniscocapsular and meniscotibial ligament attachments that merged into the PHMM and (2) there were no histological differences observed between the meniscocapsular and meniscotibial attachments. Additionally, the posterior capsule did not attach directly to the superior portion of the PHMM, providing evidence for the potential location of "hidden" meniscal ramp lesions when the knee is near full

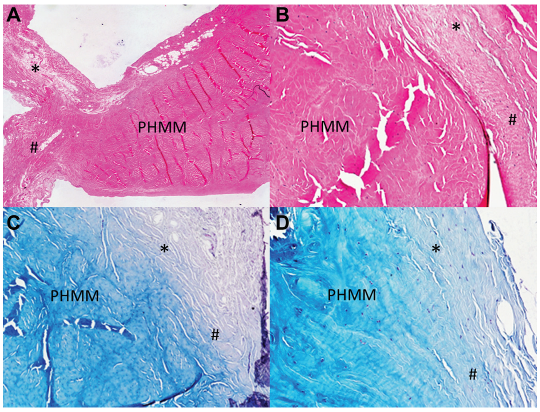

Figure 5. (A, B) Hematoxylin and eosin staining of the capsular and tibial attachments of the PHMM, demonstrating similar appearance of collagen type I and cell density with no observed differences between the attachments. (C, D) Glycosaminoglycan expression in meniscocapsular and meniscotibial attachments was visually similar, with a clear decrease in expression from high to low as the meniscus transitioned toward to the capsular and tibial attachments (anterior to posterior). (A, B) There is no difference in the fiber orientation between the meniscocapsular and meniscotibial attachments of the PHMM, while (C, D) these 2 structures are indistinguishable regarding their collagen composition as they converge and attach to the PHMM. (A) 2× magnification, (B-D) 4× magnification. *Meniscocapsular attachment. #Meniscotibial attachment. PHMM, posterior horn medial meniscus.

extension. Specifically, this hidden area may be responsible for missed diagnoses of ramp tears during preoperative MRI scans, and it further supports the utility of viewing the PHMM posteromedially during arthroscopy to confirm or disprove the presence of a ramp lesion at the time of ACL surgery.

To date, there is no consensus regarding the definition of a ramp lesion, because different anatomic locations have been proposed as the site of injury. Originally, a ramp lesion was defined as a longitudinal tear 2.5 cm in length at the meniscocapsular junction.[22] In the current study, the posteromedial meniscocapsular junction was 2.0 cm long; thus, a 2.5-cm tear may not be an accurate definition for a ramp lesion. Similarly, Ahn et al[2] performed clinical follow-up with second-look arthroscopy and recommended that peripheral tears of the PHMM >1 cm be repaired during concomitant ACL reconstruction. In contrast, Liu et al[16] evaluated clinical outcomes at a mean follow-up of 2 years among patients with ACL reconstruction and concomitant stable ramp lesions <1.5 cm and reported no significant difference in outcomes between trephination and meniscal repair. The authors theorized that all meniscal ramp lesions <1.5 cm in length were stable and thus may not require surgical repair with a concomitant ACL reconstruction.

The anatomic and histologic analysis of the current study demonstrates a shared attachment of the meniscocapsular and meniscotibial structures on the PHMM. Thaunat et al[23] described a classification system for meniscal ramp lesions with 5 types—involving both meniscocapsular separation and meniscotibial ligament disruption, with or without partial tearing at their attachments to the PHMM, as well as tears at the red-red and red-white aspects of the PHMM. Based on the findings of the current study, the previously described classification system may not be appropriate for surgical planning, because a tear in the meniscocapsular or meniscotibial attachment of the PHMM could dictate the same treatment (ie, repair).

The intuitive theories behind inherent knee instability and meniscal ramp lesions are becoming more recognized. If the superior meniscocapsular joint capsule or the inferior meniscotibial ligament is torn, this may create further instability with anterior tibial translation and knee rotation.[1,6,10,17,21] However, from our anatomic and histologic analysis, we found that these 2 structures share a common PHMM attachment; thus, we theorize that the meniscocapsular and meniscotibial attachments may function together as an anatomic unit. A recent biomechanical study supports the aforementioned findings, because there were no significant differences in knee kinematics between a meniscocapsular-based tear and a meniscotibial-based tear in ACL-deficient and ACL-reconstructed knees.[10] This suggests that although ramp lesions may occur in 2 separate locations outside the meniscal substance of the PHMM, instead of at only the meniscocapsular junction of the PHMM as previously described, an inside-out repair of the PHMM may be adequate to address lesions of both structures and restore knee stability.

The POL meniscofemoral attachment was found to be a direct expansion of the posteromedial capsule, located directly between the posterior meniscocapsular attachment and the dMCL meniscofemoral attachment. The POL consists of 3 main fascial attachments that course from the distal semimembranosus tendon, previously termed the *superficial, central*, and *capsular arms*.[12] The central arm forms the main portion of the POL and, with the capsular arm, merges directly with the posteromedial capsule and attaches firmly to the PHMM.[13,14] These quantified anatomic descriptions may be useful for intraoperative planning during anatomic-based repair of POL tears in medial-sided knee injuries.[5]

The dMCL had a broad, firm meniscofemoral and meniscotibial attachment to the midbody of the medial meniscus, located between the meniscofemoral attachment of the POL and the anteromedial capsule.[7,14] The center of the dMCL meniscofemoral attachment was located at the midportion of the medial meniscus, with a mean curved distance of 50.5% of the total meniscal length. The dMCL meniscotibial attachment inserted a mean 6.4 mm inferior to the articular cartilage margin of the medial tibial plateau, which may serve as an anatomic landmark for tibial suture anchor placement during dMCL repairs.

The semimembranosus muscle-tendon complex had a firm attachment to the PHMM in the majority of specimens (86%). This attachment may have a dynamic role in posteromedial corner and medial meniscal stability. However, further biomechanical studies are needed to evaluate this anatomic relationship.

The present study has some limitations inherent to a cadaveric study design. To visualize the medial meniscus for measurements, the femur had to be sectioned sagittally. Although a detailed dissection was performed to clearly visualize the anatomic attachments and fiber orientations, distances were calculated as absolute 3-dimensional vector norms, which do not provide directional information.

CONCLUSION

The anatomy of the area where a medial meniscal ramp tear occurs revealed that the 2 posterior meniscal attachments merged at a common attachment on the PHMM. Histologic analysis validated a shared attachment point of the meniscocapsular and meniscotibial attachments of the PHMM. The findings of this study provide the anatomic foundation for an improved understanding of the role of the meniscocapsular and meniscotibial attachments of the PHMM and the anatomic basis of ramp tears. This will help to refine injury classification and allow for a more precise definition of a meniscal ramp lesion.

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Appendix C

***Paper III* - Biomechanics**

Effect of Meniscocapsular and Meniscotibial Lesions in ACL-Deficient and ACL-Reconstructed Knees

A Biomechanical Study

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Background: Ramp lesions were initially defined as a tear of the peripheral attachment of the posterior horn of the medial meniscus at the meniscocapsular junction. The separate biomechanical roles of the meniscocapsular and meniscotibial attachments of the posterior medial meniscus have not been fully delineated.

Purpose: To evaluate the biomechanical effects of meniscocapsular and meniscotibial lesions of the posterior medial meniscus in anterior cruciate ligament (ACL)–deficient and ACL-reconstructed knees and the effect of repair of ramp lesions.

Study Design: Controlled laboratory study.

Methods: Twelve matched pairs of human cadaveric knees were evaluated with a 6 degrees of freedom robotic system. All knees were subjected to an 88-N anterior tibial load, internal and external rotation torques of 5 N·m, and a simulated pivot-shift test of 10-N valgus force coupled with 5-N·m internal rotation. The paired knees were randomized to the cutting of either the meniscocapsular or the meniscotibial attachments after ACL reconstruction (ACLR). Eight comparisons of interest were chosen before data analysis was conducted. Data from the intact state were compared with data from the subsequent states. The following states were tested: intact (n = 24), ACL deficient (n = 24), ACL deficient with a meniscocapsular lesion (n = 12), ACL deficient with a meniscotibial lesion (n = 12), ACL deficient with both meniscocapsular and meniscotibial lesions (n = 24), ACLR with both meniscocapsular and meniscotibial lesions (n = 16), and ACLR with repair of both meniscocapsular and meniscotibial lesions (n = 16). All states were compared with the previous states. For the repair and reconstruction states, only the specimens that underwent repair were compared with their intact and sectioned states, thus excluding the specimens that did not undergo repair.

Results: Cutting the meniscocapsular and meniscotibial attachments of the posterior horn of the medial meniscus significantly increased anterior tibial translation in ACL-deficient knees at 30° ($P \leq .020$) and 90° ($P < .005$). Cutting both the meniscocapsular and meniscotibial attachments increased tibial internal (all $P > .004$) and external (all $P < .001$) rotation at all flexion angles in ACL-reconstructed knees. Reconstruction of the ACL in the presence of meniscocapsular and meniscotibial tears restored anterior tibial translation ($P > .053$) but did not restore internal rotation ($P < .002$), external rotation ($P < .002$), and the pivot shift ($P < .05$). To restore the pivot shift, an ACLR and a concurrent repair of the meniscocapsular and meniscotibial lesions were both necessary. Repairing the meniscocapsular and meniscotibial lesions after ACLR did not restore internal rotation and external rotation at angles >30°.

Conclusion: Meniscocapsular and meniscotibial lesions of the posterior horn of the medial meniscus increased knee anterior tibial translation, internal and external rotation, and the pivot shift in ACL-deficient knees. The pivot shift was not restored with an isolated ACLR but was restored when performed concomitantly with a meniscocapsular and meniscotibial repair. However, the effect of this change was minimal; although statistical significance was found, the overall clinical significance remains unclear. The ramp lesion repair used in this study failed to restore internal rotation and external rotation at higher knee flexion angles. Further studies should examine improved meniscus repair techniques for root tears combined with ACLRs.

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Clinical Relevance: Meniscal ramp lesions should be repaired at the time of ACLR to avoid continued knee instability (anterior tibial translation) and to eliminate the pivot-shift phenomenon.

Keywords: knee; meniscus; biomechanics; ramp lesion

There has been increasing interest in the biomechanical and clinical effects of lesions of the posterior horn of the medial meniscus, specifically tears at the meniscocapsular junction (termed "ramp" lesions), which have been reported to be present in 9% to 17% of all anterior cruciate ligament (ACL) tears.[2,5,13] Ramp lesions were initially defined as a tear of the peripheral attachment of the posterior horn of the medial meniscus at the meniscocapsular junction.[2,21] However, recent literature suggested that ramp lesions might actually be due to an injury to the meniscotibial ligament attachment to the posterior horn of the medial meniscus.[16,18,19] The meniscotibial ligament is an attachment that originates on the posterior tibia and inserts on the inferior surface of the posterior horn of the medial meniscus.[16,19] The inconsistency in the definition is also a result of the difficulty in diagnosing these tears on magnetic resonance imaging.[2,5,19]

The medial meniscus has been reported to have an essential role in stabilizing the knee in chronically ACL-deficient knees.[1,3,15,17] Posterior medial meniscal tears are reported to increase knee instability in ACL-deficient knees.[1,20] An understanding of the biomechanical effects of tears to the meniscocapsular attachment (MCA) and the meniscotibial attachment (MTA) of the posterior aspect of the medial meniscus in ACL-deficient and ACL-reconstructed knees is still lacking. This information is important in understanding ramp lesions and the roles of the posterior medial meniscal attachments on knee stability. There is controversy over the definition of ramp lesions and whether ramp lesions affect knee kinematics in ACL-reconstructed knees. Persistent instability after ACL reconstruction (ACLR) because of unaddressed concomitant medial meniscal injury will potentially increase forces on the ACL graft, ultimately leading to failure.[1,15,20]

Furthermore, research regarding the biomechanical effectiveness of meniscal ramp repair is limited and has been reported on an all-inside repair technique[20]; however, an inside-out repair has yet to be studied biomechanically for these lesions. Thus, the purpose of this study was to assess the biomechanical effects of sectioning the MCA and MTA of the posterior horn of the medial meniscus in ACL-deficient and ACL-reconstructed knees. We hypothesized that there would be increased anterior tibial translation (ATT) and rotational instability during simulated Lachman testing, pivot-shift testing, and internal/external rotation testing in the presence of untreated medial meniscal ramp lesions and that a repair would restore knee kinematics.

METHODS

Specimen Preparation

Twelve matched pairs (n = 24) of fresh-frozen male cadaveric knee specimens (mean age, 61.0 years; range, 54-66 years) with no evidence of prior injury, previous surgery, osteoarthritis, or meniscus or ligament injury were used for this study. Institutional review board approval was not required because deidentified cadaveric specimens are exempt from review at our institution. The cadaveric specimens utilized in this study were donated to a tissue bank for the purpose of medical research and then purchased by our institution. All specimens were stored at −20°C and thawed at room temperature 24 hours before preparation. Before testing, each specimen underwent a diagnostic arthroscopy to confirm the absence of intra-articular pathology. The posterior horn of the medial meniscus was visualized through a standard anterolateral portal and an accessory posteromedial portal.

In preparation for potting, the tibial, fibular, and femoral diaphyses were cut 20 cm from the joint line. Sharp dissection to bone was performed; all soft tissues were removed 10 cm distal and proximal to the joint line; and the fibula was fixed to the tibia in its anatomic position. The tibia, fibula, and femur were potted in a cylindrical mold filled with PMMA (polymethyl methacrylate; Fricke Dental International Inc). During specimen preparation for each knee, range of motion (flexion-extension and internal-external rotation) was actively tested to detect and reduce the potential effect of joint stiffness and rigidity.

Robotic Testing Setup

Each knee was held in an inverted orientation, with the potted distal end secured in a custom-made fixture

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Figure 1. Schematic representation of the robotic setup with the inverted knee mounted in the testing system.

mounted onto a universal force/torque sensor (Delta F/T Transducer; ATI Industrial Automation) attached to the end effector of a 6 degrees of freedom robotic arm (Kuka KR-60-3; Kuka Robotics). The potted femur was then rigidly fixed onto a stationary pedestal (Figure 1). Next, the stylus tip of a portable measuring arm (Romer Absolute Arm, Hexagon Metrology; manufacturer-reported point repeatability, 0.025 mm) was used to define the knee joint coordinate system by collecting points at the medial- and lateral-most aspects of the tibial plateau, at the medial and lateral femoral epicondyles, and along the tibial diaphysis.[12,25] The coordinate system defined the knee joint center of rotation and the anterior-posterior, medial-lateral, and superior-inferior axes. Before testing, each knee was robotically subjected to a full passive path motion (0° to 120° of flexion) with minimal forces and torques on all axes. The native passive path of the knee in neutral rotation was recorded from full extension to 120° in 1° increments with minimized forces (<5 N) and torques (<0.5 N·m) in the remaining 5 degrees of freedom. A 10-N compressive load was applied along the axis of the tibial shaft to ensure tibiofemoral contact throughout testing. This robotic testing setup was previously described and validated for knee joint kinematic testing.[10,11] The average time of testing for 1 specimen was approximately 4 hours.

Biomechanical Testing

The intact state was tested first in all knees, followed by the ACL cut state. The knees of each pair were then randomly assigned to either cutting MTA first or MCA first, after the ACL sectioning. For knees that underwent MTA sectioning first, the MCA was sectioned next, and for those that underwent meniscocapsular sectioning first, the MTA was sectioned next such that all knees had both the MTA and the MCA sectioned. The ACL was then reconstructed in all knees, followed by repair of the MCA and MTA. The following states were tested: intact (n = 24), ACL deficient (n = 24), ACL deficient with a meniscocapsular lesion (n = 12), ACL deficient with a meniscotibial lesion (n = 12), ACL deficient with both meniscocapsular and meniscotibial lesions (n = 24), ACLR with both meniscocapsular and meniscotibial lesions (n = 16), and ACLR with repair of both meniscocapsular and meniscotibial lesions (n = 16). After the first 8 specimens were tested,

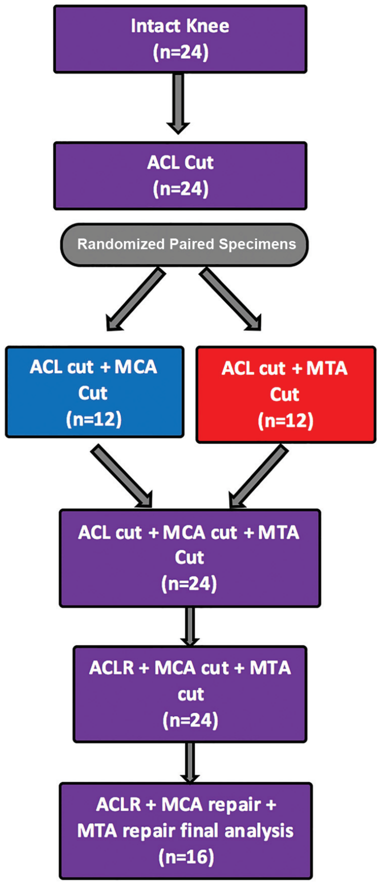

Figure 2. Flowchart depicting the order of biomechanical testing states for all specimens per randomization. ACL, anterior cruciate ligament; ACLR, anterior cruciate ligament reconstruction; MCA, meniscocapsular attachment; MTA, meniscotibial attachment.

all specimens underwent a posttest arthrotomy to assess the success of the outside-in repair technique utilized. In all 8 specimens, the repairs were found to have failed, and the repair technique was switched to an inside-out repair in the robot. Posttesting arthrotomy of all remaining specimens (n = 16) demonstrated a successful repair of the meniscocapsular and meniscotibial lesion. The postrepair testing of the initial 8 specimens was not included in the final analysis (ACLR, MCA repair, MTA repair) (Figure 2).

The knees were subjected to the following testing conditions: anterior tibial load of 88 N, internal and external rotation torques of 5 N·m, and a simulated pivot-shift test of 10-N valgus force coupled with 5-N·m internal rotation torque as previously described.[8] ATT was tested at 30° and 90°, simulated pivot-shift test at 15° and 30°, and internal/external rotation at 0° to 90° with 15° increments. For each state, anterior tibial displacement, internal rotation, and external rotation were compared with the intact state for all testing conditions.

Surgical Technique

An anatomic single-bundle ACLR was performed in all specimens as previously described.[10] The ACL was reconstructed with a bone–patellar tendon–bone allograft with 10-mm bone blocks. To create an MCA lesion, the knee was flexed to 90°; a scalpel was then inserted through the posteromedial portal; and a tear was made in the meniscocapsular junction, extending 2.5 cm medially from the medial meniscal root attachment. The meniscocapsular lesion was repaired with an arthroscopic-assisted inside-out technique with 4 to 6 meniscal sutures (No. 2 FiberWire; Arthrex, Inc) with the knee in the robot at 90° of flexion (Figure 3).

To simulate the MTA lesion, a longitudinal posterior approach was performed with a dissection made between the gastrocnemius muscle heads. The posterior capsule, oblique popliteal ligament, champagne glass drop-off, and the semimembranosus tendon were visualized. A horizontal incision was made through the distal capsule, medial to the posterior cruciate ligament tibial facet and 1.5 cm distal to the joint line. The MTA was detached with a scalpel from this point to the level of the semimembranosus tibial attachment on the tibia (Figure 4). The meniscotibial lesion was repaired with the knee in full extension, with 2 suture anchors (SwiveLock; Arthrex, Inc) placed in the proximal aspect of the medial tibial plateau and reinforced with 2 No. 2 FiberWire sutures to restore the MTA (Figure 5). All meniscal lesions, repairs, and ACLRs were performed by 2 board-certified orthopaedic surgeons (G.M., J.C.) with experience in arthroscopy and meniscal surgery. The same 2 board-certified surgeons have performed several knee biomechanical studies and anatomy studies.

Statistical Analysis

Eight comparisons of interest were chosen before data analysis was conducted (Table 1). For this study, statistical power was considered in the context of a detectable effect size (Cohen *d*), given the fixed study design and sample size. Based on an overall alpha level of .05 with Bonferroni correction for 8 comparisons and 2-tailed testing, repeated measures comparisons of group means involving 12, 16, and 24 specimens are sufficient to detect effect sizes of 1.29, 1.06, and 0.82 with 80% statistical power, respectively.

Data were analyzed after subtracting each specimen's intact values. For the repair and reconstruction states, only the specimens that underwent repair were compared with their intact and sectioned states, thus excluding the specimens that did not undergo repair. Because all measurement variables were reasonably normally distributed and the comparisons included different sample sizes, paired *t* tests were used to make all comparisons among knee conditions. The Holm method was used to control the family-wise type I error rate to .05 within each experiment and flexion angle combination, and Holm-adjusted P values were presented. The design of the experiment is presented in Figure 2. Adjusted P values <.05 were deemed statistically significant. The statistical software R was used for all analyses (R Foundation for Statistical Computing with *ggplot2*).[7]

RESULTS

ATT During an 88-N Anterior Load

Cutting the MCA significantly increased ATT in ACL-deficient knees by 0.5 mm and 0.8 mm at 30° and 90°, respectively (both $P < .005$). Cutting the MTA significantly increased ATT in ACL-deficient knees but to a lesser degree (Table 2). Cutting both the MCA and MTA significantly increased ATT in ACL-deficient knees ($P < .001$). Reconstruction of the ACL in the presence of MCA and MTA tears restored ATT relative to the intact state at both 30° and 90° (both $P > .05$).

Internal Tibial Rotation During a 5-N·m Internal Rotation Torque

Cutting the MCA significantly increased tibial internal rotation between 30° and 90° (all $P < .04$), while cutting the MTA increased internal tibial rotation at all flexion angles (all $P < .005$) in ACL-deficient knees. Cutting both the MCA and MTA significantly increased internal rotation at all flexion angles (all $P < .001$) (Appendix Table A1, available in the online version of this article). Reconstruction of the ACL in the presence of meniscocapsular and meniscotibial lesions did not restore internal rotation (all $P < .003$). Anterior cruciate reconstruction with repair of the MCA and MTA restored internal rotation to the intact state at 0° to 15° but did not at 30° to 90° (all $P < .001$) (Figure 6).

External Tibial Rotation During a 5-N·m External Rotation Torque

Cutting the MCA significantly increased tibial external rotation by 0.7° to 1.0° at all flexion angles (all $P < .004$),

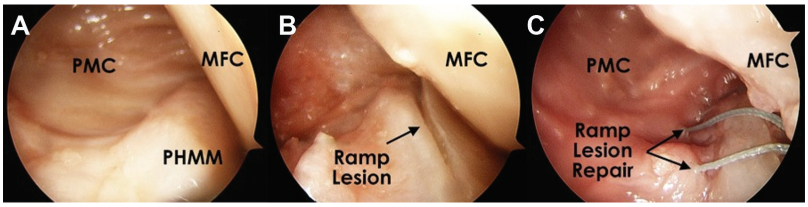

Figure 3. Arthroscopic image of a meniscocapsular lesion. (A) Intact meniscocapsular junction with camera inserted through the intercondylar notch. (B) With an accessory posteromedial portal, a scalpel was inserted and used to re-create a meniscocapsular tear. (C) Inside-out meniscal repair with sutures placed in a vertical mattress fashion, first through the posterior horn of the medial meniscus and second through the posteromedial capsule. MFC, medial femoral condyle; PHMM, posterior horn medial meniscus; PMC, posteromedial capsule.

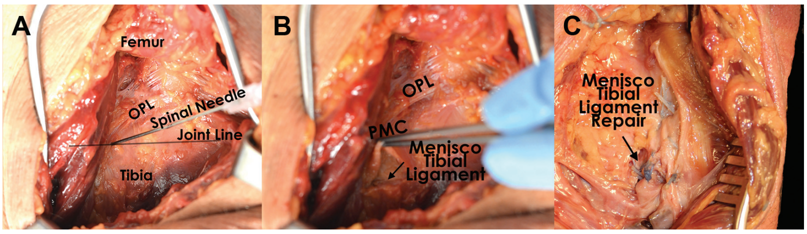

Figure 4. Open image of a meniscotibial lesion. (A) Open posterior dissection with intact meniscotibial ligament and pertinent landmarks. (B) To identify the meniscotibial ligament, an 18-gauge spinal needle was inserted into the posteromedial joint line, and an incision was made approximately 1 cm medial to the posterior cruciate ligament tibial facet and 1.5 cm from the joint line. A scalpel was then inserted directly inferior to the meniscus, and a cut was made on the fibers attaching the meniscus to the tibia to re-create a meniscotibial ligament tear. (C) Open posterior repair of the meniscotibial attachment with the knee in full extension with 2 suture anchors placed in the proximal aspect of the medial tibial plateau. OPL, oblique posterior ligament; PMC, posteromedial capsule.

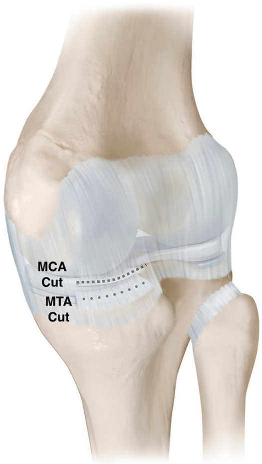

Figure 5. Illustration of the tear locations for the meniscocapsular and meniscotibial attachments. MCA, meniscocapsular attachment; MTA, meniscotibial attachment.

TABLE 1
Comparison of Test States for Statistical Analysis[a]

	n[b]
ACL cut, MCA and MTA intact	
ACL cut, MCA cut, MTA intact	12
ACL cut, MTA cut, MCA intact	12
ACL cut, MCA and MTA cut	24
ACLR, MCA and MTA cut	
ACL cut, MCA and MTA cut	24
ACLR, MCA and MTA repair	16
ACL cut, MCA and MTA cut: ACLR, MCA and MTA repair	16
Intact knee	
ACLR, MCA and MTA cut	24
ACLR, MCA and MTA repair	16

[a]The meniscus repair failed in 8 knees; thus, 16 knees were analyzed for final MCA and MTA repair. ACL, anterior cruciate ligament, ACLR, anterior cruciate ligament reconstruction; MCA, meniscocapsular attachment; MTA, meniscotibial attachment.
[b]The number of specimens used in a given repeated measures comparison.

TABLE 2
Anterior Tibial Translation During an 88-N Anterior Tibial Load for the Different Testing States[a]

	Anterior Tibial Translation,[b] mm			
	MCA 30°	MCA 90°	MTA 30°	MTA 90°
Intact (n = 24)	6.7 ± 2.4	4.5 ± 2.0	5.7 ± 1.7	3.9 ± 1.7
ACL cut (n = 24)	9.1 ± 3.4	5.1 ± 2.1	9.1 ± 2.9	5.7 ± 2.7
ACL cut + meniscocapsular cut + meniscotibial intact (n = 12)	9.9 ± 3.6	5.6 ± 2.3	NA	NA
ACL cut + meniscocapsular intact + meniscotibial cut (n = 12)	NA	NA	9.4 ± 3.0	5.9 ± 2.7
ACL cut + meniscocapsular cut + meniscotibial cut (n = 24)	10.2 ± 3.7	5.8 ± 2.4	9.8 ± 3.1	6.2 ± 2.9
ACLR + meniscocapsular cut + meniscotibial cut (n = 24)	–0.6 ± 1.7	1.0 ± 1.0	–0.3 ± 1.0	0.3 ± 1.4
ACLR + meniscocapsular repair + meniscotibial repair (n = 16)	–0.5 ± 1.8	0.9 ± 1.3	–0.3 ± 0.9	0.1 ± 1.3

[a]All values (mean ± SD) are reported as intact subtracted, with negative values interpreted as less knee motion as compared with the intact. In the MCA group, the MCA was sectioned first, followed by the MTA. In the MTA group, the MTA was sectioned first, followed by the MCA. The meniscus repair failed in 8 knees; thus, 16 knees were analyzed for final MCA and MTA repair. ACL, anterior cruciate ligament, ACLR, anterior cruciate ligament reconstruction; MCA, meniscocapsular attachment; MTA, meniscotibial attachment; NA, not applicable.
[b]By testing group and knee flexion angle.

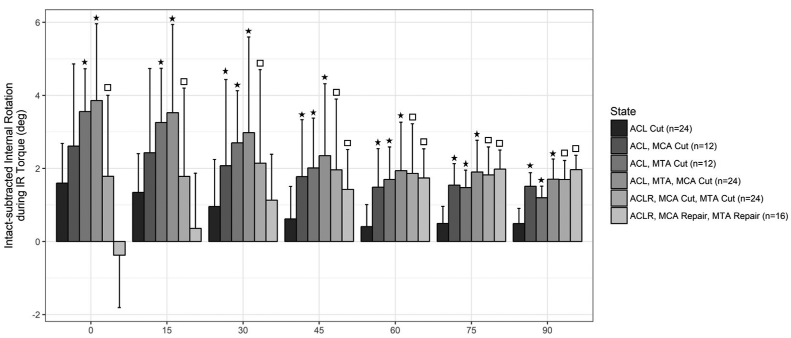

Figure 6. Changes in tibial internal rotation (IR) during a 5-N·m IR torque for the different testing states. ACL, anterior cruciate ligament; ACLR, anterior cruciate ligament reconstruction; MCA, meniscocapsular attachment; MTA, meniscotibial attachment. An asterisk (*) indicates a significant difference from the ACL-deficient state. The ACLR and repair states were compared with the intact state, and a square (□) indicates significant difference versus the intact state. Values (mean ± SD) are presented as intact subtracted, with negative values interpreted as less knee motion as compared with the intact.

and cutting the MTAs also increased external tibial rotation at all flexion angles (all $P < .001$) in ACL-deficient knees. Cutting both the MCA and MTA significantly increased external tibial rotation at all flexion angles (all $P < .001$) as compared with the intact state (Table 3). Reconstruction of the ACL in the presence of meniscocapsular and meniscotibial lesions did not restore tibial external rotation to intact state at all flexion angles (all $P < .003$). Reconstruction of the ACL and repair of meniscocapsular and meniscotibial lesions overconstrained the knee at 0° and restored external rotation to the intact state at 15° but not from 30° to 90° (Figure 7).

Simulated Pivot-Shift Test

Cutting either the MCA or the MTA in ACL-deficient knees significantly increased ATT and internal rotation during a simulated pivot-shift test at 15° and 30° of knee flexion (Table 4). Cutting both the MCA and the MTA significantly increased ATT and internal rotation during a simulated pivot-shift test in ACL-deficient knees (all $P < .001$). Reconstruction of the ACL alone in the presence of meniscocapsular and meniscotibial lesions did not restore pivot shift to the intact state ($P < .05$). Reconstruction of the ACL and repair of the meniscocapsular and meniscotibial lesions restored ATT during a pivot-shift test to a near-intact state at 15° ($P > .99$) and 30° ($P = .116$). Reconstruction of the ACL and repair of the meniscocapsular and meniscotibial lesions restored internal rotation during a simulated pivot-shift test to the intact state at 15° ($P = .309$) but not at 30° ($P < .001$).

DISCUSSION

The main findings of this study were that tears to both the MCA and the MTA of the posterior horn of the medial meniscus resulted in increased ATT, internal rotation,

TABLE 3
Tibial External Rotation During a 5-N·m External Rotation Torque for the Different Testing States[a]

	Group	External Rotation,[b] deg						
		0°	15°	30°	45°	60°	75°	90°
ACL cut (n = 12)	MCA	–0.2 ± 0.3	–0.3 ± 0.4	–0.1 ± 0.3	–0.2 ± 0.3	–0.1 ± 0.4	–0.4 ± 0.4	–0.4 ± 0.5
ACL cut (n = 12)	MTA	–0.2 ± 0.2	–0.1 ± 0.3	–0.4 ± 0.4	–0.2 ± 0.5	–0.3 ± 0.4	–0.3 ± 0.4	–0.4 ± 0.5
ACL cut + meniscocapsular cut + meniscotibial intact (n = 12)	MCA	–1 ± 0.4	–1 ± 0.5	–1.1 ± 0.5	–1.1 ± 0.5	–1.1 ± 0.5	–1.3 ± 0.8	–1.4 ± 0.6
ACL cut + meniscocapsular intact + meniscotibial cut (n = 12)	MTA	–0.9 ± 0.3	–0.8 ± 0.4	–0.9 ± 0.5	–0.9 ± 0.5	–0.9 ± 0.5	–0.9 ± 0.6	–1 ± 0.6
ACL cut + meniscocapsular cut + meniscotibial cut (n = 12)	MCA	–1.5 ± 0.9	–1.5 ± 0.9	–1.5 ± 0.9	–1.4 ± 0.7	–1.4 ± 0.6	–1.6 ± 0.9	–1.7 ± 1
ACL cut + meniscocapsular cut + meniscotibial cut (n = 12)	MTA	–1 ± 0.4	–1 ± 0.5	–1.1 ± 0.5	–1.2 ± 0.6	–1.2 ± 0.6	–1.3 ± 0.7	–1.3 ± 0.8
ACLR + meniscocapsular cut + meniscotibial cut (n = 12)	MCA	–1.1 ± 0.8	–1.2 ± 0.8	–1.4 ± 0.9	–1.4 ± 0.8	–1.5 ± 0.7	–1.7 ± 0.9	–1.8 ± 1.1
ACLR + meniscocapsular cut + meniscotibial cut (n = 12)	MTA	–0.7 ± 0.6	–0.7 ± 0.8	–1.1 ± 0.5	–1.1 ± 0.4	–1.3 ± 0.6	–1.3 ± 0.7	–1.4 ± 0.8
ACLR + meniscocapsular repair + meniscotibial repair (n = 8)	MCA	1.7 ± 1.4	0.2 ± 1	–0.8 ± 0.5	–1 ± 0.5	–1.2 ± 0.5	–1.5 ± 1	–1.5 ± 0.8
ACLR + meniscocapsular repair + meniscotibial repair (n = 8)	MTA	0.6 ± 1.1	–0.3 ± 1.1	–0.8 ± 0.7	–0.9 ± 0.6	–1.1 ± 0.8	–1.1 ± 1.1	–1.2 ± 1.2

[a]All values (mean ± SD) are reported as intact subtracted, with negative values interpreted as less knee motion as compared with the intact. In the MCA group, the MCA was sectioned first, followed by the MTA. In the MTA group, the MTA was sectioned first, followed by the MCA. The meniscal repair failed in 8 knees; thus, 16 knees were analyzed for final MCA and MTA repair. ACL, anterior cruciate ligament; ACLR, anterior cruciate ligament reconstruction; MCA, meniscocapsular attachment group; MTA, meniscotibial attachment group.
[b]By knee flexion angle.

external rotation, and pivot shift in ACL-deficient knees. Patients with high-grade Lachman and pivot-shift test results in the presence of an ACL tear and those with persistent instability after an ACLR should be evaluated for a potential ramp lesion of the posterior horn of the medial meniscus. In addition, the repair technique used in this study could restore the pivot shift at lower flexion angles, yet it failed to restore internal and external rotation at higher flexion angles. Future research should evaluate different repair techniques that can further restore rotational stability at higher flexion angles.

Meniscal ramp lesions have been defined as vertical tears in the meniscocapsular junction associated with ACL tears, and recent studies suggest detrimental effects in knee stability if these lesions are not addressed at time of surgery. Muriuki et al[14] described changes in tibiofemoral contact pressures after vertical tears of the posterior horn of the medial meniscus as compared with radial split tears. The authors concluded that vertical tears of the medial meniscus increased contact pressure and reduced contact area in the medial and lateral compartments, with no difference as compared with a total medial meniscectomy. In 2001, Papageorgiou et al[15] demonstrated the biomechanical interdependence between the ACL-reconstructed graft and the medial meniscus. They reported increased force up to 54% in the ACL-reconstructed graft after a medial meniscectomy, further advocating the potential for increased ACL graft failure with medial meniscal deficiency. Recent data suggest that medial meniscocapsular tears, when left untreated, predispose the ACL-reconstructed knee to increased ATT and potential increased strain in the ACL-reconstructed graft[20] (unpublished data, C. Edgar, MD, PhD, 2015).

In the present study, cutting the MCA and MTA significantly increased ATT in ACL-deficient knees. Ahn et al[1] evaluated the effect of sectioning the MCA and reported significant increases in ATT at all flexion angles except 90°, and this was improved after repair of the lesions, supporting the findings of the present study that meniscocapsular lesions increase instability in ACL-deficient knees. Interestingly, in the study by Ahn et al, lesions of the MCA resulted in comparable changes in ATT in ACL-deficient knees to total medial meniscectomy. These findings were supported by Stephen et al,[20] who reported increased ATT after creation of meniscocapsular lesions in ACL-deficient knees, which were not restored by ACLR alone. Repair of the meniscocapsular lesions and ACLR were necessary to restore knee kinematics. However, in the present study, ACLR restored ATT to a near intact state. Peltier et al[16] reported an increase in ATT during anterior tibial load after sectioning of the ACL, MCA, and MTA, as compared with the intact state. However, sectioning the MCA and MTA in ACL-deficient knees did not significantly change ATT.[16] The authors reported an increase of 2.6 mm in ATT after sectioning the MCA in ACL-deficient knees, but this was not statistically significant. In contrast, the current study reports a significant increase of 0.8 mm of ATT for the same states. This statistical discrepancy can perhaps be explained by the total sample size used in each study (n = 9 vs n = 16) and by the measurement devices used (Rolimeter with manual forces vs a 6 degrees of freedom

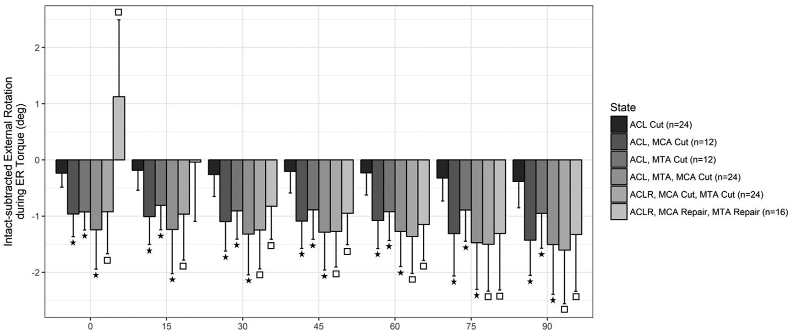

Figure 7. Changes in tibial external rotation (ER) during a 5-N·m ER torque for the different states. ACL, anterior cruciate ligament; ACLR, anterior cruciate ligament reconstruction; MCA, meniscocapsular attachment; MTA, meniscotibial attachment. An asterisk (*) indicates a significant difference from the ACL-deficient state. The ACLR and repair states were compared with the intact state, and a square (□) indicates significant difference versus the intact state. Values (mean ± SD) are presented as intact subtracted, with negative values interpreted as less knee motion as compared with the intact.

robotic system). Previous research showed a side-to-side difference as small as 3 mm with a maximum manual force with a KT-1000 arthrometer to be indicative of ACL tears[9,23]; thus, the 0.8 mm achieved with an 88-N load in the current study seems practical for increased ATT. However, the ACL is the primary stabilizer for ATT, and when it is adequately reconstructed, the changes in ATT after creation of a ramp lesion may not be significant as observed in the present study.

Cutting both the MCA and the MTA of the posterior horn of the medial meniscus significantly increased internal rotation, external rotation, and pivot shift in ACL-deficient knees. These findings suggest that injuries to the MCA and/or MTA of the medial meniscus can cause increased knee rotation and translation. In the present study, ACLR in the presence of meniscocapsular and meniscotibial lesions did not restore pivot shift, which was restored only after an ACLR was performed and the meniscocapsular and meniscotibial lesions were repaired. These findings imply that patients with an ACL tear and a concomitant ramp lesion may have a high-grade pivot shift on examination, and if the meniscal lesion is not repaired during ACLR, these patients may have persistent rotational instability. The medial meniscus is firmly attached to the posterior margin of the tibial plateau,[24] resulting in the meniscus acting as a secondary stabilizer for anterior translation and tibial rotation in ACL-deficient knees. Peltier et al[16] reported significantly increased tibial internal rotation and external rotation after sectioning both the MCA and the MTA. Ahn et al[1] reported no significant change in tibial rotation after creating a meniscocapsular lesion in an ACL-deficient knee. Studies by Ahn et al[1] and Peltier et al[16] focused on ACL-deficient knees—as opposed to ACL-reconstructed knees in the present study (because most surgeons reconstruct ACLs)—but there is a controversy over the repair of ramp lesions. Stephen et al[20] reported no significant change in internal rotation after creating a meniscocapsular lesion in ACL-deficient knees; however, external rotation was increased across all flexion angles in the same testing state. These were restored after repair of the meniscocapsular lesion. In the present study, repair of the meniscocapsular and meniscotibial lesions did not restore internal and external tibial rotations at angles >30°. It is possible that our repair did not restore internal/external rotation at angles >30° because the meniscocapsular lesions were not fixed in full knee extension. Fixing the meniscocapsular lesion in extension with an inside-out repair with a patient in the supine position can be challenging. Tying the sutures at 90° better reflects what is performed in surgery with a meniscocapsular repair with the patient supine. However, since the skin and other soft tissues were not present and thus would not limit exposure as they would clinically, it is probable that our repair was more secure and taut than what would be created clinically. Furthermore, of clinical importance, the meniscotibial lesion was repaired with the knee near full extension, with the capsule taut. Future studies should examine improved meniscus repair techniques for ramp lesions combined with ACLRs.

There is still controversy about the definition of a ramp lesion. Smigielski et al[18] reported that the superior part of the medial meniscal posterior horn had no capsular attachment, while the inferior part was attached to the tibia via the meniscotibial ligament. This led some authors to argue that ramp lesions involve the MTA of the medial meniscus.[16] It is also not clearly defined in the literature whether ramp lesions are complete or partial tears of the peripheral posterior horn.[22] Complete tears could have similar biomechanical effects to tears involving the MTA because of the loss of the bony attachment from the meniscus to the tibia, resulting in meniscal displacement. Biomechanical studies have used different methods of creating meniscocapsular lesions, which can lead to different findings.[1,20] It is also possible that ramp lesions are not all the same, and a thorough evaluation of each tear should be performed. Furthermore, more studies are needed to

TABLE 4
Changes in ATT and Tibial IR During a Simulated Pivot-Shift Test for the Different Testing States at 15° and 30° of Knee Flexion[a]

	Pivot Shift (ATT),[b] mm			
	MCA 15°	MCA 30°	MTA 15°	MTA 30°
ACL cut (n = 24)	1.5 ± 1.7	0.9 ± 1.8	1.4 ± 0.9	1.0 ± 0.7
ACL cut + meniscocapsular cut + meniscotibial intact (n = 12)	2.6 ± 2.6	2.0 ± 2.6	NA	NA
ACL cut + meniscocapsular intact + meniscotibial cut (n = 12)	NA	NA	3.6 ± 1.9	2.9 ± 1.8
ACL cut + meniscocapsular cut + meniscotibial cut (n = 24)	3.9 ± 3.5	3.0 ± 3.6	3.8 ± 1.9	3.1 ± 1.9
ACLR + meniscocapsular cut + meniscotibial cut (n = 24)	2.7 ± 3.6	3.0 ± 3.6	2.3 ± 1.9	2.8 ± 1.8
ACLR + meniscocapsular repair + meniscotibial repair (n = 16)	0.6 ± 1.8	2.0 ± 1.6	1.0 ± 1.6	1.9 ± 1.1
	Pivot Shift (IR),[b] deg			
ACL cut (n = 24)	4.4 ± 3.0	3.6 ± 4.0	4.6 ± 1.7	4.0 ± 1.9
ACL cut + meniscocapsular cut + meniscotibial intact (n = 12)	5.2 ± 3.6	4.4 ± 4.4	NA	NA
ACL cut + meniscocapsular intact + meniscotibial cut (n = 12)	NA	NA	5.7 ± 1.8	4.8 ± 2.2
ACL cut + meniscocapsular cut + meniscotibial cut (n = 24)	6.0 ± 4.1	4.9 ± 4.7	6.0 ± 1.8	5.3 ± 2.3
ACLR + meniscocapsular cut + meniscotibial cut (n = 24)	1.5 ± 3.7	2.0 ± 3.6	1.4 ± 1.9	2.0 ± 1.7
ACLR + meniscocapsular repair + meniscotibial repair (n = 16)	–0.7 ± 2.7	1.2 ± 2.7	0.1 ± 1.6	1.3 ± 1.3

[a]All values (mean ± SD) are reported as intact subtracted, with negative values interpreted as less knee motion compared with the intact. In the MCA group, the MCA was sectioned first, followed by the MTA. In the MTA group, the MTA was sectioned first, followed by the MCA. The meniscus repair failed in 8 knees; thus, 16 knees were analyzed for final MCA and MTA repair. ACL, anterior cruciate ligament; ACLR, anterior cruciate ligament reconstruction; ATT, anterior tibial translation; IR, internal rotation; MCA, meniscocapsular attachment; MTA, meniscotibial attachment; NA, not applicable.
[b]By testing group and knee flexion angle.

elucidate the anatomy of the menisci and the attachments of the medial meniscus to the capsule and tibia.

Meniscal ramp repair has been described with all-inside devices,[20] a hybrid technique with all-inside and outside-in repair via an accessory posteromedial portal,[22] and an inside-out repair technique.[6] Inside-out repair was reported to allow for more versatility in repairing the meniscus with an arguably stronger construct, because the meniscus is sutured directly to the capsule.[4,6] A previous laboratory study demonstrated that an all-inside repair technique for meniscal ramp lesions was able to restore knee kinematics.[20] In contrast, the repair techniques (inside-out meniscocapsular and open meniscotibial) utilized in the current study failed to restore knee kinematics at higher knee flexion angles. To our knowledge, this is the first biomechanics study to examine the effects of a meniscotibial ligament repair and an inside-out repair of a meniscocapsular lesion. Currently, there is limited understanding on the posterior horn of the medial meniscal stabilizers. In the present study, both the MCA and the MTA were found to have an important role in stabilizing the knee joint. The findings of the current study suggest that it is important to diagnose and treat both meniscocapsular and meniscotibial ramp lesions.

We acknowledge some limitations to this study. Inherent to a time-zero cadaveric study, the results do not reflect the biological incorporation of the ACL graft and its effects on reconstruction performance. The opening in the capsule, which was created to perform the MTA cut, could have contributed to the measured laxity, and this was not measured. Furthermore, the multiple testing conditions may produce certain laxity in the surrounding soft tissue structures. However, this effect was limited by randomizing the order of the testing. In addition, we limited the effect of dependent variables by using the same materials and commercially prepared allografts for every reconstruction. Also, several pilot tests were performed to establish reproducible and highly accurate testing procedures with a 6 degrees of freedom robotic system.

CONCLUSION

Meniscocapsular and meniscotibial lesions of the posterior horn of the medial meniscus increased knee ATT, internal and external rotation, and the pivot shift in ACL-deficient knees. The pivot shift was not restored with an isolated ACLR but was restored when performed concomitantly with a meniscocapsular and meniscotibial repair. However, the effect of this change was minimal; although statistical significance was found, the overall clinical significance remains unclear. The ramp lesion repair failed to restore internal rotation and external rotation at higher knee flexion angles. Further studies should examine improved meniscal repair techniques for root tears combined with ACLRs.

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Appendix D

***Paper IV* – Survey**

Original Research

Current Trends Among US Surgeons in the Identification, Treatment, and Time of Repair for Medial Meniscal Ramp Lesions at the Time of ACL Surgery

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Investigation performed at The Steadman Clinic, Vail, Colorado, USA

Background: Given the potential hidden nature of medial meniscal ramp lesions and the controversy regarding treatment, it is important to understand the current trends regarding the identification and treatment strategies of meniscal ramp lesions by the leading surgeons and educators in the field of sports medicine.

Purpose: To better understand the current trends in orthopaedic surgery regarding arthroscopic identification and treatment of medial meniscal ramp lesions at the time of anterior cruciate ligament (ACL) surgery.

Study Design: Cross-sectional study.

Methods: An electronic questionnaire was sent in a blinded fashion to 91 directors of orthopaedic sports medicine fellowship training programs in the United States. Participants' email addresses were obtained through the American Orthopaedic Society for Sports Medicine directory of current fellowship program directors. Inclusion criteria were only those surgeons who currently performed ACL reconstruction surgery. Exclusion criteria were those surgeons who did not perform ACL reconstruction or who chose to opt out of the survey.

Results: Overall, 19 surgeons opted out of the survey; 36 responded from the remaining 72 surveys (50%). The majority (n = 31, 86%) reported routinely checking for a medial meniscal ramp lesion via inspection of the posteromedial meniscocapsular junction during an ACL reconstruction. The most common repair technique cited was all-inside (n = 24, 66.7%), followed by inside-out (n = 8, 22.2%). Three (8%) surgeons indicated that they did not repair meniscal ramp lesions. Regarding surgical treatment (repair vs no treatment), the majority reported using the extent of the tear (89%; partial vs full thickness) and the stability of the tear upon probing (81%) as the main criteria for intraoperative decision making. Nineteen (52.8%) surgeons required a mean time of <15 minutes for meniscal ramp repair; 16 surgeons (44.4%), 15 to 30 minutes; and 1 surgeon (2.8%), 30 to 45 minutes.

Conclusion: This study provides insight regarding meniscal ramp tear identification, treatment, and repair strategies from the fellowship directors of sports medicine orthopaedic surgery in the United States. Such information may be useful for current orthopaedic surgeons to advance their practice according to the current trends surrounding ACL reconstruction and medial meniscal ramp repair.

Keywords: ramp lesion; medial meniscus; anterior cruciate ligament reconstruction; survey

Meniscal ramp lesions are becoming increasingly recognized. Ramp lesions have been described as tears at the posterior meniscocapsular junction and/or tears of the posterior meniscotibial ligament, and they have a reported incidence of 16% to 40% of all anterior cruciate ligament (ACL) tears.[3,9,13,14] Based on their location, these lesions may be arthroscopically "hidden" during normal anterior viewing; thus, an accessory posteromedial portal is necessary to confirm or deny their presence. In addition, there is controversy regarding identification strategies and surgical treatment options (repair versus no treatment). Some authors have advocated for the surgical repair of all meniscal ramp lesions at the time of ACL reconstruction, owing to an increased risk of persistent instability and potential ACL reconstruction graft failure when not treated.[4,5,11,15] However, given the vascularization of the capsule and the red-red zone of the meniscus,[1,2] some clinical studies have cited the potential for these tears to heal without surgical treatment.[6,10] Therefore, the purpose of this research survey was to better understand the current

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trends in orthopaedic surgery regarding arthroscopic identification and treatment of medial meniscal ramp lesions at the time of ACL surgery.

METHODS

Questionnaire Development

A questionnaire was electronically sent in a blinded fashion to 91 directors of orthopaedic sports medicine fellowship training programs in the United States (Table 1). Participants' email addresses were obtained through the American Orthopaedic Society for Sports Medicine directory of current fellowship program directors. A cover letter that accompanied the questionnaire stated the purpose of the questionnaire and ensured anonymity. All survey participants had the opportunity to decline the questionnaire. Inclusion criteria included only those surgeons who currently performed ACL reconstruction surgery. Exclusion criteria were those surgeons who did not perform ACL reconstruction or who chose to opt out of the survey. The survey was sent out and responses were collected from January 2018 to July 2018. We developed the questionnaire according to previous trends in the literature regarding meniscal ramp lesions and by expert opinion and knowledge from years of clinical practice. This study was deemed exempt from approval by an institutional review board.

Statistical Analysis

Data were prospectively collected via an online survey tool (www.surveymonkey.com). Data were extracted from the online survey database and summarized. Standard descriptive statistics were performed.

RESULTS

Overall, 19 surgeons opted out of the survey; 36 responded from the remaining 72 surveys (50%). A total of 14 (38.9%) surgeons reported that their recognition of meniscal ramp lesions began ≥7 years ago; 8 surgeons (22.2%), 5 to 6 years; 12 surgeons (33.3%), 2 to 4 years; and 2 surgeons (5.6%), 1 year ago. The majority (n = 31, 86%) indicated routinely checking for a medial meniscal ramp lesion during an ACL reconstruction via inspection of the posteromedial meniscocapsular junction. The most common inspection strategy cited for evaluation of a ramp tear was the modified Gillquist view (transnotch approach; n = 24, 67%). Three (8%) surgeons reported the use of an accessory posteromedial portal during evaluation of a ramp lesion.

Regarding diagnosis, 11% did not preoperatively diagnose ramp lesions, while 89% used magnetic resonance imaging (MRI) for diagnosis, with 56% identifying a posteromedial tibial bone bruise as a secondary sign of a ramp lesion. Eight (22.2%) surgeons reported that MRI was "rarely" accurate in diagnosing medial meniscal ramp lesions, as compared with 12 (33.3%) and 16 (44.4%) who indicated that MRI was "sometimes" accurate and "often" accurate, respectively. Twenty (55.5%) surgeons cited the preoperative use of physical examination findings as an indicator for potential medial meniscal ramp lesion. The most common physical examination findings reported were a grade III pivot shift (n = 9, 25%) and a grade III Lachman test (n = 8, 22.2%).

The most common meniscal ramp repair technique cited was all-inside (n = 24, 66.7%), followed by inside-out (n = 8, 22.2%). Three (8%) surgeons reported that they did not repair meniscal ramp lesions, and 1 (2.7%) surgeon cited a hybrid meniscal repair technique. Regarding surgical treatment (repair versus no treatment), the majority of surgeons reported using the extent of the tear (89%; partial versus full thickness) and the stability of tear upon probing (81%) as the main criteria for intraoperative decision making. Nine surgeons (25%) cited involvement of the meniscotibial ligament as a criterion for meniscal repair, and 21 (58.3%) surgeons indicated size of the tear (ie, >2.5 or <2.5 cm in length) as a decision-making criterion. A total of 19 (52.8%) surgeons reported requiring a mean time of <15 minutes for meniscal ramp repair, 16 surgeons (44.4%) needed 15 to 30 minutes, and 1 surgeon (2.8%) needed 30 to 45 minutes. No surgeon (0%) needed ≥60 minutes (Figure 1).

The majority of surgeons (n = 22, 61.1%) reported routine assessment of intraoperative knee stability (ie, Lachman testing) following ramp repair: 12 surgeons (33.3%) cited a subjective difference in knee stability prior to ACL reconstruction with a ramp repair, while 10 surgeons (27.8%) did not notice a subjective difference in knee stability. The most common prescribed weightbearing status following ACL reconstruction and meniscal ramp repair was weightbearing as tolerated with the use of crutches for 2 to 4 weeks (n = 23, 64%). The most common prescribed return-to-play timeline following primary ACL reconstruction and concomitant medial meniscal ramp repair was 7 to 8 months (n = 13, 36%) (Table 2).

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Ethical approval for this study was waived by the Vail Valley Medical Center Institutional Review Board (protocol No. 2017-42).

TABLE 1
Survey Questionnaire[a]

Q1: Do you identify the posteromedial meniscocapsular junction (ie, location of "ramp" lesions) routinely at the time of ACL surgery? If yes, please specify how you locate these lesions during arthroscopy:
- A. No (14%)
- B. Anterior view (11%)
- C. Modified Gillquist view, by placing the scope through the intercondylar notch medial to the PCL (67%)
- D. Accessory posteromedial portal (8%)

Q2: What repair technique do you use for meniscal ramp lesions at the time of ACL surgery?
- Inside-out technique (22%)
- All-inside technique (67%)
- I do not repair meniscal ramp lesions (8%)
- Other (please specify) (3%)

Q3: What clinical information do you use to diagnose a medial meniscal ramp lesion during preoperative planning? Please select all that apply:
- MRI: High-intensity signal between posterior horn of medial meniscus and posteromedial capsule (89%)
- MRI: Posteromedial tibial bone bruise pattern (56%)
- Exam: Grade III Lachman test (22%)
- Exam: Grade III pivot shift (during exam under anesthesia) (25%)
- Exam: Positive/gross anterior drawer test (8%)
- I do not preoperatively diagnose meniscal ramp lesions (11%)
- Other (please specify) (0%)

Q4: What criteria do you use to make a decision regarding meniscal repair vs no treatment for medial meniscal ramp lesions? Please select all that apply:
- Extent of tear (ie, partial vs complete) (89%)
- Meniscal stability (ie, gross anterior displacement of medial meniscus upon probing) (81%)
- Size of tear (>2.5 or <2.5 cm in length) (58%)
- Involvement of meniscotibial ligament (25%)
- Other (please specify) (0%)

Q5: Do you notice a subjective difference in the reduction of the amount of knee instability following a ramp repair (anterior tibial translation or pivot shift) before completing your ACL reconstruction (ie, Lachman reduces from a "3" to a "2")?
- A. Yes (33%)
- B. No (28%)
- C. Do not assess knee stability after meniscal repair during surgery (39%)

Q6: When did you begin to recognize meniscal ramp lesions during your career?
- A. 1 y ago (6%)
- B. 2-4 y ago (33%)
- C. 5-6 y ago (22%)
- D. ≥7 y ago (39%)

Q7: What is the average time it takes you to repair a medial meniscal ramp lesion during surgery?
- A. <15 min (53%)
- B. 15-30 min (44%)
- C. 30-45 min (3%)
- D. ≥60 min (0%)

Q8: What is your prescribed weightbearing status following an ACL reconstruction and medial meniscal ramp repair?
- A. Weightbearing as tolerated with crutches × 2-4 wk (64%)
- B. Nonweightbearing × 4 wk (6%)
- C. Nonweightbearing × 6 wk (3%)
- D. Partial weightbearing × 2-4 wk (28%)
- E. Other (please specify) (0%)

Q9: What is your prescribed return-to-play timeline following a primary ACL reconstruction and medial meniscal ramp repair?
- A. 5-6 mo (6%)
- B. 6-7 mo (33%)
- C. 7-8 mo (36%)
- D. ≥9 mo (25%)

Q10: How often is preoperative MRI accurate in diagnosing medial meniscal ramp tears?
- A. Never (0%)
- B. Rarely (22%)
- C. Sometimes (33%)
- D. Often (44%)
- E. Always (0%)

[a]Questions assessed the surgeon's expertise in preoperative diagnosis, intraoperative identification, and treatment strategies of medial meniscal ramp lesions at the time of ACL surgery. Respondents' answers are provided in the form of overall percentages in parentheses next to the corresponding answers. ACL, anterior cruciate ligament; MRI, magnetic resonance imaging; PCL, posterior cruciate ligament.

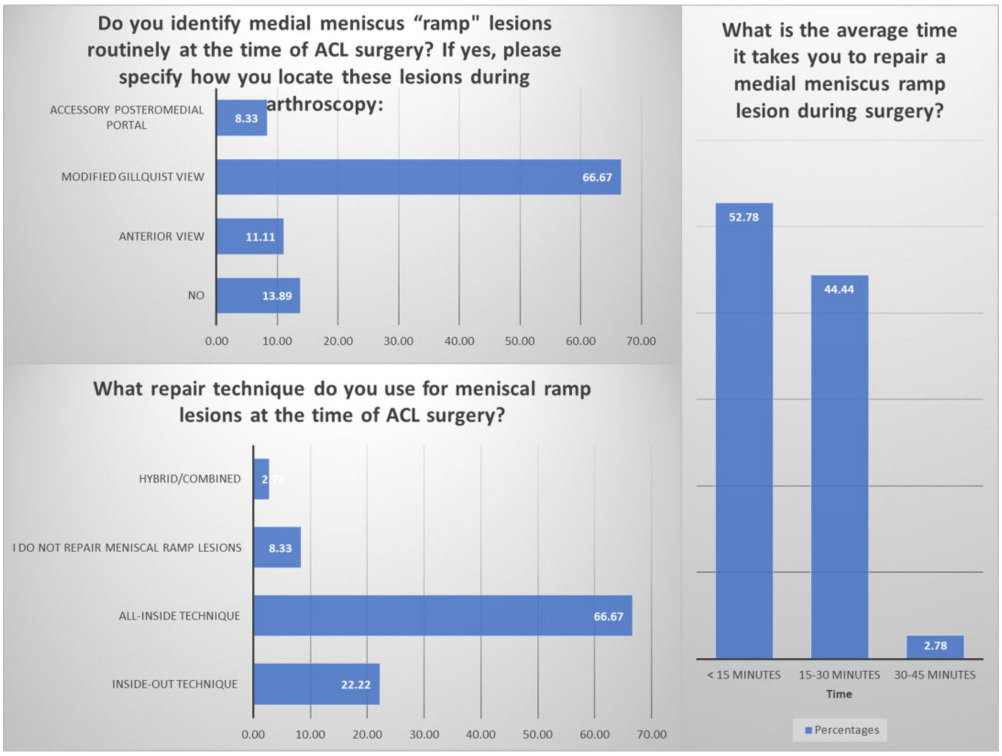

Figure 1. Survey responses of the orthopaedic sports medicine fellowship directors in the United States (N = 36) regarding identification, treatment, and time of repair for medial meniscal ramp lesions. ACL, anterior cruciate ligament.

TABLE 2
Mean Return-to-Play Timeline Reported by Orthopaedic Sports Medicine Fellowship Directors in the United States (N = 36)[a]

	5-6 mo	6-7 mo	7-8 mo	≥9 mo
"What is your prescribed return-to-play timeline following a primary ACL reconstruction and medial meniscal ramp repair?"	2 (6)	12 (33)	13 (36)	9 (25)

[a]Results are reported as n (%). ACL, anterior cruciate ligament.

DISCUSSION

This study reports the preferences and treatment strategies of the current US orthopaedic fellowship directors in the field of sports medicine. Specifically, the majority of surgeons surveyed reported that they routinely identify and repair meniscal ramp lesions at time of ACL surgery (86%), use an all-inside repair technique (67%), require <15 minutes for repair (53%), and allow their patients to return to full activities at postoperative 7 to 8 months (36%). These guidelines may be helpful for orthopaedic surgeons and may lead to established criteria for the treatment of ACL tears with concomitant medial meniscal ramp lesions.

In the current survey, the modified Gillquist view (transnotch, advancing the arthroscope medial to the posterior cruciate ligament) was the most common utilized approach to identify a potential ramp lesion. However, previous authors have advocated for the use of an accessory posteromedial portal to both visualize and repair ramp lesions.[12,14,16] In a study evaluating the diagnostic accuracy of adding a posteromedial portal for evaluation of ramp lesions, Sonnery-Cottet et al[14] documented a high rate (17%) of missed meniscocapsular tears before adding a posteromedial portal. However, in the current survey, only 8% of surgeons indicated the use of an accessory posteromedial portal during evaluation of a ramp lesion. Thus, the reported necessity of this accessory portal was not common in clinical practice by the orthopaedic sports medicine fellowship directors in the United States. Consequently, an accessory posteromedial portal may not be necessary for visualization with the previously established modified Gillquist view.[7]

The most common meniscal ramp repair technique reported in this survey was all-inside (67%), followed by inside-out (22%). Previous literature has described various meniscal ramp repair techniques; however, clinical outcomes have been published only for all-inside ramp repair techniques.[8,16,17] Thaunat et al[16] documented good outcomes following combined ACL reconstruction and all-inside meniscal ramp repair, with a 9% clinical failure rate. Liu et al[10] evaluated outcomes comparing all-inside versus no repair (trephination only) among patients who underwent ACL reconstruction with stable meniscal ramp lesions. These authors cited no significant differences between the repair and no-repair groups and no significant differences in meniscal healing rates. These reports support the potential for stable meniscal ramp lesions to heal without surgical repair; however, only 8% of our survey respondents indicated that they do not repair meniscal ramp lesions. Thus, the current trend (92%) by US orthopaedic sports medicine fellowship directors supports medial meniscal ramp repair.

The most commonly prescribed postoperative rehabilitation protocols after ACL reconstruction and meniscal ramp repair were weightbearing as tolerated with the use of crutches for 2 to 4 weeks (64%) and allowing patients to return to full activity at postoperative 7 to 8 months (36%). Thaunat et al[16] reported full weightbearing by week 3 and return to full activities by 9 months following combined ACL reconstruction and meniscal ramp repair. Thus, the cited rehabilitation programs by the orthopaedic sports medicine fellowship directors in the United States are consistent with previous literature.

This study has limitations inherent to those of a survey questionnaire. As such, the subjective reports and common trends of the survey respondents cannot be validated with evidence-based recommendations, although these practices may be adopted into future research studies for validation. In addition, there was a relatively low response rate for the orthopaedic sports medicine fellowship directors. This may have introduced bias into the results, which should thus be interpreted with caution.

CONCLUSION

This survey provides insight regarding meniscal ramp tear identification, treatment, and repair strategies from the fellowship directors of sports medicine orthopaedic surgery in the United States. This information may be useful for current orthopaedic surgeons to advance their practice according to the current trends surrounding ACL reconstruction and medial meniscal ramp repair.

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Appendix E

***Paper V* - Clinical Outcomes**

Clinical Characteristics and Outcomes Following Primary ACL Reconstruction and Meniscal Ramp Repair

Abstract

Background: Satisfactory outcomes have been reported following all-inside meniscal ramp repair with combined anterior cruciate ligament reconstruction (ACLR). However, clinical outcomes following ACLR with inside-out meniscal ramp repair is limited.

Purpose/Hypothesis: To evaluate patient reported outcomes following ACLR and medial meniscus ramp repair compared to age, gender, and activity-level matched patients with isolated ACLR. The null hypothesis was that there would be no significant differences in clinical outcomes between patient groups at a minimum of 2-years postoperatively.

Study Design: Case Control; Level of evidence 3.

Methods: Patients who underwent primary ACLR with bone-patellar tendon-bone (BPTB) autograft by a single surgeon were retrospectively identified. A subgroup of patients with combined ACLR and meniscal ramp repair were identified with minimum 2-years postoperative follow-up and were matched to an isolated ACLR cohort. Subjective patient-reported questionnaires, knee stability, and return to level of activity/sport were collected.

Results: There were 851 primary ACLR patients identified; 158 (18.6%) had medial meniscal ramp lesions confirmed at arthroscopy. The most common clinical characteristics in patients with ramp lesions were chronic injuries (68.4%), contact mechanism (88%), concomitant lateral meniscus tears (63.2%), and concomitant lateral meniscus posterior root tears (22.2%). Fifty of 58 patients were identified with 2-year follow-up with combined ACLR and ramp lesions were matched to 50 isolated ACLR patients. Both groups reported significant improvements in subjective outcomes from preoperatively to postoperatively ($p < 0.001$). There were no significant differences in postoperative outcomes between combined ACLR with ramp repair and isolated ACLR ($p > 0.05$). Meniscal ramp patients had increased preoperative knee laxity demonstrated by grade 3 Lachman (44% vs. 6%) and pivot shift (38% vs. 12%) testing compared to isolated ACLR patients (p=0.005).

Conclusion: This study demonstrates similar clinical outcomes, post-operative physical exam knee stability, and return to sport rates for combined ACLR with BPTB autograft and inside-out meniscal ramp repair compared to isolated ACLR patients in a matched cohort. Clinicians should have a high index of suspicion for presence of ramp lesions in patients with ACL tears who report a contact mechanism of injury, chronic injuries, grade 3 knee instability, and concomitant lateral meniscus pathology.

INTRODUCTION

Meniscal ramp lesions have become increasingly recognized throughout the orthopaedic surgery literature. Ramp lesions are characterized as a continuum of tears located along the posteromedial meniscocapsular junction and/or meniscotibial attachment of the posterior horn of the medial meniscus, associated with anterior cruciate ligament (ACL) tears.[1-4] The collective awareness of such injuries has led to improved diagnostic strategies,[5, 6] knowledge of tear incidence at time of ACL reconstruction (ACLR),[7, 8] and reported risk factors for increased risk of meniscal ramp tear.[9, 10]

Despite this improved awareness, there is a paucity of literature reporting on the results of surgical treatment. Similar results have been reported between surgical repair and nonoperative treatment following stable meniscal ramp tears left *in situ* at time of ACLR.[11] In contrast, successful outcomes have also been reported in patients who underwent concomitant ACLR and medial meniscus ramp repair via an all-inside technique at a minimum of 2 years postoperatively.[12] As the controversy of different treatment strategies remains unclear, a matched cohort of patients who undergo ACLR and combined repair for unstable medial meniscus ramp tears compared to isolated ACLR may provide insight for clinicians considering the potential differing treatment options. Therefore, the purpose of this study was to evaluate patient reported outcomes following ACLR and medial meniscus ramp repair compared to age, gender, and activity-level matched patients with isolated ACLR. The null hypothesis was that there would be no significant differences in outcomes between patient groups at a minimum of 2 years postoperatively.

METHODS

Study Design

This study was approved following review from an institutional review board (*institution and protocol number blinded for review*). Demographic data and clinical outcome scores were collected on all primary ACL reconstruction patients that were performed by a single board-certified orthopaedic surgeon (*initials blinded for review*). Inclusion criteria included patients who underwent combined primary ACLR with bone-patellar tendon-bone (BPTB) autograft and medial meniscus ramp repair for an unstable medial meniscus ramp lesion from April 2010 to January 2017 with a minimum 2-year follow-up. Patients with a combined ACLR and medial meniscus ramp repair were matched in a 1-to-1 allocation according to age, gender, and activity-level, with patients who underwent primary isolated ACLR. Exclusion criteria included patients who underwent multi-ligament knee reconstruction, previous meniscus surgery, displayed concomitant lateral meniscus tears, meniscal root tears, meniscal radial tears, concomitant cartilage procedures, concomitant osteotomy procedures, concomitant fractures, bilateral ACLR, revision ACLR, and ACLR with allograft or hamstring tendon.

Surgical Technique

All included patients underwent anatomic, single-bundle, primary ACLR with BPTB autograft according to a previously described and biomechanically validated technique.[13-15] All included patients with unstable meniscal ramp lesions underwent inside-out meniscal repair according to a previously described and biomechanically validated technique.[1, 16] A repairable meniscal ramp lesion was considered a complete tear located within the meniscocapsular and/or meniscotibial attachment of the posterior horn of the medial meniscus, that was unstable on probing. Ramp lesions were evaluated utilizing a modified Gillquist view by placing the arthroscope through the intercondylar notch medial to the posterior cruciate ligament and using a probe above the medial meniscus to push against the posteromedial capsular attachment (Figure 1).

Postoperative Rehabilitation Protocol

The postoperative rehabilitation protocol was identical for patients who underwent combined ACLR with meniscal ramp repair and isolated ACLR. All patients were allowed to bear weight as tolerated upon discharge and were instructed to use crutches until they could ambulate without a limp. Physical therapy commenced within twenty-four hours after surgery to initiate early range-of-motion (ROM), muscle reactivation, and to control edema. Rehabilitation included straight leg raises in an immobilizer until there was no extension lag at which point patients were transitioned to a functional hinge knee brace (CTi, Ossur Americas, Foothill Ranch, CA). Patients were allowed to begin straight-ahead running exercises at 4 months, with restrictions on pivoting and twisting. Gradual return to play progression was initiated after 6 months following the successful completion of a functional sports test. Return to sports or activity was allowed when the patient achieved normal strength, stability, and knee ROM comparable to the contralateral side, at around 7 to 9 months postoperatively.

Patient-Reported Outcomes, Patient Satisfaction, and Complications

At a minimum 2 years following the index surgery, patients were administered an electronic subjective questionnaire, which included the following clinical outcome measures: Lysholm score, the Western Ontario & McMaster Universities Osteoarthritis Index (WOMAC) score, the Short Form-12 (SF-12) physical component summary (PCS), the Tegner Activity scale, the International Knee Documentation Committee (IKDC) score, and patient satisfaction with outcome. Patient satisfaction was measured on a 1 to 10 scale with 10 being very satisfied and 1 being very unsatisfied. Demographic characteristics were recorded including age, gender, body mass index (BMI), and sport/activity at time of ACL injury. Data regarding knee ROM and stability on physical exam (Lachman and pivot shift tests) were collected both preoperatively and at a minimum of 2 years postoperatively. Additionally, level of return to sport and preinjury activity level was collected and classified as ‘lower than preinjury level’, ‘same level as preinjury level’, or ‘above preinjury level’. Meniscal repair failure was defined as any subsequent surgery that required revision meniscal repair. Complications were recorded, including reintervention surgery requiring partial meniscectomy, ACLR graft failure (ipsilateral and contralateral), deep vein thrombosis, or arthrofibrosis requiring a lysis of adhesions.

Statistical Analysis

For outcome variables comparing preoperative and postoperative scores, a paired t-test was utilized. Because ceiling or floor effects are common in the outcome scales we assessed, non-parametric, rank-based statistical methods were used for group comparisons of postoperative patient-reported outcomes. Specifically, because each ACLR with ramp tear patient was matched to an isolated ACLR patient, the Wilcoxon Signed Rank test was used for these postoperative group comparisons. Independent t-tests were used to compare age and BMI between groups. Comparisons of categorical data including gender, chronicity, knee stability on physical exam, complication rate, and return to preinjury level of activity were performed by use of Chi-square tests and Fisher Exact tests. All *p* values were two-tailed and an alpha level of less than 0.05 was considered significant. Unless otherwise noted, medians were reported with 1st and 3rd quartiles in brackets and means were reported ± standard deviation (SD). All statistical analyses were performed by use of SPSS version 9.4 (Chicago, IL).

RESULTS

Patient Demographics and Clinical Characteristics

There were 1176 ACLR patients identified, with 851 (72.4%) primary ACLR and 325 (27.6%) revision ACLR patients. Of the 851 primary ACLR patients, 158 (18.6%) had medial meniscal ramp lesions confirmed at arthroscopy. Of the 158 patients with meniscal ramp lesions, 84 (53.2%) were male and 74 (46.8%) were female. One-hundred eight (68.4%) patients had chronic injuries (≥ 6 weeks from time of injury) and 50 (31.6%) patients had acute injuries (<6 weeks from time of injury). The majority of ramp patients reported a contact mechanism (n=139, 88%) at the time of injury compared to a noncontact mechanism (n=19, 12%). Sixty-two percent (n=98) had an isolated ACL injury with a meniscal ramp lesion, while 38% (n=60) had an additional ligamentous knee injury. A concomitant lateral meniscus tear was identified in 100 (63.2%) ramp lesion patients and a concomitant lateral meniscus posterior root tear was identified in 35 (22.2%) of ramp lesion patients.

Fifty-eight patients met the inclusion criteria of ACLR with combined inside-out repair of unstable medial meniscus ramp lesion. Fifty patients had adequate follow-up during the data collection period and 8 patients were lost to follow-up (86% retention rate). These patients were evaluated for clinical outcomes and matched to a group of isolated ACLR patients which served as the control group (Figure 2). The average follow-up was 2.8 years (range, 2.0 to 8.0). There were no significant differences in age ($p = 0.667$), gender ($p = 1.00$), BMI ($p = 0.261$), or chronicity of injury ($p = 0.529$) between patients in the repair group versus control group (Table 1 and Figure 3).

Patient-Reported Outcomes

The median outcome scores significantly improved from preoperatively to postoperatively for SF-12 (38 [32, 46] to 57 [51, 59]), WOMAC pain (5 [3, 10] to 0 [0, 1]), WOMAC stiffness (4 [2, 4] to 1 [0, 2]), WOMAC total (28 [17, 52] to 0 [0, 8]), Lysholm (53 [31, 69] to 86 [80, 95]), Tegner (2 [1, 3] to 8 [6, 9]), and IKDC (66 [62, 72], 78 [72, 80]) following combined ACLR with meniscal ramp repair ($p < 0.001$). Similarly, in isolated ACLR, the median outcome scores significantly improved from preoperatively to postoperatively for SF12 PCS (38 [31, 44], 57 [54, 58]), WOMAC pain (5 [4, 9], 0 [0, 2]), WOMAC stiffness (3 [2, 5], 0 [0, 2]), WOMAC total (32 [22, 50], 2 [0, 7]), Lysholm (53 [37, 66], 85 [80, 94]), Tegner (2 [1, 3], 7 [6, 8]), and IKDC (65 [55, 69], 77 [72, 84]) ($p < 0.001$). At final follow-up, there were no significant differences between patients who underwent combined ACLR with meniscal ramp repair and isolated ACLR for subjective outcomes postoperatively ($p > 0.05$) (Table 2).

Clinical Outcomes and Return to Sport

Average preoperative ROM of the injured knee was -2.2 $\pm$ 1.6 degrees of extension to 136.6 $\pm$ 2.9 degrees of flexion and -2.7 $\pm$ 1.8 degrees of extension to 136.1 $\pm$ 2.1 degrees of flexion for ACLR with ramp repair and isolated ACLR groups, respectively. Average postoperative ROM -1.0 $\pm$ 2.8 degrees of extension to 135.2 $\pm$ 5.7 degrees of flexion and -1.2 $\pm$ 1.2 degrees of extension to 135.6 $\pm$ 1.9 degrees of flexion for ACLR with ramp repair and isolated ACLR groups, respectively. Meniscal ramp patients had evidence of increased knee laxity preoperatively as demonstrated by grade 3 Lachman (44% vs. 6%) and pivot shift (38% vs. 12%) tests compared to isolated ACLR patients (p= 0.005). Patients in both groups demonstrated improved anterior knee stability as reported by grading of the Lachman and pivot shift tests, from preoperative to postoperative status (Table 3). The majority of patients in the ACLR with ramp repair group (84%) and isolated ACLR group (90%) returned to the same preinjury level of activity. There were no significant differences in return to level of activity/sport between ACLR with meniscal ramp repair and isolated ACLR patients (p = 0.658) (Table 4).

Complications/Failures

There were six reported complications in the ACLR with meniscal ramp repair group (12%) and four reported complications in the isolated ACLR group (8%), with no significant difference between frequencies of complications (p = 0.505). One patient had a failed inside-out meniscal ramp repair (2%) and underwent a revision medial meniscus ramp repair at 12 months postoperatively from the index surgery. One patient suffered a partial re-tear of their meniscal ramp repair and underwent subsequent partial medial meniscectomy (2%). In both groups, there were no ACLR graft failures at a mean 2.8 years postoperatively and one patient (2%) in the isolated ACLR group reported a contralateral ACL tear. Table 5 details the complications and failures of patients in both groups.

DISCUSSION

The main finding of this study was there were no significant differences between patients who underwent combined ACLR with a meniscal ramp repair compared to a matched cohort of isolated ACLR patients. The incidence of meniscal ramp lesions in all ACL tear patients was 18.6% confirmed at the time of arthroscopy. The most common clinical characteristics identified in patients with ramp lesions were chronic injuries, contact mechanism of injury, concomitant lateral meniscus tear, and concomitant lateral meniscus posterior root tear.

Patients who underwent ACLR with BPTB autograft and inside-out meniscal ramp repair for unstable medial meniscus ramp tears reported improved subjective outcomes, knee stability on physical exam, and 88% returned to activity/sport at the same or higher level compared to preoperatively. In a randomized control, Liu et al.[11] reported similar subjective outcomes and knee stability for patients who underwent all-inside meniscus repair and trephination without repair for stable meniscal ramp lesions at a minimum of 2 years postoperatively ($p > 0.05$). Additionally, there no significant differences regarding the healing status of the meniscal ramp lesions between the two groups on follow-up MRI scan ($p = 0.543$). Due to the potential for stable ramp lesions to heal without repair, these authors recommended conservative treatment for stable ramp lesions at the time of ACLR.[11] Recently, Sonnery-Cottet et al.[10] reported an 11% rate of meniscectomy at a mean 45.6 months following all-inside meniscal ramp repair. In the current study, the rate of meniscectomy was 2% at a mean 33.6 months following inside-out ramp repair. Therefore, the authors recommend inside-out repair of all unstable meniscal ramp lesions at the time of ACLR.

In our study, the majority of patients with ACL tears and concomitant meniscal ramp lesions reported chronic injuries (n=108, 68.4%), a contact mechanism at time of injury (n=139, 88%), and were males (n=84, 53.2%). Additionally, the most common associated pathologies were concomitant lateral meniscus tears (n=100, 63.2%), and concomitant lateral meniscus posterior root tears (n=35, 22.2%). Identification of preoperative risk factors for potential ramp lesions can allow for increased awareness and improved diagnosis at the time of ACLR. Trends in patient characteristics have been previously reported with arthroscopically confirmed meniscal ramp lesions. Specifically, male sex, younger age (< 30 years old), a concomitant lateral meniscus tear, contact injury mechanism, increased medial meniscus slope, revision ACLR, and chronic injuries have been significantly associated with the presence of meniscal ramp lesions ($p < 0.05$).[8-10, 18, 19] The current study further supports these previously identified clinical characteristics of patients with meniscal ramp lesions with an additional finding of a 22% incidence for concomitant lateral meniscus posterior root tears. This finding may help explain the increased amount of knee instability during the pivot shift maneuver which has been previously described in biomechanical models.[20, 21]

Unstable meniscal ramp patients with an ACL tear demonstrated significant preoperative knee laxity as demonstrated by increased grade 3 Lachman and pivot shift testing compared to isolated ACL tear patients alone (p<0.05). Meniscal deficiency has been reported as the most significant factor to predict graft failure following ACLR.[22] The posterior horn of the medial meniscus is a known secondary stabilizer to anterior tibial translation and thus may help stabilize the ACL-deficient knee.[23, 24] In contrast, when the ACL is torn in combination with a meniscal ramp lesion, there may be increased anterior knee translation.[1] This finding has been previously described by Sonnery-Cottet et al.[10] who reported a preoperative side-to-side laxity difference in anterior knee translation of > 6 mm. Our results corroborate this finding with 44% of patients with ACL tears and meniscal ramp lesions demonstrating grade 3 Lachman's testing compared to 6% of isolated ACL tear patients (p=0.005). Therefore, when grade 3 anterior knee instability is noted on physical exam, clinicians should include a posterior horn medial meniscus tear in their differential diagnosis of associated secondary pathology. Despite the known preoperative increase in instability findings, stability on physical exam improved in all patients and no significant differences were found in clinical knee laxity grading between groups at final follow-up ($p > 0.05$).

Results of the current study demonstrate that inside-out meniscal ramp repair for unstable ramp lesions with concomitant ACLR compared to isolated ACLR was equivalent in terms of clinical outcomes at a minimum of 2-years postoperatively. Recent biomechanical data suggest these lesions may result in increased anterior tibial displacement and increase strain on both the native ACL and ACL reconstructed graft.[2, 25, 26] In the current study, there were no significant differences in rate of complications between groups (12% ACLR with ramp repair, 8% isolated ACLR) ($p = 0.505$). Additionally, the rate of meniscal ramp repair failure following inside-out meniscal repair was 2% which is lower than previous reports of 11% following all-inside ramp repair.[10] Therefore, the current authors recommend inside-out ramp repair at the time of ACLR due to potential increased knee kinematics associated with ramp tears in ACL reconstructed knees and equivalence compared to isolated ACLR.[1, 25]

There were some inherent limitations of this study. First, to justify the necessity of inside-out repair for all unstable meniscal ramp lesions over sufficiency of nonoperative treatment, future multi-center outcomes studies are needed. Second, we reported on clinical outcomes following a single surgeon's patients including the same ACLR and meniscal ramp repair technique which may not be generalizable. Therefore, it is possible to achieve different clinical outcomes with different ACLR techniques and different meniscal repair techniques. However, this consistency allowed for direct comparisons between patients utilizing a 1-to-1 matching study design. The current study failed to evaluate healing rates via second-look arthroscopy and thus clinical outcomes cannot infer biological healing.

CONCLUSION

This study demonstrates similar clinical outcomes, post-operative physical exam knee stability, and return to sport rates for combined ACLR with BPTB autograft and inside-out meniscal ramp repair compared to isolated ACLR patients in a matched cohort. Clinicians should have a high index of suspicion for presence of ramp lesions in patients with ACL tears who report a contact mechanism of injury, chronic injuries, grade 3 knee instability, and concomitant lateral meniscus pathology.

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Figure Legends:

Figure 1. Arthroscopic photos of medial meniscus ramp repair utilizing an inside-out vertical mattress technique. A) Medial meniscal instability when viewing anteriorly as depicted by increased anterior meniscal translation upon probing. B) Modified Gillquist view showing complete disruption at the meniscocapsular junction, followed by C) re-approximation of the meniscocapsular attachment during suture placement through meniscus and posteromedial capsule. D) Completed inside-out meniscal ramp repair illustrating stability and double-row vertical mattress suture placement. MFC: medial femoral condyle, PMC: posteromedial capsule, MM: medial meniscus.

Figure 2. Flow diagram of patient inclusion according to STROBE guidelines.[17] Patients with combined anterior cruciate ligament reconstruction (ACLR) and medial meniscus ramp repair were matched in a 1-to-1 allocation according to age, gender, and activity-level, with patients who underwent primary isolated ACLR. BPTP: bone-patellar tendon bone.

Figure 3. Sport activity reported at time of ACL tear in patients with concomitant ACL reconstruction (ACLR) and medial meniscal ramp repair (n=50) versus isolated ACL reconstruction (n=50).

Tables:

Table 1. Patient demographics for patients with combined medial meniscus ramp repair and primary ACL reconstruction (n=50).[a] Patients were matched according to gender, age, and activity-level to a control group of isolated ACL reconstruction patients (n=50).

	Total	Male	Female
Meniscus Ramp Repair and ACLR			
Patients	n = 50	n = 22	n = 28
Age	30.5 ± 11.4	33.1 ± 15.3	35.4 ± 16.0
BMI	23.4 ± 2.5	25.2 ± 2.6	22.5 ± 2.7
Acute Injuries[£]	n = 31		
Chronic Injuries	n = 19		
Isolated ACLR			
Patients	n = 50	n = 22	n = 28
Age	31.4 ± 10.3	33.9 ± 15.7	34.5 ± 15.0
BMI	24.2 ± 3.4	24.0 ± 3.8	23.0 ± 2.8
Acute Injuries	n = 34		
Chronic Injuries	n = 16		

[a]Values are reported as number or mean ± SD. BMI, body mass index; ACLR, anterior cruciate ligament reconstruction. [£]Acute injuries were considered to occur < 6 weeks from time of injury to surgery and chronic injuries were considered ≥ 6 weeks.

Table 2. Patient-reported subjective outcomes between isolated ACL reconstruction (ACLR) patients and combined ACL reconstruction with meniscal ramp repair patients. [a] There were no significant differences reported at a mean 2.8 years postoperatively ($p > 0.05$).

Outcome	**Isolated ACLR**	**Combined ACLR and Ramp Repair**	**P Value**
SF-12 PCS	57 [54, 58]	57 [51, 59]	0.330
WOMAC Pain	0 [0, 2]	0 [0, 1]	0.969
WOMAC Stiffness	0 [0, 2]	1 [0, 2]	0.903
WOMAC Total	2 [0, 7]	0 [0, 8]	0.427
Lysholm	85 [80, 94]	86 [80, 95]	0.842
Tegner	7 [6, 8]	8 [6, 9]	0.417
IKDC	77 [72, 84]	78 [72, 80]	0.200
Satisfaction	9 [8, 10]	9 [8, 10]	0.908

[a]Values are reported as median values [1st quartile, 3rd quartile]. WOMAC, Western Ontario and McMaster Universities Arthritis Index; SF-12 PCS, 12 item Short Form Health Survey Physical Component Summary; IKDC, International Knee Documentation Committee questionnaire.

Table 3. Frequencies of anterior knee stability on physical exam as reported by subjective grading of Lachman and pivot shift maneuvers for patients with combined ACL reconstruction (ACLR) with medial meniscal ramp repair (n=50) and matched isolated ACL reconstruction patients (n=50). Results are reported as total number followed by percentages. Statistical differences in categorical data between preoperative and postoperative frequencies were computed via a chi-square test.

Examination Test	**Isolated ACLR (n/%)**	**Combined ACLR and Ramp Repair (n/%)**	***P* Value**

Lachman (Preoperative)			
Grade 1	1 / 2%	0 / 0%	
Grade 2	46 / 92%	28 / 56%	
Grade 3	3 / 6%	22 / 44%	*<0.001
Lachman (Postoperative)			
Grade 0	44 / 88%	45 / 90%	
Grade 1	6 / 12%	5 / 10%	0.749
Pivot Shift (Preoperative)			
Grade 1	2 / 4%	0 / 0%	
Grade 2	42 / 84%	31 / 62%	
Grade 3	6 / 12%	19 / 38%	*0.005
Pivot Shift (Postoperative)			
Grade 0	50 / 100%	50 / 100%	1.00

*Statistical significance = $P < .05$. ACL, anterior cruciate ligament.

Table 4. Frequencies of level of return to activity/sport for patients with combined ACL reconstruction (ACLR) with medial meniscal ramp repair (n=50) and matched isolated ACL reconstruction patients (n=50). Results are reported as total number followed by percentages.

Return to Activity / Sport Level	Isolated ACLR (n/%)	Combined ACLR and Ramp Repair (n/%)
Lower Level	4 / 8%	6 / 12%
Same Level	45 / 90%	42 / 84%
Higher Level	1 / 2%	2 / 4%

*Return to sport was characterized according to subjectively reported values and measured as a comparison to preinjury activity/sport level. ACL, anterior cruciate ligament.

Table 5. Detailed complications and reintervention surgeries reported for patients with combined ACL reconstruction (ACLR) with medial meniscal ramp repair (n=50) and matched isolated ACL reconstruction patients (n=50). Complications are reported as total number followed by percentages.

Patient	Complication	Reintervention
Isolated ACLR		
#1	Arthrofibrosis	Lysis of adhesions
#2	Painful hardware	Deep hardware removal
#3	Contralateral ACL tear	ACL reconstruction
#4	Acute injury	Osteochondral allograft transplant
Combined ACLR and Ramp Repair		
#1	Cyclops lesion	Debridement cyclops lesion
#2	Partial re-tear medial meniscus repair	Partial medial meniscectomy
#3	Acute injury	ORIF patellar fracture
#4	Arthrofibrosis	Lysis of adhesions
#5	Acute injury	Lateral collateral ligament reconstruction
#6	Arthrofibrosis	Lysis of adhesions

ORIF, open reduction internal fixation.

Appendix F

Raw Data – Anatomy Measurements (*Paper II*)

Attachment Lengths	**Avg (mm)**
Attachment Length - Posterior Capsule	20.15409351
Attachment Length - Deep MCL Meniscofemoral	14.82326742
Attachment Length - Deep MCL Meniscotibial	17.70381161
Attachment Length - POL Meniscofemoral	8.25966565
Attachment Length - POL Meniscotibial	8.989680676
Attachment Length - Meniscotibial Ligament	13.91664725
Distance Between Landmarks	**Avg (Anterior, Lateral, Superior) (mm)**
Distance Intermeniscal Ligament to Anterior Root Attachment	[-5.3005653337249115, -8.573449337695493, 3.8363044844233385]
Distance Deep MCL Meniscofemoral Attachment to Semimembranosis	[-16.447981262681889, 13.332042096791525, -2.8571244621945318]
Distance PCL Attachment to Humphrey	[4.6915754999566861, 4.923581242893432, 14.05046188790149]
Distance Posterior Meniscotibial Ligament to POL Meniscotibial Attachment	[5.9147921289544767, -16.537762925260303, -1.9128310495484868]
Distance PCL Facet to Meniscotibial Ligament	[-9.675276489369141, -13.481520114825523, -2.3387979747254151]

Distance Posterior MM Root to Meniscotibial Ligament	[-16.552276455375917, -7.731749527499888, -9.4939360951149112]
Vertical Distance Between Landmarks	**Avg (mm)**
Vertical Distance Post Capsule Attachment to Art Cart Margin	2.909277792
Vertical Distance Deep MCL Meniscotibial to Art Cart Margin	-6.36660248
Vertical Distance Semimembranosis to Art Cart Margin	0.657077724
Vertical Distance POL Meniscotibial Attachment to Art Cart Margin	-6.725631391
Vertical Distance POL Meniscotibial Attachment to Bone Margin	-1.564844668
Vertical Distance Meniscotibial Ligament Attachment to Art Cart Margin	-5.89567975
	Avg (from posterior, medial, & anterior locations on attachment) (mm)
Vertical Distance (from Post, Medial, & Anterior Attachments) Deep MCL Meniscotibial to Art Cart Margin	[-6.552934037268094, -6.1484931561162712, -6.9124946629468011]
Curved Distance Between Landmarks	**Avg (mm)**
Curved Distance Deep MCL Meniscofemoral to Post MM Root	45.87948533
Curved Distance Deep MCL Meniscofemoral to Ant MM Root	51.22837727
Curved Distance Deep MCL Meniscotibial to PCL	50.49392974
Curved Distance Deep MCL Meniscotibial to Post MM Root	
Curved Distance MPML to Anterior Root Attachment on MM	20.14753259
Curved Distance POL Meniscofemoral Ligament to Posterior Root Attachment on MM	34.11767913
Curved Distance POL Meniscofemoral Ligament to Medial Tibial Eminence Apex	43.64047386
Where Things Attach	**Avg (low end, high end) (% & mm)**
Where Capsule Attaches Along Meniscus Thickness	36.41666849

Where Deep MCL Meniscofemoral Attaches on Medial Meniscus (% Range)	[37.059741157622682, 50.471308306086677]
Where Deep MCL Meniscofemoral Attaches on Medial Meniscus (Absolute Vals)	[39.584923366025329, 53.946280792833875]
Where Deep MCL Meniscotibial Attaches on Medial Meniscus (% Range)	[35.459890959004433, 51.920578906826044]
Where Deep MCL Meniscotibial Attaches on Medial Meniscus (Absolute Vals)	[37.916892197882134, 55.314298430797486]
Where POL Meniscofemoral Attaches on Medial Meniscus (% Range)	[31.238836781512774, 38.667029303513928]
Where POL Meniscofemoral Attaches on Medial Meniscus (Absolute Vals)	[33.455808171741872, 41.383889339541753]
Where POL Meniscotibial Attaches on Medial Meniscus (% Range)	[31.858240191674682, 39.949733808997536]
Where POL Meniscotibial Attaches on Medial Meniscus (Absolute Vals)	[33.78207994346252, 42.346585840650398]
Where Semimembranosus Attaches on Medial Meniscus (% Range)	[25.661915036817799, 33.89177542793653]
Where Semimembranosus Attaches on Medial Meniscus (Absolute Vals)	[27.203918268235167, 35.962073736530478]
Where MPML Attaches on Medial Meniscus (% Range)	[67.134941475191994, 74.43361416823312]

Where MPML Attaches on Medial Meniscus (Absolute Vals)	[71.344749209127599, 78.967171870198527]

Std	Min	Max	N
5.992846438	11.31089448	33.22718896	14
3.248466893	10.01542504	21.11970642	14
3.42540932	12.89104556	24.47768809	14
2.091745037	5.899571128	13.04368921	14
2.328021655	4.012964049	13.63722363	14
5.425757774	6.476061886	27.4025119	13

Std (Anterior, Lateral, Superior)	Min (Anterior, Lateral, Superior)	Max (Anterior, Lateral, Superior)	N
[3.9685957096077749, 4.510024566105491, 1.731614140190493]	[-10.029430588437354, -14.896056432675977, 2.233256165345785]	[-0.31830862680262229, -4.6848480367442882, 6.2410779573218509]	[3]
[6.2593559446292435, 5.4161337851535443, 2.8955239477887722]	[-30.007266899917454, 4.6069335812350118, -7.9713574046362226]	[-7.8347693774636014, 23.621475024709213, 1.5225357967267428]	[14]
[3.5957561853795323, 2.6479356985990501, 2.0216846684843155]	[-2.6126105824369859, 0.9056465467719792, 9.3710112787977931]	[8.7763235548528193, 8.5910807726917309, 17.757196204351374]	[9]
[6.8723940154749936, 4.4648191180994559, 2.7460348407803519]	[-3.6820824273228823, -24.941341927203837, -6.6552018832750548]	[22.473619168229902, -8.349508639309164, 2.9956057940136134]	[12]
[3.7557200554292676, 4.5229739923942249, 1.9803162693375072]	[-17.047685804214424, -21.791931537217927, -4.4752303300009233]	[-3.3593101424464713, -7.3283780100119271, 1.6934953016233436]	[13]

[3.2890399919624222, 5.1833196351223734, 2.7671857607455843]	[-25.622663667921138, -19.813609280062654, -15.736197143053527]	[-12.899342236696658, -1.7009519966085351, -5.9262714948958344]	[13]
Std	**Min**	**Max**	**N**
2.41885459	-1.114504012	7.303916036	14
1.947309711	-11.18146637	-3.687859534	14
3.005127247	-5.264947517	3.979754486	14
1.752264983	-10.1618188	-3.398850532	10
2.336426028	-4.445573362	5.114958856	14
1.340978206	-7.970711148	-3.688156714	14
Std (from posterior, medial, & anterior locations on attachment)	**Min (from posterior, medial, & anterior locations on attachment)**	**Max (from posterior, medial, & anterior locations on attachment)**	**N**
[1.6407739333761329, 2.1260151849149427, 2.1985063030059768]	[-9.7488056606522715, -11.373566928637983, -12.483761385031709]	[-4.5898349047301927, -3.279678431836702, -3.5707242365540282]	14
Std	**Min**	**Max**	**N**
7.033885565	35.34341686	55.60773383	14
5.799965302	41.86460304	63.43817554	14
5.822988412	42.45385114	59.74559521	14
6.791439549	37.00867368	57.90587146	14
5.974210272	9.675956966	30.06190206	12
6.712400926	26.57195995	48.68063829	12
8.247475426	35.16498249	61.94335246	12
Std (low end, high end)	**Min**	**Max**	**N**
19.84440126	-4.805409091	67.24350495	13

[4.4291155624661469, 4.8781965822841951]	29.68635808	57.77800603	14
[6.332860897019966, 7.9903216477167165]	30.48465589	66.22348999	14
[4.4890547413651651, 5.9041691834959158]	27.80892366	64.15562623	14
[6.6349575771763201, 7.6672436744015453]	29.32802991	71.39263174	14
[4.3140172737741862, 5.2063901251861253]	22.98740801	49.90125645	13
[5.7448356694874798, 6.8997709721937452]	23.60556392	53.44499506	13
[7.465825932242371, 8.456236970672407]	23.02601133	59.2994007	13
[8.1814967074478382, 9.2277528383288345]	23.64520532	60.80612626	13
[4.469561946919554, 4.9085539508139018]	19.08444759	44.39664153	12
[4.940010833154159, 5.795181292372698]	19.53507524	45.52470612	12
[7.288857663691938, 9.7845733806402713]	50.1918678	84.15329167	14

[8.3066495243245999, 10.321024531221344]	55.06276678	94.31942195	14

Appendix G

Raw Data – Biomechanical Analysis (*Paper III*)

Meniscus Ramp Repair - Analysis Report

Grant J. Dornan, MSc

September 23, 2017

Contents

1 Methods

Full Statistical Methods Section BORROWED FROM CUTTING STUDY

Three comparisons of interest were chosen prior to conducting the data analysis: ACL cut vs ACL+MCL cut (repeated measures comparison of 12 knees), ACL cut vs ACL+MTL cut (repeated measures comparison of 12 knees) and ACL cut vs ACL+MCL+MTL cut repeated measures comparison of 24 knees). Data was analyzed after subtracting each specimen's intact values. Because all measurement variables were reasonably normally distributed and the comparisons included different sample sizes, paired t-tests were used to make all comparisons among knee conditions. Holm's method was used to control the familywise type-1 error rate to 0.05 within each experiment and flexion angle combination, and Holm-adjusted p-values were presented. The design of the experiment is presented in Figure ##. Adjusted p-values less than 0.05 were deemed statistically significant. The statistical software R was used for all analyses (R, R Foundation for Statistical Computing with *ggplot2*).

Most important software citations

- R Core Team (2015). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL http://www.R-project.org/.
- H. Wickham. ggplot2: Elegant Graphics for Data Analysis. Springer-Verlag New York, 2009.

2 Simulated Anterior Drawer Test - Anterior Displacement Measurement

2.1 Manipulate Data

```
# Create delta-intact data with dplyr gather/spread/gather
dat2.att.spread <- dat2.att %>% select(Pair, Specimen, Group,
    Flexion, State, Value) %>% spread(data = ., key = State,
    value = Value, fill = NA)
dat2.att.deltaintact.spread <- dat2.att.spread
dat2.att.deltaintact.spread[, 5:10] <- dat2.att.spread[, 5:10] -
    dat2.att.spread[, 5]
dat2.att.deltaintact <- gather(dat2.att.deltaintact.spread, key = State,
    value = Value, Intact:ACLR.RampRepair, -(Pair:Flexion), factor_key = TRUE)
dat2.att.deltaintact <- dat2.att.deltaintact %>% subset(State !=
    "Intact") %>% subset(!is.na(Value)) %>% droplevels()
str(dat2.att.deltaintact)
```

```
~~~ 'data.frame':   128 obs. of  6 variables:
~~~  $ Pair    : Factor w/ 8 levels "5","6","7","8",..: 1 1 1 1 2 2 2 2 3 3 ...
~~~  $ Specimen: num  5 5 17 17 6 6 18 18 7 7 ...
~~~  $ Group   : Factor w/ 2 levels "MCLcut","MTLcut": 1 1 2 2 1 1 2 2 1 1 ...
~~~  $ Flexion : num  30 90 30 90 30 90 30 90 30 90 ...
~~~  $ State   : Factor w/ 5 levels "ACLR.MCL.MTL",..: 1 1 1 1 1 1 1 1 1 1 ...
~~~  $ Value   : num  0.278 1.662 -0.455 -0.629 -0.599 ...
```

```
head(dat2.att.deltaintact)
```

```
~~~     Pair Specimen  Group Flexion        State     Value
~~~  33    5        5 MCLcut      30 ACLR.MCL.MTL  0.277743
~~~  34    5        5 MCLcut      90 ACLR.MCL.MTL  1.661859
~~~  35    5       17 MTLcut      30 ACLR.MCL.MTL -0.454738
~~~  36    5       17 MTLcut      90 ACLR.MCL.MTL -0.628621
~~~  37    6        6 MCLcut      30 ACLR.MCL.MTL -0.598879
~~~  38    6        6 MCLcut      90 ACLR.MCL.MTL  0.961727
```

2.2 Summary Stats

Table 1: Anterior Translation (mm) during Simulated Anterior Drawer Test

Group	State	Flexion	n	nmiss	mean	sd	min	Q1.25.	median	Q3.75.	max
MCLcut	Intact	30	8	0	5.69	2.07	3.28	4.35	5.13	6.76	8.79
MCLcut	ACLR.MCL.MTL	30	8	0	5.36	0.93	4.17	4.74	5.26	6.08	6.73
MCLcut	ACLR.mcl.MTL	30	8	0	5.58	0.97	4.50	4.76	5.41	6.49	6.95
MCLcut	ACLR.mcl.mtl	30	8	0	5.56	1.05	4.36	4.80	5.38	6.39	7.11
MCLcut	ACLR.RampRepair	30	8	0	5.16	1.41	3.04	4.02	5.34	6.13	6.97
MCLcut	Intact	90	8	0	3.58	1.70	1.91	2.45	3.10	4.23	7.16
MCLcut	ACLR.MCL.MTL	90	8	0	4.45	1.88	2.74	3.40	3.76	4.85	8.28
MCLcut	ACLR.mcl.MTL	90	8	0	4.75	1.69	3.26	3.93	4.19	4.92	8.62
MCLcut	ACLR.mcl.mtl	90	8	0	4.57	1.77	2.94	3.58	4.03	4.94	8.57
MCLcut	ACLR.RampRepair	90	8	0	4.51	1.85	2.76	3.49	4.13	4.73	8.61
MTLcut	Intact	30	8	0	5.17	1.59	3.79	3.91	4.78	5.71	8.43
MTLcut	ACLR.MCL.MTL	30	8	0	5.14	1.27	3.29	4.31	4.99	6.16	6.90
MTLcut	ACLR.MCL.mtl	30	8	0	5.32	1.32	3.18	4.52	5.26	6.43	7.06
MTLcut	ACLR.mcl.mtl	30	8	0	5.07	1.69	2.52	4.01	4.97	6.14	7.88
MTLcut	ACLR.RampRepair	30	8	0	4.88	1.65	2.66	3.80	4.79	5.58	7.82
MTLcut	Intact	90	8	0	3.39	1.66	2.35	2.71	2.88	3.09	7.44
MTLcut	ACLR.MCL.MTL	90	8	0	3.39	1.42	1.20	2.21	4.02	4.34	5.03
MTLcut	ACLR.MCL.mtl	90	8	0	3.55	1.42	1.16	2.58	4.09	4.46	5.34
MTLcut	ACLR.mcl.mtl	90	8	0	3.48	1.70	1.20	2.07	4.08	4.36	6.05
MTLcut	ACLR.RampRepair	90	8	0	3.53	1.68	0.94	2.49	3.96	4.50	5.93

Table 2: Anterior Translation (mm) during Simulated Anterior Drawer Test - Version 2

State	Flexion	n	nmiss	mean	sd	min	Q1.25.	median	Q3.75.	max
Intact	30	16	0	5.43	1.80	3.28	3.93	4.87	6.16	8.79
ACLR.MCL.MTL	30	16	0	5.25	1.08	3.29	4.37	5.24	6.12	6.90
ACLR.mcl.MTL	30	8	0	5.58	0.97	4.50	4.76	5.41	6.49	6.95
ACLR.MCL.mtl	30	8	0	5.32	1.32	3.18	4.52	5.26	6.43	7.06
ACLR.mcl.mtl	30	16	0	5.31	1.38	2.52	4.38	5.13	6.32	7.88
ACLR.RampRepair	30	16	0	5.02	1.49	2.66	3.96	5.05	6.03	7.82
Intact	90	16	0	3.49	1.62	1.91	2.55	2.93	3.47	7.44
ACLR.MCL.MTL	90	16	0	3.92	1.70	1.20	2.86	3.86	4.42	8.28
ACLR.mcl.MTL	90	8	0	4.75	1.69	3.26	3.93	4.19	4.92	8.62
ACLR.MCL.mtl	90	8	0	3.55	1.42	1.16	2.58	4.09	4.46	5.34
ACLR.mcl.mtl	90	16	0	4.03	1.77	1.20	3.26	4.03	4.62	8.57
ACLR.RampRepair	90	16	0	4.02	1.78	0.94	2.90	4.03	4.59	8.61

Table 3: Anterior Translation (mm) during Simulated Anterior Drawer Test, Intact-Subtracted

Group	State	Flexion	n	nmiss	mean	sd	min	Q1.25.	median	Q3.75.	max
MCLcut	ACLR.MCL.MTL	30	8	0	-0.33	1.63	-2.58	-1.42	-0.39	0.54	2.31
MCLcut	ACLR.mcl.MTL	30	8	0	-0.11	1.59	-2.28	-1.06	-0.35	0.89	2.26
MCLcut	ACLR.mcl.mtl	30	8	0	-0.13	1.48	-2.47	-0.84	-0.22	0.77	1.86
MCLcut	ACLR.RampRepair	30	8	0	-0.52	1.78	-2.98	-1.89	-0.32	0.45	1.93
MCLcut	ACLR.MCL.MTL	90	8	0	0.87	1.57	-1.74	0.11	1.04	1.45	3.63
MCLcut	ACLR.mcl.MTL	90	8	0	1.17	1.27	-1.21	0.55	1.30	1.97	2.82
MCLcut	ACLR.mcl.mtl	90	8	0	0.99	1.24	-1.53	0.68	1.24	1.62	2.37
MCLcut	ACLR.RampRepair	90	8	0	0.93	1.34	-1.72	0.33	1.28	1.79	2.35
MTLcut	ACLR.MCL.MTL	30	8	0	-0.03	1.16	-1.53	-0.66	-0.18	0.55	2.15
MTLcut	ACLR.MCL.mtl	30	8	0	0.15	1.21	-1.38	-0.66	-0.02	0.76	2.49
MTLcut	ACLR.mcl.mtl	30	8	0	-0.10	1.15	-1.26	-0.87	-0.37	0.28	2.37
MTLcut	ACLR.RampRepair	30	8	0	-0.29	0.87	-1.16	-1.12	-0.32	0.17	1.27
MTLcut	ACLR.MCL.MTL	90	8	0	0.00	1.42	-2.41	-0.81	0.26	1.08	1.56
MTLcut	ACLR.MCL.mtl	90	8	0	0.16	1.35	-2.11	-0.58	0.54	1.20	1.57
MTLcut	ACLR.mcl.mtl	90	8	0	0.09	1.26	-1.40	-1.17	0.33	1.18	1.42
MTLcut	ACLR.RampRepair	90	8	0	0.13	1.33	-1.51	-1.18	0.39	1.19	1.81

Table 4: Anterior Translation (mm) during Simulated Anterior Drawer Test, Intact-Subtracted - Version 2

State	Flexion	n	nmiss	mean	sd	min	Q1.25.	median	Q3.75.	max
ACLR.MCL.MTL	30	16	0	-0.18	1.37	-2.58	-1.17	-0.32	0.55	2.31
ACLR.mcl.MTL	30	8	0	-0.11	1.59	-2.28	-1.06	-0.35	0.89	2.26
ACLR.MCL.mtl	30	8	0	0.15	1.21	-1.38	-0.66	-0.02	0.76	2.49
ACLR.mcl.mtl	30	16	0	-0.12	1.28	-2.47	-0.87	-0.25	0.34	2.37
ACLR.RampRepair	30	16	0	-0.41	1.36	-2.98	-1.14	-0.32	0.17	1.93
ACLR.MCL.MTL	90	16	0	0.43	1.51	-2.41	-0.45	0.94	1.30	3.63
ACLR.mcl.MTL	90	8	0	1.17	1.27	-1.21	0.55	1.30	1.97	2.82
ACLR.MCL.mtl	90	8	0	0.16	1.35	-2.11	-0.58	0.54	1.20	1.57
ACLR.mcl.mtl	90	16	0	0.54	1.29	-1.53	-0.63	1.08	1.42	2.37
ACLR.RampRepair	90	16	0	0.53	1.35	-1.72	-0.32	0.89	1.51	2.35

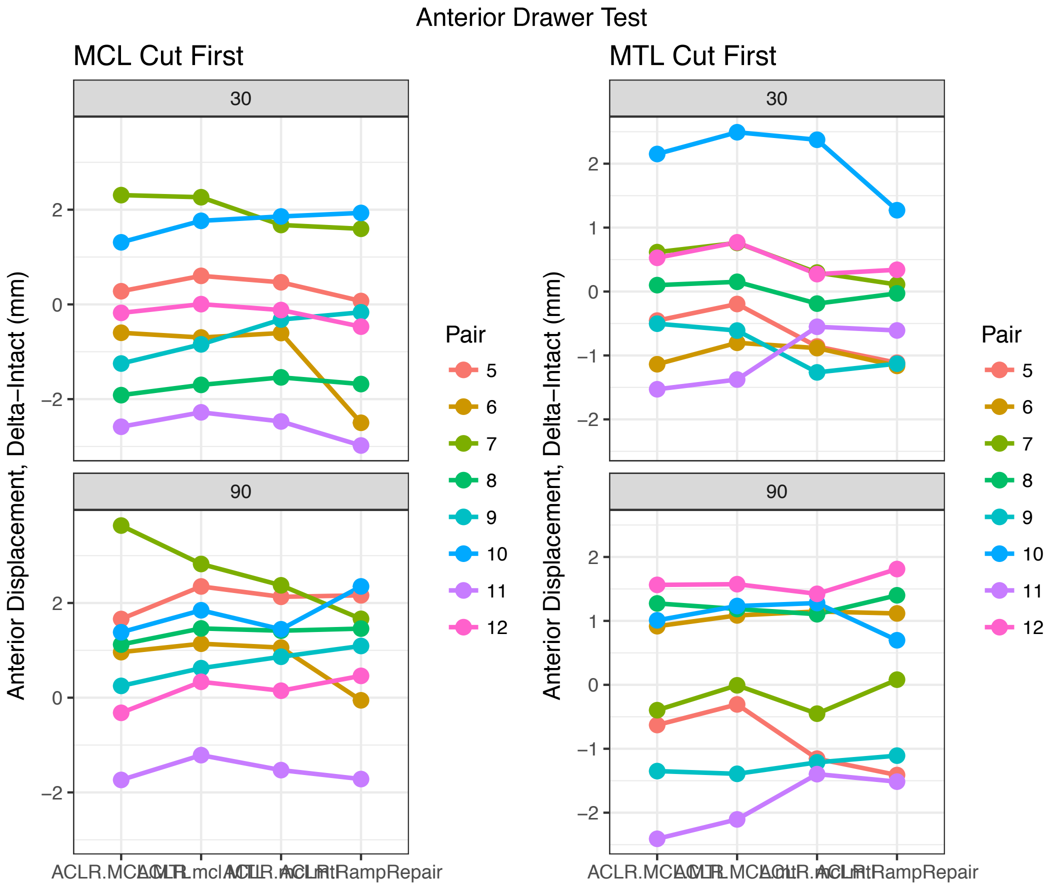
2.2.1 For Paper

Table 5: Mean ± SD Anterior Tibial Translation by Cut State and Flexion Angle - Non-Intact-Subtracted

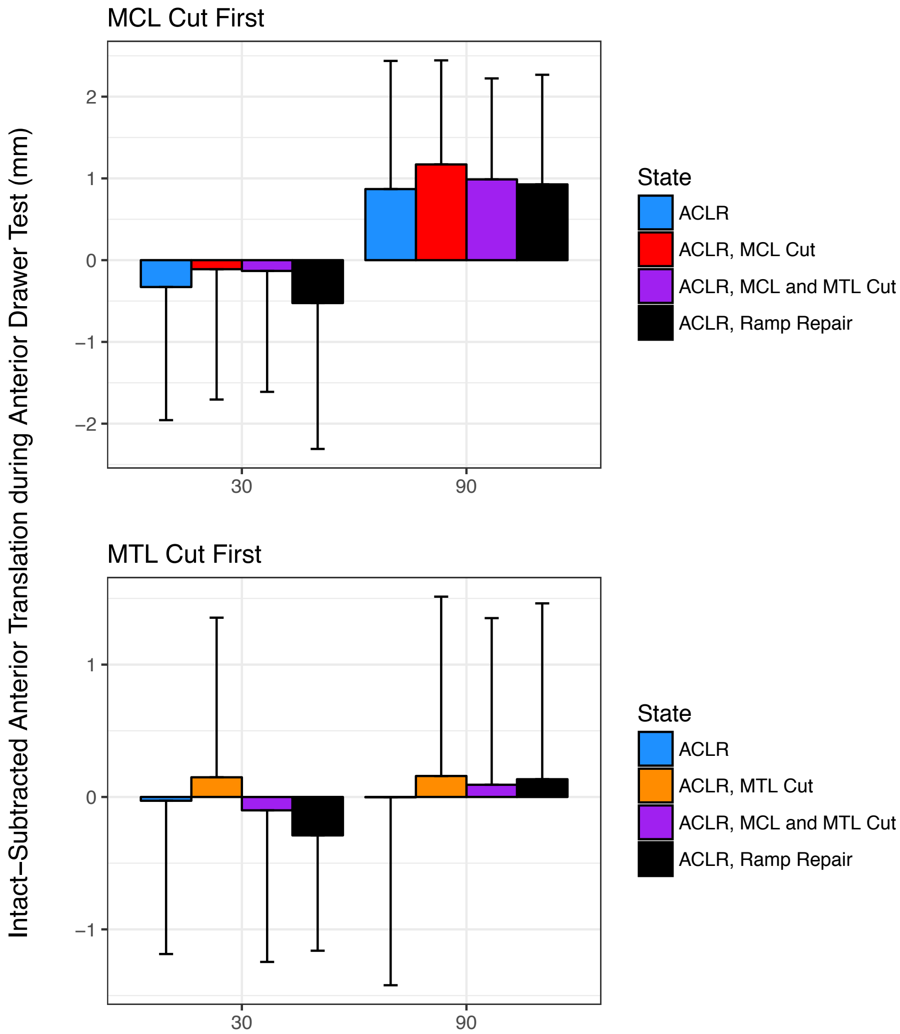
State	30	90
Intact	5.4 ± 1.8	3.5 ± 1.6
ACLR.MCL.MTL	5.2 ± 1.1	3.9 ± 1.7
ACLR.mcl.MTL	5.6 ± 1	4.7 ± 1.7
ACLR.MCL.mtl	5.3 ± 1.3	3.6 ± 1.4
ACLR.mcl.mtl	5.3 ± 1.4	4 ± 1.8
ACLR.RampRepair	5 ± 1.5	4 ± 1.8

2.3 Plot Data

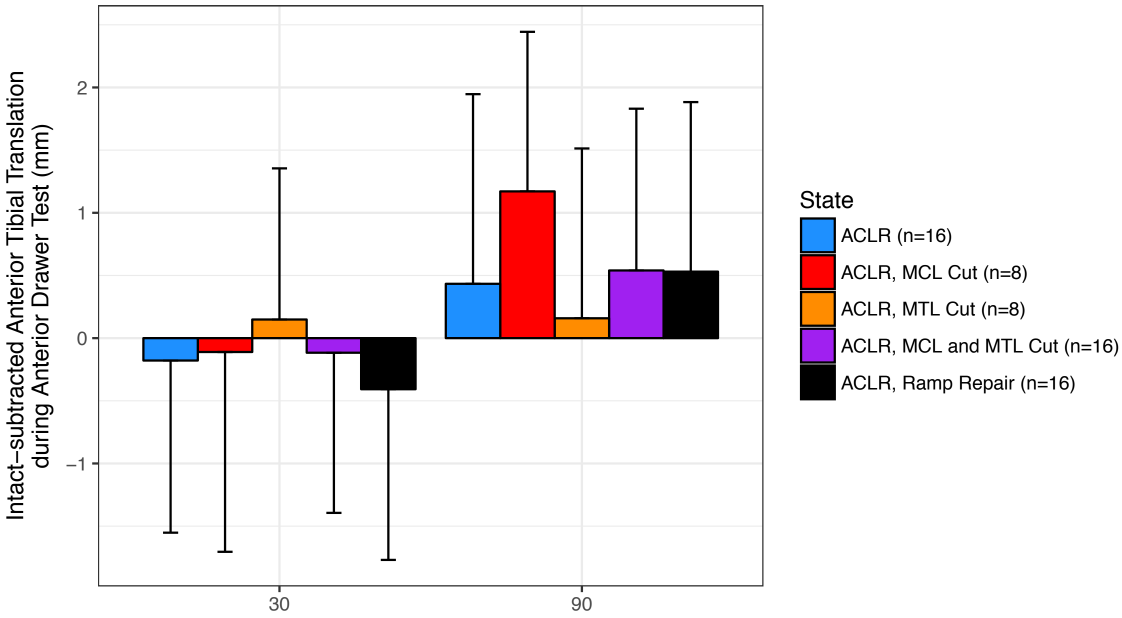
2.3.1 Spaghetti plots to inspect subject-level data



2.3.2 Bar Plot


MCL Cut First
MTL Cut First
Intact−Subtracted Anterior Translation during Anterior Drawer Test (mm)
2
1
0
−1
−2
30
90
State
ACLR
ACLR, MCL Cut
ACLR, MCL and MTL Cut
ACLR, Ramp Repair
ACLR, MTL Cut

2.3.3 New Bar Plot




```
~~~  pdf
~~~    2

~~~  pdf
~~~    2

~~~  pdf
~~~    2
```

2.4 Custom set of T-tests

Table 6: T-tests for Anterior Displacement during Anterior Drawer Test (mm), intact-subtracted data

	Flexion Angle	n	Mean Diff	SD Diff	CI LB	CI UB	Holm P
Intact vs ACLR+MCL+MTL	30	16	-0.18	1.37	-0.91	0.55	1.0000
Intact vs ACLR-MCL+MTL	30	8	-0.11	1.59	-1.44	1.22	1.0000
Intact vs ACLR+MCL-MTL	30	8	0.15	1.21	-0.86	1.16	1.0000
Intact vs ACLR-MCL-MTL	30	16	-0.12	1.28	-0.80	0.56	1.0000
Intact vs ACLR+RampRepair	30	16	-0.41	1.36	-1.13	0.32	1.0000
ACLR+MCL+MTL vs ACLR-MCL+MTL	30	8	-0.22	0.20	-0.39	-0.05	0.1601
ACLR+MCL+MTL vs ACLR+MCL-MTL	30	8	-0.18	0.15	-0.30	-0.05	0.1305
ACLR+MCL+MTL vs ACLR-MCL-MTL	30	16	-0.06	0.50	-0.33	0.20	1.0000
ACLR+MCL+MTL vs ACLR+RampRepair	30	16	0.23	0.73	-0.16	0.62	1.0000
ACLR-MCL-MTL vs ACL+RampRepair	30	16	0.29	0.53	0.01	0.58	0.3634
Intact vs ACLR+MCL+MTL	90	16	0.43	1.51	-0.37	1.24	1.0000
Intact vs ACLR-MCL+MTL	90	8	1.17	1.27	0.11	2.24	0.3534
Intact vs ACLR+MCL-MTL	90	8	0.16	1.35	-0.97	1.29	1.0000
Intact vs ACLR-MCL-MTL	90	16	0.54	1.29	-0.15	1.23	0.9187
Intact vs ACLR+RampRepair	90	16	0.53	1.35	-0.19	1.25	0.9187
ACLR+MCL+MTL vs ACLR-MCL+MTL	90	8	-0.30	0.48	-0.70	0.10	0.9187
ACLR+MCL+MTL vs ACLR+MCL-MTL	90	8	-0.16	0.18	-0.31	-0.01	0.3561
ACLR+MCL+MTL vs ACLR-MCL-MTL	90	16	-0.11	0.51	-0.38	0.16	1.0000
ACLR+MCL+MTL vs ACLR+RampRepair	90	16	-0.10	0.79	-0.52	0.32	1.0000
ACLR-MCL-MTL vs ACL+RampRepair	90	16	0.01	0.50	-0.26	0.27	1.0000

3 Simulated Internal Rotation Test

3.1 Manipulate Data

```
# Create delta-intact data with dplyr gather/spread/gather
dat2.ir.spread <- dat2.ir %>% select(Pair, Specimen, Group, Flexion,
    State, Value) %>% spread(data = ., key = State, value = Value,
    fill = NA)
dat2.ir.deltaintact.spread <- dat2.ir.spread
dat2.ir.deltaintact.spread[, 5:10] <- dat2.ir.spread[, 5:10] -
    dat2.ir.spread[, 5]
dat2.ir.deltaintact <- gather(dat2.ir.deltaintact.spread, key = State,
    value = Value, Intact:ACLR.RampRepair, -(Pair:Flexion), factor_key = TRUE)
dat2.ir.deltaintact <- dat2.ir.deltaintact %>% subset(State !=
    "Intact") %>% subset(!is.na(Value)) %>% droplevels()
str(dat2.ir.deltaintact)
```

```
~~~ 'data.frame':   448 obs. of  6 variables:
~~~  $ Pair    : Factor w/ 8 levels "5","6","7","8",..: 1 1 1 1 1 1 1 1 1 1 ...
~~~  $ Specimen: num  5 5 5 5 5 5 5 17 17 17 ...
~~~  $ Group   : Factor w/ 2 levels "MCLcut","MTLcut": 1 1 1 1 1 1 1 2 2 2 ...
~~~  $ Flexion : num  0 15 30 45 60 75 90 0 15 30 ...
~~~  $ State   : Factor w/ 5 levels "ACLR.MCL.MTL",..: 1 1 1 1 1 1 1 1 1 1 ...
~~~  $ Value   : num  -0.75 -0.117 0.153 0.698 0.488 ...
```

```
head(dat2.ir.deltaintact)
```

```
~~~     Pair Specimen  Group Flexion        State     Value
~~~ 113    5        5 MCLcut       0 ACLR.MCL.MTL -0.750190
~~~ 114    5        5 MCLcut      15 ACLR.MCL.MTL -0.117009
~~~ 115    5        5 MCLcut      30 ACLR.MCL.MTL  0.153463
~~~ 116    5        5 MCLcut      45 ACLR.MCL.MTL  0.698021
~~~ 117    5        5 MCLcut      60 ACLR.MCL.MTL  0.487855
~~~ 118    5        5 MCLcut      75 ACLR.MCL.MTL  0.564558
```

3.2 Summary Stats

Table 7: Internal Rotation (deg) during Simulated IR Test

Group	State	Flexion	n	nmiss	mean	sd	min	Q1.25.	median	Q3.75.	max
MCLcut	Intact	0	8	0	8.89	2.46	5.60	7.52	8.47	10.38	13.30
MCLcut	ACLR.MCL.MTL	0	8	0	8.55	2.37	4.85	7.36	8.33	10.39	11.68
MCLcut	ACLR.mcl.MTL	0	8	0	8.72	2.45	5.04	7.49	8.44	10.51	12.27
MCLcut	ACLR.mcl.mtl	0	8	0	10.49	2.61	7.25	8.10	10.76	12.67	13.85
MCLcut	ACLR.RampRepair	0	8	0	8.03	2.82	2.90	6.50	8.58	9.52	11.77
MCLcut	Intact	15	8	0	13.85	4.90	8.56	10.22	11.85	17.79	21.93
MCLcut	ACLR.MCL.MTL	15	8	0	13.82	4.49	9.99	10.26	12.05	16.20	20.98
MCLcut	ACLR.mcl.MTL	15	8	0	13.86	4.66	9.86	10.27	11.89	16.41	21.36
MCLcut	ACLR.mcl.mtl	15	8	0	15.40	4.60	10.34	12.00	13.80	19.11	22.10
MCLcut	ACLR.RampRepair	15	8	0	13.97	4.91	8.38	10.85	12.19	17.21	21.31
MCLcut	Intact	30	8	0	17.19	5.77	10.04	13.40	15.90	20.78	25.54
MCLcut	ACLR.MCL.MTL	30	8	0	17.74	5.88	10.42	13.75	16.90	20.10	27.13
MCLcut	ACLR.mcl.MTL	30	8	0	18.02	6.02	10.47	14.02	17.40	20.19	27.81
MCLcut	ACLR.mcl.mtl	30	8	0	19.00	6.06	10.59	15.32	18.53	22.17	28.36
MCLcut	ACLR.RampRepair	30	8	0	18.44	6.16	10.44	14.45	18.14	21.09	28.14
MCLcut	Intact	45	8	0	17.33	6.67	7.72	12.82	17.21	20.60	27.68
MCLcut	ACLR.MCL.MTL	45	8	0	18.18	6.88	7.97	13.61	18.11	21.56	28.78
MCLcut	ACLR.mcl.MTL	45	8	0	18.48	7.00	8.02	13.78	18.49	21.84	29.23
MCLcut	ACLR.mcl.mtl	45	8	0	19.14	7.03	8.30	14.69	19.32	22.97	29.73
MCLcut	ACLR.RampRepair	45	8	0	19.05	7.03	8.25	14.65	19.12	23.03	29.66
MCLcut	Intact	60	8	0	15.99	6.64	7.14	11.02	15.15	20.79	25.09
MCLcut	ACLR.MCL.MTL	60	8	0	16.83	6.91	7.50	11.74	15.53	23.07	25.44
MCLcut	ACLR.mcl.MTL	60	8	0	17.35	7.07	7.67	12.16	16.17	23.65	26.22
MCLcut	ACLR.mcl.mtl	60	8	0	17.75	7.22	7.86	12.55	16.37	24.72	26.51
MCLcut	ACLR.RampRepair	60	8	0	17.80	7.19	7.97	12.58	16.54	24.63	26.52
MCLcut	Intact	75	8	0	14.60	6.59	7.04	9.17	13.61	20.77	23.24
MCLcut	ACLR.MCL.MTL	75	8	0	15.54	6.81	7.61	9.84	14.56	21.72	24.23
MCLcut	ACLR.mcl.MTL	75	8	0	16.21	6.91	8.08	10.49	15.21	22.48	24.86
MCLcut	ACLR.mcl.mtl	75	8	0	16.33	7.02	8.24	10.58	15.09	22.74	25.03
MCLcut	ACLR.RampRepair	75	8	0	16.61	6.98	8.47	11.00	15.45	23.04	25.11
MCLcut	Intact	90	8	0	13.81	6.37	6.99	8.07	13.39	18.32	22.73
MCLcut	ACLR.MCL.MTL	90	8	0	14.72	6.67	7.59	8.69	14.38	19.18	24.13
MCLcut	ACLR.mcl.MTL	90	8	0	15.38	6.67	8.06	9.42	14.97	20.02	24.61
MCLcut	ACLR.mcl.mtl	90	8	0	15.48	6.71	8.36	9.52	15.00	19.99	24.92
MCLcut	ACLR.RampRepair	90	8	0	15.76	6.59	8.70	9.95	15.29	20.40	24.83
MTLcut	Intact	0	8	0	7.45	1.11	5.91	6.77	7.45	8.31	8.87
MTLcut	ACLR.MCL.MTL	0	8	0	7.43	1.39	5.94	6.21	7.08	8.67	9.51
MTLcut	ACLR.MCL.mtl	0	8	0	9.07	1.47	6.57	8.34	9.21	9.72	11.53
MTLcut	ACLR.mcl.mtl	0	8	0	9.37	1.60	6.94	8.28	9.44	10.30	11.94
MTLcut	ACLR.RampRepair	0	8	0	7.56	1.28	5.71	6.81	7.47	8.68	9.20
MTLcut	Intact	15	8	0	13.03	3.32	9.02	11.09	12.50	15.03	19.11
MTLcut	ACLR.MCL.MTL	15	8	0	12.65	2.83	8.65	11.25	12.53	13.95	16.65
MTLcut	ACLR.MCL.mtl	15	8	0	14.42	3.51	10.15	12.54	13.43	15.44	20.13
MTLcut	ACLR.mcl.mtl	15	8	0	14.73	3.79	10.17	12.89	13.44	15.82	21.30
MTLcut	ACLR.RampRepair	15	8	0	13.63	3.28	9.84	11.55	12.99	14.59	19.45
MTLcut	Intact	30	8	0	16.77	5.49	11.52	11.68	15.54	20.91	26.36
MTLcut	ACLR.MCL.MTL	30	8	0	16.67	5.01	11.52	12.12	15.84	19.88	24.57
MTLcut	ACLR.MCL.mtl	30	8	0	18.05	5.64	11.92	14.18	16.55	21.23	27.41
MTLcut	ACLR.mcl.mtl	30	8	0	18.52	5.93	11.99	14.62	16.77	21.64	28.62
MTLcut	ACLR.RampRepair	30	8	0	17.78	5.60	12.00	13.26	16.49	20.68	27.71
MTLcut	Intact	45	8	0	18.14	7.93	10.36	11.93	14.92	24.72	31.45
MTLcut	ACLR.MCL.MTL	45	8	0	18.19	7.60	10.95	12.18	15.20	23.93	30.98
MTLcut	ACLR.MCL.mtl	45	8	0	19.37	7.94	11.36	12.32	17.29	25.41	32.68
MTLcut	ACLR.mcl.mtl	45	8	0	19.63	7.98	11.66	12.58	17.67	25.07	33.35
MTLcut	ACLR.RampRepair	45	8	0	19.27	7.78	11.65	12.55	17.10	24.76	32.80

Group	State	Flexion	n	nmiss	mean	sd	min	Q1.25.	median	Q3.75.	max
MTLcut	Intact	60	8	0	17.72	9.33	8.18	10.41	14.54	24.79	33.76
MTLcut	ACLR.MCL.MTL	60	8	0	18.29	9.32	8.88	11.12	15.04	25.56	34.06
MTLcut	ACLR.MCL.mtl	60	8	0	18.88	9.25	9.10	11.26	16.46	26.07	34.18
MTLcut	ACLR.mcl.mtl	60	8	0	19.43	9.21	9.52	11.92	17.14	26.43	35.13
MTLcut	ACLR.RampRepair	60	8	0	19.39	9.30	9.72	11.96	16.70	26.35	35.23
MTLcut	Intact	75	8	0	17.11	9.52	7.09	9.87	14.17	23.61	33.55
MTLcut	ACLR.MCL.MTL	75	8	0	18.00	9.64	7.76	10.73	14.81	24.78	34.33
MTLcut	ACLR.MCL.mtl	75	8	0	18.28	9.77	7.68	10.89	15.28	24.95	34.89
MTLcut	ACLR.mcl.mtl	75	8	0	18.89	9.76	8.42	11.40	16.00	25.64	35.62
MTLcut	ACLR.RampRepair	75	8	0	19.06	9.80	8.78	11.66	15.85	25.91	35.82
MTLcut	Intact	90	8	0	16.82	9.69	6.00	9.68	14.28	22.48	33.74
MTLcut	ACLR.MCL.MTL	90	8	0	17.68	9.69	6.83	10.63	14.87	23.80	34.28
MTLcut	ACLR.MCL.mtl	90	8	0	17.75	9.72	6.89	10.49	15.23	23.74	34.36
MTLcut	ACLR.mcl.mtl	90	8	0	18.63	9.85	7.51	11.40	16.00	24.80	35.47
MTLcut	ACLR.RampRepair	90	8	0	18.80	9.86	7.98	11.48	16.04	25.14	35.59

Table 8: Internal Rotation (deg) during Simulated IR Test - Version 2

State	Flexion	n	nmiss	mean	sd	min	Q1.25.	median	Q3.75.	max
Intact	0	16	0	8.17	1.99	5.60	6.88	7.92	8.89	13.30
ACLR.MCL.MTL	0	16	0	7.99	1.96	4.85	6.23	7.85	9.02	11.68
ACLR.mcl.MTL	0	8	0	8.72	2.45	5.04	7.49	8.44	10.51	12.27
ACLR.MCL.mtl	0	8	0	9.07	1.47	6.57	8.34	9.21	9.72	11.53
ACLR.mcl.mtl	0	16	0	9.93	2.17	6.94	8.21	9.71	11.88	13.85
ACLR.RampRepair	0	16	0	7.80	2.13	2.90	6.54	7.96	8.97	11.77
Intact	15	16	0	13.44	4.07	8.56	10.22	12.50	15.66	21.93
ACLR.MCL.MTL	15	16	0	13.24	3.67	8.65	10.26	12.53	15.23	20.98
ACLR.mcl.MTL	15	8	0	13.86	4.66	9.86	10.27	11.89	16.41	21.36
ACLR.MCL.mtl	15	8	0	14.42	3.51	10.15	12.54	13.43	15.44	20.13
ACLR.mcl.mtl	15	16	0	15.07	4.08	10.17	12.27	13.76	18.68	22.10
ACLR.RampRepair	15	16	0	13.80	4.04	8.38	11.14	12.82	16.40	21.31
Intact	30	16	0	16.98	5.44	10.04	11.95	15.54	20.91	26.36
ACLR.MCL.MTL	30	16	0	17.20	5.31	10.42	12.60	16.40	19.88	27.13
ACLR.mcl.MTL	30	8	0	18.02	6.02	10.47	14.02	17.40	20.19	27.81
ACLR.MCL.mtl	30	8	0	18.05	5.64	11.92	14.18	16.55	21.23	27.41
ACLR.mcl.mtl	30	16	0	18.76	5.80	10.59	14.62	18.19	22.02	28.62
ACLR.RampRepair	30	16	0	18.11	5.70	10.44	13.26	17.87	20.68	28.14
Intact	45	16	0	17.73	7.09	7.72	11.93	17.08	24.68	31.45
ACLR.MCL.MTL	45	16	0	18.18	7.01	7.97	12.27	17.45	23.93	30.98
ACLR.mcl.MTL	45	8	0	18.48	7.00	8.02	13.78	18.49	21.84	29.23
ACLR.MCL.mtl	45	8	0	19.37	7.94	11.36	12.32	17.29	25.41	32.68
ACLR.mcl.mtl	45	16	0	19.38	7.27	8.30	12.82	18.67	24.85	33.35
ACLR.RampRepair	45	16	0	19.16	7.17	8.25	12.71	18.65	24.76	32.80
Intact	60	16	0	16.86	7.88	7.14	10.83	14.54	23.79	33.76
ACLR.MCL.MTL	60	16	0	17.56	7.96	7.50	11.62	15.04	24.83	34.06
ACLR.mcl.MTL	60	8	0	17.35	7.07	7.67	12.16	16.17	23.65	26.22
ACLR.MCL.mtl	60	8	0	18.88	9.25	9.10	11.26	16.46	26.07	34.18
ACLR.mcl.mtl	60	16	0	18.59	8.04	7.86	12.30	17.14	25.80	35.13
ACLR.RampRepair	60	16	0	18.60	8.07	7.97	12.34	16.70	25.78	35.23
Intact	75	16	0	15.86	8.02	7.04	9.20	14.17	21.43	33.55
ACLR.MCL.MTL	75	16	0	16.77	8.16	7.61	9.89	14.81	23.07	34.33
ACLR.mcl.MTL	75	8	0	16.21	6.91	8.08	10.49	15.21	22.48	24.86
ACLR.MCL.mtl	75	8	0	18.28	9.77	7.68	10.89	15.28	24.95	34.89
ACLR.mcl.mtl	75	16	0	17.61	8.32	8.24	10.62	16.00	24.48	35.62
ACLR.RampRepair	75	16	0	17.84	8.32	8.47	11.00	15.85	24.61	35.82
Intact	90	16	0	15.32	8.07	6.00	8.33	14.28	21.03	33.74
ACLR.MCL.MTL	90	16	0	16.20	8.18	6.83	9.02	14.87	22.43	34.28

State	Flexion	n	nmiss	mean	sd	min	Q1.25.	median	Q3.75.	max
ACLR.mcl.MTL	90	8	0	15.38	6.67	8.06	9.42	14.97	20.02	24.61
ACLR.MCL.mtl	90	8	0	17.75	9.72	6.89	10.49	15.23	23.74	34.36
ACLR.mcl.mtl	90	16	0	17.05	8.30	7.51	9.81	16.00	23.36	35.47
ACLR.RampRepair	90	16	0	17.28	8.25	7.98	10.15	16.04	23.56	35.59

Table 9: Internal Rotation (deg) during Simulated IR Test, Intact-Subtracted

Group	State	Flexion	n	nmiss	mean	sd	min	Q1.25.	median	Q3.75.	max
MCLcut	ACLR.MCL.MTL	0	8	0	-0.34	1.63	-2.64	-1.10	-0.29	0.16	2.30
MCLcut	ACLR.mcl.MTL	0	8	0	-0.17	1.75	-2.59	-0.96	-0.21	0.43	2.46
MCLcut	ACLR.mcl.mtl	0	8	0	1.60	1.85	-0.68	0.60	0.99	2.35	4.98
MCLcut	ACLR.RampRepair	0	8	0	-0.86	1.77	-3.65	-1.75	-1.00	0.50	1.46
MCLcut	ACLR.MCL.MTL	15	8	0	-0.03	1.55	-2.57	-0.61	-0.11	0.29	2.70
MCLcut	ACLR.mcl.MTL	15	8	0	0.01	1.45	-2.36	-0.50	-0.19	0.29	2.47
MCLcut	ACLR.mcl.mtl	15	8	0	1.55	1.73	0.17	0.31	0.90	2.15	5.27
MCLcut	ACLR.RampRepair	15	8	0	0.12	1.70	-2.41	-0.82	-0.12	1.27	2.67
MCLcut	ACLR.MCL.MTL	30	8	0	0.55	0.97	-1.10	0.12	0.47	0.93	2.07
MCLcut	ACLR.mcl.MTL	30	8	0	0.82	1.14	-1.04	0.49	0.56	1.11	2.58
MCLcut	ACLR.mcl.mtl	30	8	0	1.81	1.33	0.54	0.89	1.34	2.33	4.54
MCLcut	ACLR.RampRepair	30	8	0	1.25	1.34	0.04	0.31	0.88	1.63	3.86
MCLcut	ACLR.MCL.MTL	45	8	0	0.85	0.75	0.07	0.27	0.79	1.07	2.43
MCLcut	ACLR.mcl.MTL	45	8	0	1.14	0.77	0.29	0.55	1.07	1.45	2.66
MCLcut	ACLR.mcl.mtl	45	8	0	1.81	1.06	0.58	1.28	1.73	2.03	4.08
MCLcut	ACLR.RampRepair	45	8	0	1.72	1.13	0.52	1.20	1.40	1.99	4.23
MCLcut	ACLR.MCL.MTL	60	8	0	0.83	0.80	0.35	0.36	0.44	0.99	2.67
MCLcut	ACLR.mcl.MTL	60	8	0	1.36	0.83	0.53	1.05	1.13	1.27	3.26
MCLcut	ACLR.mcl.mtl	60	8	0	1.76	1.19	0.72	1.23	1.33	1.73	4.54
MCLcut	ACLR.RampRepair	60	8	0	1.81	1.11	0.83	1.31	1.43	1.79	4.40
MCLcut	ACLR.MCL.MTL	75	8	0	0.94	0.41	0.56	0.64	0.91	1.01	1.83
MCLcut	ACLR.mcl.MTL	75	8	0	1.60	0.54	1.04	1.24	1.50	1.75	2.73
MCLcut	ACLR.mcl.mtl	75	8	0	1.73	0.71	1.17	1.29	1.59	1.79	3.39
MCLcut	ACLR.RampRepair	75	8	0	2.01	0.67	1.36	1.69	1.87	2.06	3.49
MCLcut	ACLR.MCL.MTL	90	8	0	0.91	0.35	0.53	0.66	0.79	1.15	1.40
MCLcut	ACLR.mcl.MTL	90	8	0	1.57	0.35	1.00	1.37	1.53	1.79	2.13
MCLcut	ACLR.mcl.mtl	90	8	0	1.67	0.39	1.28	1.37	1.48	1.99	2.23
MCLcut	ACLR.RampRepair	90	8	0	1.95	0.30	1.51	1.71	1.96	2.14	2.37
MTLcut	ACLR.MCL.MTL	0	8	0	-0.02	1.15	-2.51	-0.20	0.16	0.52	1.30
MTLcut	ACLR.MCL.mtl	0	8	0	1.62	1.00	0.65	0.79	1.40	2.28	3.32
MTLcut	ACLR.mcl.mtl	0	8	0	1.92	0.92	0.81	1.24	2.03	2.17	3.73
MTLcut	ACLR.RampRepair	0	8	0	0.11	0.86	-1.21	-0.43	0.44	0.74	0.97
MTLcut	ACLR.MCL.MTL	15	8	0	-0.38	1.39	-2.81	-0.75	-0.06	0.25	1.64
MTLcut	ACLR.MCL.mtl	15	8	0	1.39	1.63	-0.93	0.66	1.03	1.99	4.31
MTLcut	ACLR.mcl.mtl	15	8	0	1.71	1.80	-1.33	0.74	1.81	2.47	4.61
MTLcut	ACLR.RampRepair	15	8	0	0.60	1.37	-1.68	0.03	0.71	1.43	2.48
MTLcut	ACLR.MCL.MTL	30	8	0	-0.10	1.28	-2.07	-0.59	0.07	0.70	1.71
MTLcut	ACLR.MCL.mtl	30	8	0	1.28	1.54	-0.97	0.34	1.02	2.02	3.82
MTLcut	ACLR.mcl.mtl	30	8	0	1.75	1.69	-0.68	0.58	1.69	2.55	4.58
MTLcut	ACLR.RampRepair	30	8	0	1.01	1.24	-1.32	0.33	1.38	1.71	2.65
MTLcut	ACLR.MCL.MTL	45	8	0	0.06	0.84	-1.71	-0.20	0.28	0.61	0.92
MTLcut	ACLR.MCL.mtl	45	8	0	1.24	1.31	-0.21	0.39	0.92	1.51	3.89
MTLcut	ACLR.mcl.mtl	45	8	0	1.49	1.53	-0.81	0.77	1.31	2.13	4.19
MTLcut	ACLR.RampRepair	45	8	0	1.13	1.04	-0.85	0.74	1.32	1.67	2.65
MTLcut	ACLR.MCL.MTL	60	8	0	0.57	0.41	-0.16	0.32	0.62	0.84	1.15
MTLcut	ACLR.MCL.mtl	60	8	0	1.16	0.65	0.43	0.83	1.10	1.29	2.56
MTLcut	ACLR.mcl.mtl	60	8	0	1.71	0.69	1.03	1.34	1.47	1.87	3.25
MTLcut	ACLR.RampRepair	60	8	0	1.67	0.33	1.27	1.52	1.57	1.73	2.29
MTLcut	ACLR.MCL.MTL	75	8	0	0.89	0.30	0.46	0.76	0.81	1.07	1.44
MTLcut	ACLR.MCL.mtl	75	8	0	1.17	0.41	0.59	0.88	1.21	1.38	1.83
MTLcut	ACLR.mcl.mtl	75	8	0	1.78	0.34	1.33	1.47	1.84	2.05	2.21
MTLcut	ACLR.RampRepair	75	8	0	1.95	0.37	1.31	1.76	1.94	2.26	2.44
MTLcut	ACLR.MCL.MTL	90	8	0	0.86	0.32	0.35	0.75	0.82	1.03	1.40
MTLcut	ACLR.MCL.mtl	90	8	0	0.93	0.24	0.62	0.82	0.89	1.06	1.26
MTLcut	ACLR.mcl.mtl	90	8	0	1.81	0.31	1.49	1.65	1.73	1.89	2.36
MTLcut	ACLR.RampRepair	90	8	0	1.98	0.49	1.25	1.74	1.95	2.31	2.74

Table 10: Internal Rotation (deg) during Simulated IR Test, Intact-Subtracted - Version 2

State	Flexion	n	nmiss	mean	sd	min	Q1.25.	median	Q3.75.	max
ACLR.MCL.MTL	0	16	0	-0.18	1.38	-2.64	-0.51	-0.19	0.52	2.30
ACLR.mcl.MTL	0	8	0	-0.17	1.75	-2.59	-0.96	-0.21	0.43	2.46
ACLR.MCL.mtl	0	8	0	1.62	1.00	0.65	0.79	1.40	2.28	3.32
ACLR.mcl.mtl	0	16	0	1.76	1.42	-0.68	0.79	1.63	2.17	4.98
ACLR.RampRepair	0	16	0	-0.37	1.44	-3.65	-1.23	0.04	0.74	1.46
ACLR.MCL.MTL	15	16	0	-0.20	1.43	-2.81	-0.61	-0.11	0.25	2.70
ACLR.mcl.MTL	15	8	0	0.01	1.45	-2.36	-0.50	-0.19	0.29	2.47
ACLR.MCL.mtl	15	8	0	1.39	1.63	-0.93	0.66	1.03	1.99	4.31
ACLR.mcl.mtl	15	16	0	1.63	1.71	-1.33	0.44	1.18	2.30	5.27
ACLR.RampRepair	15	16	0	0.36	1.51	-2.41	-0.69	0.42	1.43	2.67
ACLR.MCL.MTL	30	16	0	0.22	1.15	-2.07	-0.14	0.32	0.71	2.07
ACLR.mcl.MTL	30	8	0	0.82	1.14	-1.04	0.49	0.56	1.11	2.58
ACLR.MCL.mtl	30	8	0	1.28	1.54	-0.97	0.34	1.02	2.02	3.82
ACLR.mcl.mtl	30	16	0	1.78	1.47	-0.68	0.75	1.50	2.40	4.58
ACLR.RampRepair	30	16	0	1.13	1.26	-1.32	0.31	1.19	1.71	3.86
ACLR.MCL.MTL	45	16	0	0.45	0.87	-1.71	0.19	0.46	0.90	2.43
ACLR.mcl.MTL	45	8	0	1.14	0.77	0.29	0.55	1.07	1.45	2.66
ACLR.MCL.mtl	45	8	0	1.24	1.31	-0.21	0.39	0.92	1.51	3.89
ACLR.mcl.mtl	45	16	0	1.65	1.28	-0.81	0.92	1.50	2.03	4.19
ACLR.RampRepair	45	16	0	1.43	1.09	-0.85	0.91	1.36	1.78	4.23
ACLR.MCL.MTL	60	16	0	0.70	0.63	-0.16	0.35	0.51	0.88	2.67
ACLR.mcl.MTL	60	8	0	1.36	0.83	0.53	1.05	1.13	1.27	3.26
ACLR.MCL.mtl	60	8	0	1.16	0.65	0.43	0.83	1.10	1.29	2.56
ACLR.mcl.mtl	60	16	0	1.73	0.94	0.72	1.24	1.40	1.87	4.54
ACLR.RampRepair	60	16	0	1.74	0.79	0.83	1.41	1.55	1.76	4.40
ACLR.MCL.MTL	75	16	0	0.91	0.35	0.46	0.67	0.83	1.07	1.83
ACLR.mcl.MTL	75	8	0	1.60	0.54	1.04	1.24	1.50	1.75	2.73
ACLR.MCL.mtl	75	8	0	1.17	0.41	0.59	0.88	1.21	1.38	1.83
ACLR.mcl.mtl	75	16	0	1.76	0.54	1.17	1.42	1.68	2.00	3.39
ACLR.RampRepair	75	16	0	1.98	0.52	1.31	1.76	1.87	2.26	3.49
ACLR.MCL.MTL	90	16	0	0.88	0.32	0.35	0.66	0.82	1.08	1.40
ACLR.mcl.MTL	90	8	0	1.57	0.35	1.00	1.37	1.53	1.79	2.13
ACLR.MCL.mtl	90	8	0	0.93	0.24	0.62	0.82	0.89	1.06	1.26
ACLR.mcl.mtl	90	16	0	1.74	0.35	1.28	1.48	1.71	1.99	2.36
ACLR.RampRepair	90	16	0	1.97	0.39	1.25	1.71	1.96	2.27	2.74

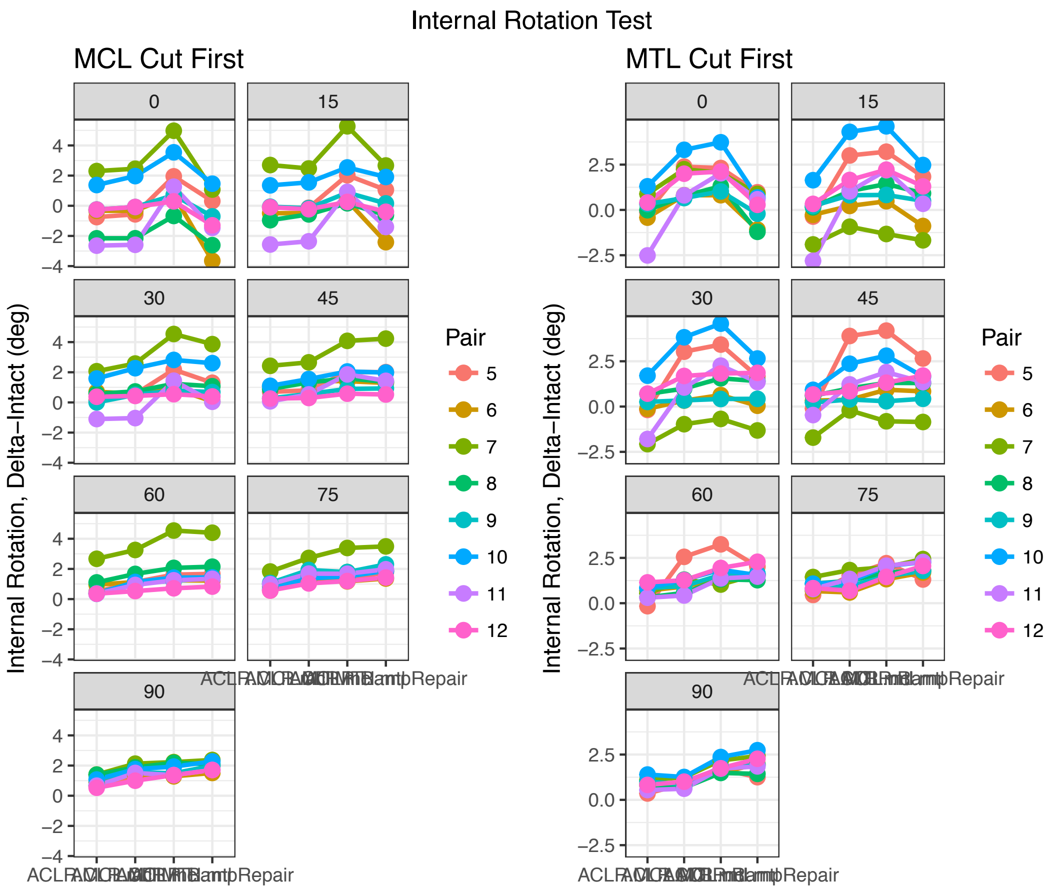
3.2.1 For Paper

Table 11: Mean ± SD Internal Rotation by Cut State and Flexion Angle - Non-Intact-Subtracted

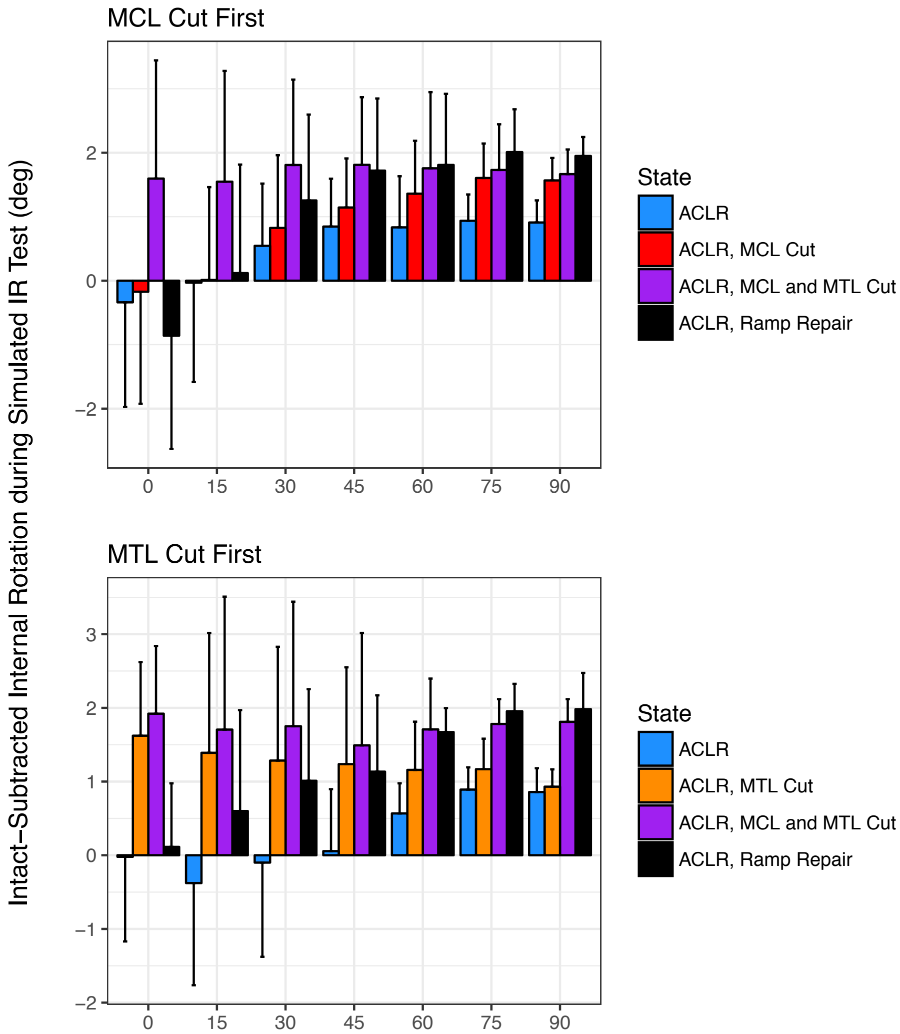
State	0	15	30	45	60	75	90
Intact	8.2 ± 2	13.4 ± 4.1	17 ± 5.4	17.7 ± 7.1	16.9 ± 7.9	15.9 ± 8	15.3 ± 8.1
ACLR.MCL.MTL	8 ± 2	13.2 ± 3.7	17.2 ± 5.3	18.2 ± 7	17.6 ± 8	16.8 ± 8.2	16.2 ± 8.2
ACLR.mcl.MTL	8.7 ± 2.4	13.9 ± 4.7	18 ± 6	18.5 ± 7	17.4 ± 7.1	16.2 ± 6.9	15.4 ± 6.7
ACLR.MCL.mtl	9.1 ± 1.5	14.4 ± 3.5	18.1 ± 5.6	19.4 ± 7.9	18.9 ± 9.2	18.3 ± 9.8	17.7 ± 9.7
ACLR.mcl.mtl	9.9 ± 2.2	15.1 ± 4.1	18.8 ± 5.8	19.4 ± 7.3	18.6 ± 8	17.6 ± 8.3	17.1 ± 8.3
ACLR.RampRepair	7.8 ± 2.1	13.8 ± 4	18.1 ± 5.7	19.2 ± 7.2	18.6 ± 8.1	17.8 ± 8.3	17.3 ± 8.3

3.3 Plot Data

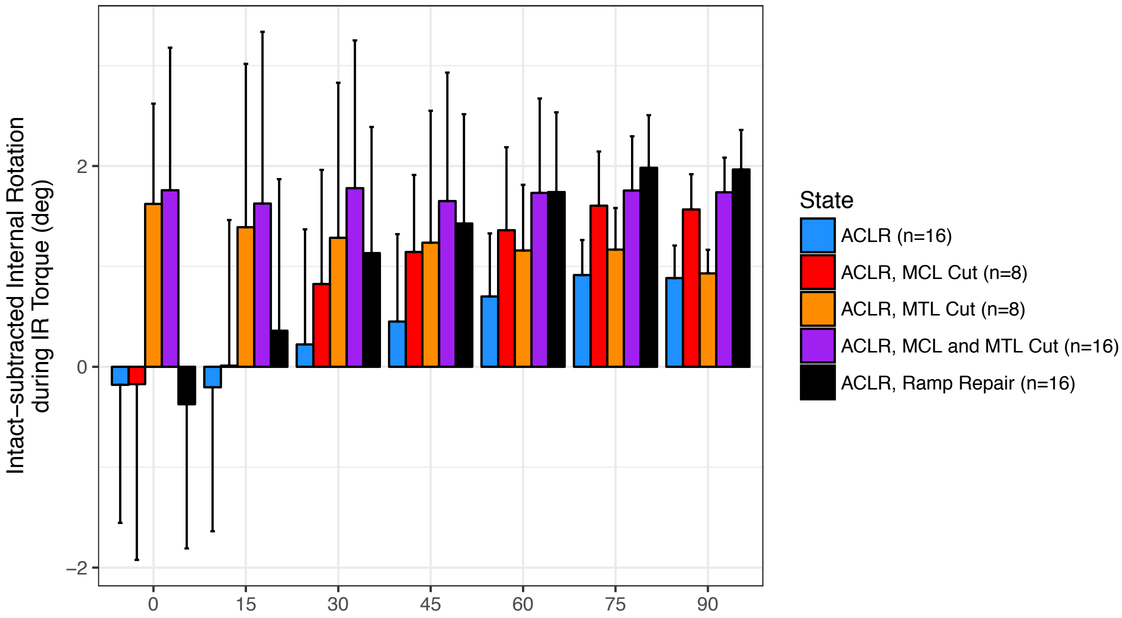
3.3.1 Spaghetti plots to inspect subject-level data



3.3.2 Bar Plot


MCL Cut First
Intact–Subtracted Internal Rotation during Simulated IR Test (deg)
−2
0
2
0
15
30
45
60
75
90
State
ACLR
ACLR, MCL Cut
ACLR, MCL and MTL Cut
ACLR, Ramp Repair
MTL Cut First
−2
−1
0
1
2
3
0
15
30
45
60
75
90
State
ACLR
ACLR, MTL Cut
ACLR, MCL and MTL Cut
ACLR, Ramp Repair

3.3.3 New Bar Plot

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3.4 Custom set of T-tests

Table 12: T-tests for Internal Rotation during IR Torque (deg), intact-subtracted data

	Flexion Angle	n	Mean Diff	SD Diff	CI LB	CI UB	Holm P
Intact vs ACLR+MCL+MTL	0	16	-0.18	1.38	-0.91	0.55	1.0000
Intact vs ACLR-MCL+MTL	0	8	-0.17	1.75	-1.64	1.29	1.0000
Intact vs ACLR+MCL-MTL	0	8	1.62	1.00	0.79	2.46	0.0150
Intact vs ACLR-MCL-MTL	0	16	1.76	1.42	1.00	2.52	0.0014
Intact vs ACLR+RampRepair	0	16	-0.37	1.44	-1.14	0.39	1.0000
ACLR+MCL+MTL vs ACLR-MCL+MTL	0	8	-0.17	0.19	-0.32	-0.01	0.2068
ACLR+MCL+MTL vs ACLR+MCL-MTL	0	8	-1.64	0.96	-2.44	-0.84	0.0129
ACLR+MCL+MTL vs ACLR-MCL-MTL	0	16	-1.94	1.13	-2.54	-1.33	0.0001
ACLR+MCL+MTL vs ACLR+RampRepair	0	16	0.19	1.40	-0.55	0.94	1.0000
ACLR-MCL-MTL vs ACL+RampRepair	0	16	2.13	0.95	1.63	2.64	0.0000
Intact vs ACLR+MCL+MTL	15	16	-0.20	1.43	-0.97	0.56	1.0000
Intact vs ACLR-MCL+MTL	15	8	0.01	1.45	-1.20	1.22	1.0000
Intact vs ACLR+MCL-MTL	15	8	1.39	1.63	0.03	2.75	0.2774
Intact vs ACLR-MCL-MTL	15	16	1.63	1.71	0.72	2.54	0.0138
Intact vs ACLR+RampRepair	15	16	0.36	1.51	-0.45	1.16	1.0000
ACLR+MCL+MTL vs ACLR-MCL+MTL	15	8	-0.04	0.21	-0.21	0.13	1.0000
ACLR+MCL+MTL vs ACLR+MCL-MTL	15	8	-1.77	1.32	-2.87	-0.66	0.0481
ACLR+MCL+MTL vs ACLR-MCL-MTL	15	16	-1.83	1.35	-2.55	-1.11	0.0006
ACLR+MCL+MTL vs ACLR+RampRepair	15	16	-0.56	1.14	-1.17	0.04	0.3310
ACLR-MCL-MTL vs ACL+RampRepair	15	16	1.27	0.82	0.83	1.70	0.0002
Intact vs ACLR+MCL+MTL	30	16	0.22	1.15	-0.39	0.83	0.4489
Intact vs ACLR-MCL+MTL	30	8	0.82	1.14	-0.13	1.77	0.1585
Intact vs ACLR+MCL-MTL	30	8	1.28	1.54	-0.01	2.58	0.1525
Intact vs ACLR-MCL-MTL	30	16	1.78	1.47	0.99	2.56	0.0020
Intact vs ACLR+RampRepair	30	16	1.13	1.26	0.46	1.80	0.0155
ACLR+MCL+MTL vs ACLR-MCL+MTL	30	8	-0.28	0.28	-0.52	-0.04	0.1081
ACLR+MCL+MTL vs ACLR+MCL-MTL	30	8	-1.38	1.20	-2.38	-0.39	0.0679
ACLR+MCL+MTL vs ACLR-MCL-MTL	30	16	-1.56	1.23	-2.21	-0.90	0.0014
ACLR+MCL+MTL vs ACLR+RampRepair	30	16	-0.91	0.87	-1.37	-0.44	0.0062
ACLR-MCL-MTL vs ACL+RampRepair	30	16	0.65	0.62	0.32	0.97	0.0062
Intact vs ACLR+MCL+MTL	45	16	0.45	0.87	-0.01	0.91	0.1297
Intact vs ACLR-MCL+MTL	45	8	1.14	0.77	0.50	1.79	0.0198
Intact vs ACLR+MCL-MTL	45	8	1.24	1.31	0.14	2.33	0.1297
Intact vs ACLR-MCL-MTL	45	16	1.65	1.28	0.97	2.33	0.0009
Intact vs ACLR+RampRepair	45	16	1.43	1.09	0.85	2.01	0.0009
ACLR+MCL+MTL vs ACLR-MCL+MTL	45	8	-0.30	0.16	-0.43	-0.16	0.0074
ACLR+MCL+MTL vs ACLR+MCL-MTL	45	8	-1.18	1.33	-2.29	-0.07	0.1297
ACLR+MCL+MTL vs ACLR-MCL-MTL	45	16	-1.20	1.05	-1.76	-0.64	0.0025
ACLR+MCL+MTL vs ACLR+RampRepair	45	16	-0.98	0.69	-1.35	-0.61	0.0005
ACLR-MCL-MTL vs ACL+RampRepair	45	16	0.22	0.49	-0.04	0.49	0.1297
Intact vs ACLR+MCL+MTL	60	16	0.70	0.63	0.37	1.04	0.0023
Intact vs ACLR-MCL+MTL	60	8	1.36	0.83	0.67	2.05	0.0070
Intact vs ACLR+MCL-MTL	60	8	1.16	0.65	0.61	1.71	0.0062
Intact vs ACLR-MCL-MTL	60	16	1.73	0.94	1.23	2.23	0.0000
Intact vs ACLR+RampRepair	60	16	1.74	0.79	1.32	2.16	0.0000
ACLR+MCL+MTL vs ACLR-MCL+MTL	60	8	-0.53	0.23	-0.72	-0.34	0.0019
ACLR+MCL+MTL vs ACLR+MCL-MTL	60	8	-0.59	0.89	-1.33	0.15	0.2041
ACLR+MCL+MTL vs ACLR-MCL-MTL	60	16	-1.03	0.73	-1.42	-0.64	0.0003
ACLR+MCL+MTL vs ACLR+RampRepair	60	16	-1.04	0.44	-1.28	-0.80	0.0000
ACLR-MCL-MTL vs ACL+RampRepair	60	16	-0.01	0.38	-0.21	0.20	0.9317
Intact vs ACLR+MCL+MTL	75	16	0.91	0.35	0.73	1.10	0.0000
Intact vs ACLR-MCL+MTL	75	8	1.60	0.54	1.15	2.06	0.0003
Intact vs ACLR+MCL-MTL	75	8	1.17	0.41	0.82	1.51	0.0003
Intact vs ACLR-MCL-MTL	75	16	1.76	0.54	1.47	2.04	0.0000

	Flexion Angle	n	Mean Diff	SD Diff	CI LB	CI UB	Holm P
Intact vs ACLR+RampRepair	75	16	1.98	0.52	1.70	2.26	0.0000
ACLR+MCL+MTL vs ACLR-MCL+MTL	75	8	-0.67	0.17	-0.81	-0.53	0.0000
ACLR+MCL+MTL vs ACLR+MCL-MTL	75	8	-0.28	0.39	-0.60	0.05	0.0856
ACLR+MCL+MTL vs ACLR-MCL-MTL	75	16	-0.84	0.38	-1.04	-0.64	0.0000
ACLR+MCL+MTL vs ACLR+RampRepair	75	16	-1.07	0.28	-1.22	-0.92	0.0000
ACLR-MCL-MTL vs ACL+RampRepair	75	16	-0.23	0.34	-0.40	-0.05	0.0336
Intact vs ACLR+MCL+MTL	90	16	0.88	0.32	0.71	1.06	0.0000
Intact vs ACLR-MCL+MTL	90	8	1.57	0.35	1.27	1.86	0.0000
Intact vs ACLR+MCL-MTL	90	8	0.93	0.24	0.73	1.13	0.0000
Intact vs ACLR-MCL-MTL	90	16	1.74	0.35	1.55	1.92	0.0000
Intact vs ACLR+RampRepair	90	16	1.97	0.39	1.76	2.18	0.0000
ACLR+MCL+MTL vs ACLR-MCL+MTL	90	8	-0.66	0.16	-0.79	-0.52	0.0000
ACLR+MCL+MTL vs ACLR+MCL-MTL	90	8	-0.07	0.23	-0.27	0.12	0.4061
ACLR+MCL+MTL vs ACLR-MCL-MTL	90	16	-0.85	0.22	-0.97	-0.74	0.0000
ACLR+MCL+MTL vs ACLR+RampRepair	90	16	-1.08	0.27	-1.22	-0.94	0.0000
ACLR-MCL-MTL vs ACL+RampRepair	90	16	-0.23	0.26	-0.36	-0.09	0.0060

4 Simulated External Rotation Test

4.1 Manipulate Data

```
# Create delta-intact data with dplyr gather/spread/gather
dat2.er.spread <- dat2.er %>% select(Pair, Specimen, Group, Flexion,
    State, Value) %>% spread(data = ., key = State, value = Value,
    fill = NA)
dat2.er.deltaintact.spread <- dat2.er.spread
dat2.er.deltaintact.spread[, 5:10] <- dat2.er.spread[, 5:10] -
    dat2.er.spread[, 5]
dat2.er.deltaintact <- gather(dat2.er.deltaintact.spread, key = State,
    value = Value, Intact:ACLR.RampRepair, -(Pair:Flexion), factor_key = TRUE)
dat2.er.deltaintact <- dat2.er.deltaintact %>% subset(State !=
    "Intact") %>% subset(!is.na(Value)) %>% droplevels()
str(dat2.er.deltaintact)
```

```
~~~ 'data.frame':   448 obs. of  6 variables:
~~~  $ Pair    : Factor w/ 8 levels "5","6","7","8",..: 1 1 1 1 1 1 1 1 1 1 ...
~~~  $ Specimen: num  5 5 5 5 5 5 5 17 17 17 ...
~~~  $ Group   : Factor w/ 2 levels "MCLcut","MTLcut": 1 1 1 1 1 1 1 2 2 2 ...
~~~  $ Flexion : num  0 15 30 45 60 75 90 0 15 30 ...
~~~  $ State   : Factor w/ 5 levels "ACLR.MCL.MTL",..: 1 1 1 1 1 1 1 1 1 1 ...
~~~  $ Value   : num  -0.126 -0.792 -0.6 -0.832 -0.686 ...
```

```
head(dat2.er.deltaintact)
```

```
~~~     Pair Specimen  Group Flexion        State     Value
~~~ 113    5        5 MCLcut       0 ACLR.MCL.MTL -0.126047
~~~ 114    5        5 MCLcut      15 ACLR.MCL.MTL -0.792392
~~~ 115    5        5 MCLcut      30 ACLR.MCL.MTL -0.599906
~~~ 116    5        5 MCLcut      45 ACLR.MCL.MTL -0.831670
~~~ 117    5        5 MCLcut      60 ACLR.MCL.MTL -0.685770
~~~ 118    5        5 MCLcut      75 ACLR.MCL.MTL -0.447487
```

4.2 Summary Stats

Table 13: External Rotation (deg) during Simulated ER Test

Group	State	Flexion	n	nmiss	mean	sd	min	Q1.25.	median	Q3.75.	max
MCLcut	Intact	0	8	0	-10.36	1.52	-13.36	-10.88	-10.09	-9.80	-8.00
MCLcut	ACLR.MCL.MTL	0	8	0	-10.62	1.62	-13.51	-11.32	-10.44	-9.91	-8.13
MCLcut	ACLR.mcl.MTL	0	8	0	-10.76	1.62	-13.59	-11.50	-10.65	-10.06	-8.14
MCLcut	ACLR.mcl.mtl	0	8	0	-11.22	1.61	-13.88	-12.06	-11.11	-10.43	-8.60
MCLcut	ACLR.RampRepair	0	8	0	-8.69	2.15	-12.91	-9.47	-8.46	-7.41	-6.09
MCLcut	Intact	15	8	0	-13.35	2.02	-16.64	-14.57	-13.32	-11.78	-10.73
MCLcut	ACLR.MCL.MTL	15	8	0	-13.84	1.89	-17.09	-14.79	-13.75	-12.51	-11.53
MCLcut	ACLR.mcl.MTL	15	8	0	-13.89	1.94	-17.09	-15.03	-13.67	-12.57	-11.56
MCLcut	ACLR.mcl.mtl	15	8	0	-14.40	2.05	-17.77	-15.35	-14.34	-12.99	-11.82
MCLcut	ACLR.RampRepair	15	8	0	-13.15	2.77	-17.51	-14.88	-13.06	-10.67	-9.79
MCLcut	Intact	30	8	0	-16.14	4.19	-22.28	-18.60	-14.58	-13.39	-11.35
MCLcut	ACLR.MCL.MTL	30	8	0	-16.74	4.22	-23.02	-19.34	-15.42	-13.69	-11.89
MCLcut	ACLR.mcl.MTL	30	8	0	-17.00	4.41	-23.63	-20.00	-15.49	-13.84	-11.92
MCLcut	ACLR.mcl.mtl	30	8	0	-17.32	4.52	-24.19	-20.25	-15.81	-14.10	-12.09
MCLcut	ACLR.RampRepair	30	8	0	-16.97	4.60	-24.13	-19.36	-15.66	-13.63	-11.76
MCLcut	Intact	45	8	0	-17.96	6.56	-27.81	-20.87	-17.03	-13.17	-10.58
MCLcut	ACLR.MCL.MTL	45	8	0	-18.60	6.62	-28.28	-21.44	-17.93	-13.70	-10.87
MCLcut	ACLR.mcl.MTL	45	8	0	-18.77	6.68	-28.59	-21.92	-17.93	-13.88	-10.82
MCLcut	ACLR.mcl.mtl	45	8	0	-19.13	6.83	-29.04	-22.33	-18.22	-14.14	-11.06
MCLcut	ACLR.RampRepair	45	8	0	-19.00	7.00	-29.14	-22.22	-18.10	-14.11	-10.90
MCLcut	Intact	60	8	0	-19.45	8.21	-33.88	-22.94	-19.15	-13.79	-9.88
MCLcut	ACLR.MCL.MTL	60	8	0	-20.07	8.18	-34.26	-23.71	-19.74	-14.25	-10.34
MCLcut	ACLR.mcl.MTL	60	8	0	-20.37	8.28	-34.57	-24.16	-20.17	-14.32	-10.48
MCLcut	ACLR.mcl.mtl	60	8	0	-20.69	8.34	-34.90	-24.50	-20.29	-14.72	-10.70
MCLcut	ACLR.RampRepair	60	8	0	-20.65	8.40	-34.99	-24.42	-20.23	-14.85	-10.50
MCLcut	Intact	75	8	0	-20.68	8.85	-36.32	-24.83	-21.07	-14.70	-9.81
MCLcut	ACLR.MCL.MTL	75	8	0	-21.46	9.03	-37.44	-25.92	-21.66	-15.01	-10.76
MCLcut	ACLR.mcl.MTL	75	8	0	-21.78	9.01	-37.54	-26.50	-22.05	-15.30	-10.99
MCLcut	ACLR.mcl.mtl	75	8	0	-22.15	9.21	-38.18	-27.41	-22.28	-15.56	-11.00
MCLcut	ACLR.RampRepair	75	8	0	-22.17	9.19	-38.09	-27.52	-22.29	-15.73	-10.99
MCLcut	Intact	90	8	0	-22.26	9.82	-38.08	-28.31	-22.32	-15.34	-9.12
MCLcut	ACLR.MCL.MTL	90	8	0	-22.96	9.80	-38.64	-28.99	-22.76	-15.60	-10.60
MCLcut	ACLR.mcl.MTL	90	8	0	-23.30	9.84	-38.98	-29.10	-23.50	-15.94	-10.62
MCLcut	ACLR.mcl.mtl	90	8	0	-23.76	9.97	-39.49	-29.40	-24.33	-16.24	-10.94
MCLcut	ACLR.RampRepair	90	8	0	-23.72	10.01	-39.36	-29.31	-24.41	-16.30	-10.74
MTLcut	Intact	0	8	0	-9.10	1.88	-11.74	-10.59	-9.22	-7.63	-6.61
MTLcut	ACLR.MCL.MTL	0	8	0	-9.29	1.90	-11.73	-11.08	-9.07	-7.91	-6.78
MTLcut	ACLR.MCL.mtl	0	8	0	-9.50	1.88	-12.06	-11.11	-9.34	-8.18	-6.90
MTLcut	ACLR.mcl.mtl	0	8	0	-9.81	1.98	-12.36	-11.68	-9.59	-8.28	-7.21
MTLcut	ACLR.RampRepair	0	8	0	-8.52	1.37	-10.56	-9.56	-8.33	-7.60	-6.49
MTLcut	Intact	15	8	0	-13.13	2.57	-16.38	-15.61	-12.59	-11.08	-10.19
MTLcut	ACLR.MCL.MTL	15	8	0	-13.40	2.59	-16.93	-15.97	-12.80	-11.22	-10.40
MTLcut	ACLR.MCL.mtl	15	8	0	-13.54	2.65	-17.05	-16.23	-12.84	-11.35	-10.60
MTLcut	ACLR.mcl.mtl	15	8	0	-13.81	2.74	-17.48	-16.45	-12.94	-11.69	-10.79
MTLcut	ACLR.RampRepair	15	8	0	-13.41	2.75	-16.88	-16.25	-12.78	-10.92	-10.51
MTLcut	Intact	30	8	0	-15.15	2.44	-18.48	-17.56	-13.88	-13.43	-12.80
MTLcut	ACLR.MCL.MTL	30	8	0	-15.75	2.52	-19.57	-17.80	-14.31	-13.97	-13.50
MTLcut	ACLR.MCL.mtl	30	8	0	-15.87	2.59	-19.92	-17.88	-14.37	-14.08	-13.64
MTLcut	ACLR.mcl.mtl	30	8	0	-16.23	2.68	-20.34	-18.27	-14.57	-14.40	-13.99
MTLcut	ACLR.RampRepair	30	8	0	-15.96	2.82	-20.30	-18.21	-14.35	-14.10	-13.40
MTLcut	Intact	45	8	0	-15.87	3.11	-19.65	-18.45	-15.80	-14.17	-10.94
MTLcut	ACLR.MCL.MTL	45	8	0	-16.43	3.18	-21.20	-18.48	-16.26	-14.43	-11.66
MTLcut	ACLR.MCL.mtl	45	8	0	-16.61	3.17	-21.17	-18.73	-16.42	-14.64	-11.74
MTLcut	ACLR.mcl.mtl	45	8	0	-16.91	3.29	-21.62	-19.05	-16.76	-14.79	-12.03
MTLcut	ACLR.RampRepair	45	8	0	-16.73	3.45	-21.81	-19.06	-16.66	-14.54	-11.98

Group	State	Flexion	n	nmiss	mean	sd	min	Q1.25.	median	Q3.75.	max
MTLcut	Intact	60	8	0	-16.40	3.99	-20.32	-19.18	-17.97	-13.81	-9.39
MTLcut	ACLR.MCL.MTL	60	8	0	-17.07	4.12	-21.98	-19.88	-18.13	-14.29	-10.11
MTLcut	ACLR.MCL.mtl	60	8	0	-17.20	4.19	-22.22	-20.06	-18.23	-14.43	-10.08
MTLcut	ACLR.mcl.mtl	60	8	0	-17.63	4.35	-22.94	-20.49	-18.73	-14.67	-10.44
MTLcut	ACLR.RampRepair	60	8	0	-17.50	4.41	-22.80	-20.37	-18.77	-14.52	-10.44
MTLcut	Intact	75	8	0	-17.51	4.37	-21.76	-20.69	-19.04	-14.95	-8.90
MTLcut	ACLR.MCL.MTL	75	8	0	-18.18	4.55	-22.78	-21.65	-19.58	-15.11	-9.96
MTLcut	ACLR.MCL.mtl	75	8	0	-18.26	4.52	-22.87	-21.65	-19.75	-15.21	-10.15
MTLcut	ACLR.mcl.mtl	75	8	0	-18.69	4.76	-23.63	-22.17	-20.14	-15.41	-10.34
MTLcut	ACLR.RampRepair	75	8	0	-18.63	4.90	-23.73	-22.18	-20.12	-15.32	-10.32
MTLcut	Intact	90	8	0	-18.63	4.27	-23.47	-20.81	-20.06	-16.66	-9.80
MTLcut	ACLR.MCL.MTL	90	8	0	-19.40	4.56	-25.14	-21.80	-20.78	-16.76	-10.67
MTLcut	ACLR.MCL.mtl	90	8	0	-19.48	4.57	-24.87	-22.36	-20.81	-16.80	-10.70
MTLcut	ACLR.mcl.mtl	90	8	0	-20.03	4.74	-25.76	-23.14	-21.38	-17.18	-11.02
MTLcut	ACLR.RampRepair	90	8	0	-19.83	4.90	-26.05	-22.99	-21.36	-16.76	-10.92

Table 14: External Rotation (deg) during Simulated ER Test - Version 2

State	Flexion	n	nmiss	mean	sd	min	Q1.25.	median	Q3.75.	max
Intact	0	16	0	-9.73	1.77	-13.36	-10.81	-9.87	-8.83	-6.61
ACLR.MCL.MTL	0	16	0	-9.95	1.84	-13.51	-11.19	-10.21	-8.64	-6.78
ACLR.mcl.MTL	0	8	0	-10.76	1.62	-13.59	-11.50	-10.65	-10.06	-8.14
ACLR.MCL.mtl	0	8	0	-9.50	1.88	-12.06	-11.11	-9.34	-8.18	-6.90
ACLR.mcl.mtl	0	16	0	-10.52	1.89	-13.88	-11.90	-10.70	-9.32	-7.21
ACLR.RampRepair	0	16	0	-8.61	1.74	-12.91	-9.56	-8.33	-7.60	-6.09
Intact	15	16	0	-13.24	2.23	-16.64	-15.18	-12.72	-11.39	-10.19
ACLR.MCL.MTL	15	16	0	-13.62	2.20	-17.09	-15.56	-13.38	-11.77	-10.40
ACLR.mcl.MTL	15	8	0	-13.89	1.94	-17.09	-15.03	-13.67	-12.57	-11.56
ACLR.MCL.mtl	15	8	0	-13.54	2.65	-17.05	-16.23	-12.84	-11.35	-10.60
ACLR.mcl.mtl	15	16	0	-14.10	2.36	-17.77	-16.34	-13.84	-11.89	-10.79
ACLR.RampRepair	15	16	0	-13.28	2.67	-17.51	-15.93	-12.95	-10.75	-9.79
Intact	30	16	0	-15.64	3.35	-22.28	-17.61	-13.88	-13.39	-11.35
ACLR.MCL.MTL	30	16	0	-16.25	3.39	-23.02	-18.49	-14.31	-13.80	-11.89
ACLR.mcl.MTL	30	8	0	-17.00	4.41	-23.63	-20.00	-15.49	-13.84	-11.92
ACLR.MCL.mtl	30	8	0	-15.87	2.59	-19.92	-17.88	-14.37	-14.08	-13.64
ACLR.mcl.mtl	30	16	0	-16.78	3.63	-24.19	-19.42	-14.57	-14.23	-12.09
ACLR.RampRepair	30	16	0	-16.47	3.72	-24.13	-18.47	-14.39	-13.68	-11.76
Intact	45	16	0	-16.91	5.08	-27.81	-18.89	-16.23	-13.47	-10.58
ACLR.MCL.MTL	45	16	0	-17.52	5.14	-28.28	-19.34	-16.90	-14.00	-10.87
ACLR.mcl.MTL	45	8	0	-18.77	6.68	-28.59	-21.92	-17.93	-13.88	-10.82
ACLR.MCL.mtl	45	8	0	-16.61	3.17	-21.17	-18.73	-16.42	-14.64	-11.74
ACLR.mcl.mtl	45	16	0	-18.02	5.30	-29.04	-20.25	-17.18	-14.41	-11.06
ACLR.RampRepair	45	16	0	-17.86	5.46	-29.14	-19.99	-17.03	-14.30	-10.90
Intact	60	16	0	-17.93	6.43	-33.88	-20.34	-18.33	-13.81	-9.39
ACLR.MCL.MTL	60	16	0	-18.57	6.45	-34.26	-21.32	-18.55	-14.29	-10.11
ACLR.mcl.MTL	60	8	0	-20.37	8.28	-34.57	-24.16	-20.17	-14.32	-10.48
ACLR.MCL.mtl	60	8	0	-17.20	4.19	-22.22	-20.06	-18.23	-14.43	-10.08
ACLR.mcl.mtl	60	16	0	-19.16	6.62	-34.90	-22.10	-19.37	-14.67	-10.44
ACLR.RampRepair	60	16	0	-19.08	6.68	-34.99	-21.93	-19.46	-14.52	-10.44
Intact	75	16	0	-19.09	6.94	-36.32	-22.25	-19.04	-14.95	-8.90
ACLR.MCL.MTL	75	16	0	-19.82	7.11	-37.44	-23.28	-19.58	-15.11	-9.96
ACLR.mcl.MTL	75	8	0	-21.78	9.01	-37.54	-26.50	-22.05	-15.30	-10.99
ACLR.MCL.mtl	75	8	0	-18.26	4.52	-22.87	-21.65	-19.75	-15.21	-10.15
ACLR.mcl.mtl	75	16	0	-20.42	7.31	-38.18	-23.97	-20.14	-15.41	-10.34
ACLR.RampRepair	75	16	0	-20.40	7.34	-38.09	-24.05	-20.12	-15.32	-10.32
Intact	90	16	0	-20.45	7.55	-38.08	-23.78	-20.12	-16.61	-9.12
ACLR.MCL.MTL	90	16	0	-21.18	7.61	-38.64	-25.20	-20.78	-16.66	-10.60

State	Flexion	n	nmiss	mean	sd	min	Q1.25.	median	Q3.75.	max
ACLR.mcl.MTL	90	8	0	-23.30	9.84	-38.98	-29.10	-23.50	-15.94	-10.62
ACLR.MCL.mtl	90	8	0	-19.48	4.57	-24.87	-22.36	-20.81	-16.80	-10.70
ACLR.mcl.mtl	90	16	0	-21.89	7.78	-39.49	-26.22	-21.38	-17.18	-10.94
ACLR.RampRepair	90	16	0	-21.78	7.87	-39.36	-26.46	-21.36	-16.76	-10.74

Table 15: External Rotation (deg) during Simulated ER Test, Intact-Subtracted

Group	State	Flexion	n	nmiss	mean	sd	min	Q1.25.	median	Q3.75.	max
MCLcut	ACLR.MCL.MTL	0	8	0	-0.26	0.36	-0.84	-0.40	-0.20	-0.10	0.30
MCLcut	ACLR.mcl.MTL	0	8	0	-0.41	0.37	-0.97	-0.60	-0.30	-0.19	0.08
MCLcut	ACLR.mcl.mtl	0	8	0	-0.87	0.45	-1.58	-1.16	-0.64	-0.55	-0.47
MCLcut	ACLR.RampRepair	0	8	0	1.66	1.43	0.00	0.43	1.36	2.80	3.76
MCLcut	ACLR.MCL.MTL	15	8	0	-0.49	0.40	-1.24	-0.64	-0.45	-0.26	0.03
MCLcut	ACLR.mcl.MTL	15	8	0	-0.54	0.25	-0.97	-0.62	-0.47	-0.43	-0.17
MCLcut	ACLR.mcl.mtl	15	8	0	-1.05	0.40	-1.80	-1.19	-1.04	-0.77	-0.59
MCLcut	ACLR.RampRepair	15	8	0	0.20	0.98	-0.87	-0.61	0.21	0.60	2.11
MCLcut	ACLR.MCL.MTL	30	8	0	-0.60	0.29	-1.07	-0.78	-0.57	-0.43	-0.22
MCLcut	ACLR.mcl.MTL	30	8	0	-0.86	0.47	-1.69	-1.15	-0.70	-0.56	-0.28
MCLcut	ACLR.mcl.mtl	30	8	0	-1.19	0.50	-1.92	-1.59	-0.98	-0.83	-0.66
MCLcut	ACLR.RampRepair	30	8	0	-0.84	0.55	-1.85	-1.08	-0.78	-0.41	-0.17
MCLcut	ACLR.MCL.MTL	45	8	0	-0.65	0.26	-0.97	-0.86	-0.65	-0.45	-0.29
MCLcut	ACLR.mcl.MTL	45	8	0	-0.81	0.29	-1.08	-1.05	-0.87	-0.68	-0.24
MCLcut	ACLR.mcl.mtl	45	8	0	-1.17	0.40	-1.82	-1.38	-1.24	-0.94	-0.48
MCLcut	ACLR.RampRepair	45	8	0	-1.05	0.52	-1.92	-1.28	-1.15	-0.70	-0.33
MCLcut	ACLR.MCL.MTL	60	8	0	-0.62	0.26	-1.00	-0.77	-0.59	-0.44	-0.28
MCLcut	ACLR.mcl.MTL	60	8	0	-0.91	0.35	-1.33	-1.20	-0.95	-0.67	-0.35
MCLcut	ACLR.mcl.mtl	60	8	0	-1.23	0.48	-2.16	-1.46	-1.19	-0.83	-0.74
MCLcut	ACLR.RampRepair	60	8	0	-1.20	0.53	-2.17	-1.38	-1.18	-0.88	-0.56
MCLcut	ACLR.MCL.MTL	75	8	0	-0.78	0.54	-1.76	-0.99	-0.86	-0.37	-0.13
MCLcut	ACLR.mcl.MTL	75	8	0	-1.10	0.62	-2.46	-1.19	-1.04	-0.75	-0.49
MCLcut	ACLR.mcl.mtl	75	8	0	-1.47	0.93	-3.58	-1.52	-1.17	-1.05	-0.65
MCLcut	ACLR.RampRepair	75	8	0	-1.49	0.97	-3.76	-1.42	-1.17	-1.04	-0.66
MCLcut	ACLR.MCL.MTL	90	8	0	-0.70	0.52	-1.49	-0.86	-0.60	-0.37	-0.12
MCLcut	ACLR.mcl.MTL	90	8	0	-1.03	0.46	-1.66	-1.50	-0.88	-0.75	-0.50
MCLcut	ACLR.mcl.mtl	90	8	0	-1.49	0.72	-2.85	-1.89	-1.29	-0.95	-0.76
MCLcut	ACLR.RampRepair	90	8	0	-1.45	0.78	-2.95	-1.75	-1.26	-0.96	-0.62
MTLcut	ACLR.MCL.MTL	0	8	0	-0.18	0.58	-0.93	-0.45	-0.24	0.00	0.75
MTLcut	ACLR.MCL.mtl	0	8	0	-0.39	0.65	-1.26	-0.73	-0.55	-0.14	0.73
MTLcut	ACLR.mcl.mtl	0	8	0	-0.70	0.57	-1.56	-0.97	-0.60	-0.41	0.16
MTLcut	ACLR.RampRepair	0	8	0	0.58	1.14	-0.75	0.02	0.18	0.95	2.88
MTLcut	ACLR.MCL.MTL	15	8	0	-0.28	0.69	-1.23	-0.73	-0.39	0.16	0.81
MTLcut	ACLR.MCL.mtl	15	8	0	-0.41	0.68	-1.29	-0.84	-0.55	-0.05	0.79
MTLcut	ACLR.mcl.mtl	15	8	0	-0.68	0.87	-1.59	-1.31	-0.82	-0.38	0.97
MTLcut	ACLR.RampRepair	15	8	0	-0.28	1.13	-1.42	-0.83	-0.58	-0.26	2.29
MTLcut	ACLR.MCL.MTL	30	8	0	-0.60	0.41	-1.09	-0.93	-0.65	-0.28	-0.04
MTLcut	ACLR.MCL.mtl	30	8	0	-0.72	0.48	-1.44	-1.03	-0.78	-0.39	-0.08
MTLcut	ACLR.mcl.mtl	30	8	0	-1.08	0.54	-1.86	-1.51	-1.03	-0.68	-0.41
MTLcut	ACLR.RampRepair	30	8	0	-0.81	0.67	-1.82	-1.38	-0.61	-0.41	0.16
MTLcut	ACLR.MCL.MTL	45	8	0	-0.56	0.51	-1.55	-0.76	-0.46	-0.33	0.10
MTLcut	ACLR.MCL.mtl	45	8	0	-0.74	0.46	-1.51	-0.90	-0.71	-0.52	-0.11
MTLcut	ACLR.mcl.mtl	45	8	0	-1.04	0.51	-1.96	-1.22	-1.06	-0.79	-0.36
MTLcut	ACLR.RampRepair	45	8	0	-0.85	0.62	-2.16	-0.96	-0.83	-0.53	0.00
MTLcut	ACLR.MCL.MTL	60	8	0	-0.67	0.60	-1.94	-0.73	-0.68	-0.40	0.18
MTLcut	ACLR.MCL.mtl	60	8	0	-0.80	0.63	-2.18	-0.88	-0.75	-0.53	0.01
MTLcut	ACLR.mcl.mtl	60	8	0	-1.23	0.74	-2.90	-1.33	-0.97	-0.87	-0.50
MTLcut	ACLR.RampRepair	60	8	0	-1.10	0.77	-2.76	-1.21	-0.99	-0.82	-0.10
MTLcut	ACLR.MCL.MTL	75	8	0	-0.67	0.56	-1.44	-1.03	-0.74	-0.38	0.37
MTLcut	ACLR.MCL.mtl	75	8	0	-0.76	0.56	-1.36	-1.15	-0.87	-0.49	0.39
MTLcut	ACLR.mcl.mtl	75	8	0	-1.19	0.81	-2.40	-1.55	-1.20	-0.91	0.32
MTLcut	ACLR.RampRepair	75	8	0	-1.13	1.07	-2.65	-1.55	-1.27	-0.81	1.05
MTLcut	ACLR.MCL.MTL	90	8	0	-0.77	0.67	-1.68	-1.27	-0.69	-0.24	0.13
MTLcut	ACLR.MCL.mtl	90	8	0	-0.85	0.79	-2.29	-1.31	-0.67	-0.38	0.21
MTLcut	ACLR.mcl.mtl	90	8	0	-1.39	0.98	-3.21	-1.81	-1.14	-0.87	-0.11
MTLcut	ACLR.RampRepair	90	8	0	-1.20	1.24	-3.13	-1.62	-1.09	-0.78	0.93

Table 16: External Rotation (deg) during Simulated ER Test, Intact-Subtracted - Version 2

State	Flexion	n	nmiss	mean	sd	min	Q1.25.	median	Q3.75.	max
ACLR.MCL.MTL	0	16	0	-0.22	0.47	-0.93	-0.42	-0.24	-0.10	0.75
ACLR.mcl.MTL	0	8	0	-0.41	0.37	-0.97	-0.60	-0.30	-0.19	0.08
ACLR.MCL.mtl	0	8	0	-0.39	0.65	-1.26	-0.73	-0.55	-0.14	0.73
ACLR.mcl.mtl	0	16	0	-0.79	0.50	-1.58	-1.15	-0.60	-0.51	0.16
ACLR.RampRepair	0	16	0	1.12	1.37	-0.75	0.11	0.60	1.78	3.76
ACLR.MCL.MTL	15	16	0	-0.38	0.56	-1.24	-0.71	-0.45	-0.05	0.81
ACLR.mcl.MTL	15	8	0	-0.54	0.25	-0.97	-0.62	-0.47	-0.43	-0.17
ACLR.MCL.mtl	15	8	0	-0.41	0.68	-1.29	-0.84	-0.55	-0.05	0.79
ACLR.mcl.mtl	15	16	0	-0.86	0.68	-1.80	-1.27	-1.04	-0.58	0.97
ACLR.RampRepair	15	16	0	-0.04	1.05	-1.42	-0.74	-0.46	0.41	2.29
ACLR.MCL.MTL	30	16	0	-0.60	0.35	-1.09	-0.89	-0.57	-0.32	-0.04
ACLR.mcl.MTL	30	8	0	-0.86	0.47	-1.69	-1.15	-0.70	-0.56	-0.28
ACLR.MCL.mtl	30	8	0	-0.72	0.48	-1.44	-1.03	-0.78	-0.39	-0.08
ACLR.mcl.mtl	30	16	0	-1.13	0.51	-1.92	-1.53	-0.98	-0.76	-0.41
ACLR.RampRepair	30	16	0	-0.82	0.59	-1.85	-1.32	-0.67	-0.41	0.16
ACLR.MCL.MTL	45	16	0	-0.60	0.40	-1.55	-0.86	-0.49	-0.42	0.10
ACLR.mcl.MTL	45	8	0	-0.81	0.29	-1.08	-1.05	-0.87	-0.68	-0.24
ACLR.MCL.mtl	45	8	0	-0.74	0.46	-1.51	-0.90	-0.71	-0.52	-0.11
ACLR.mcl.mtl	45	16	0	-1.10	0.45	-1.96	-1.36	-1.12	-0.90	-0.36
ACLR.RampRepair	45	16	0	-0.95	0.56	-2.16	-1.21	-0.89	-0.53	0.00
ACLR.MCL.MTL	60	16	0	-0.64	0.45	-1.94	-0.73	-0.66	-0.40	0.18
ACLR.mcl.MTL	60	8	0	-0.91	0.35	-1.33	-1.20	-0.95	-0.67	-0.35
ACLR.MCL.mtl	60	8	0	-0.80	0.63	-2.18	-0.88	-0.75	-0.53	0.01
ACLR.mcl.mtl	60	16	0	-1.23	0.60	-2.90	-1.46	-1.03	-0.86	-0.50
ACLR.RampRepair	60	16	0	-1.15	0.64	-2.76	-1.31	-1.08	-0.84	-0.10
ACLR.MCL.MTL	75	16	0	-0.73	0.53	-1.76	-1.03	-0.81	-0.38	0.37
ACLR.mcl.MTL	75	8	0	-1.10	0.62	-2.46	-1.19	-1.04	-0.75	-0.49
ACLR.MCL.mtl	75	8	0	-0.76	0.56	-1.36	-1.15	-0.87	-0.49	0.39
ACLR.mcl.mtl	75	16	0	-1.33	0.85	-3.58	-1.55	-1.18	-0.92	0.32
ACLR.RampRepair	75	16	0	-1.31	1.01	-3.76	-1.52	-1.17	-0.98	1.05
ACLR.MCL.MTL	90	16	0	-0.73	0.58	-1.68	-1.24	-0.60	-0.25	0.13
ACLR.mcl.MTL	90	8	0	-1.03	0.46	-1.66	-1.50	-0.88	-0.75	-0.50
ACLR.MCL.mtl	90	8	0	-0.85	0.79	-2.29	-1.31	-0.67	-0.38	0.21
ACLR.mcl.mtl	90	16	0	-1.44	0.83	-3.21	-1.89	-1.20	-0.91	-0.11
ACLR.RampRepair	90	16	0	-1.33	1.01	-3.13	-1.75	-1.18	-0.84	0.93

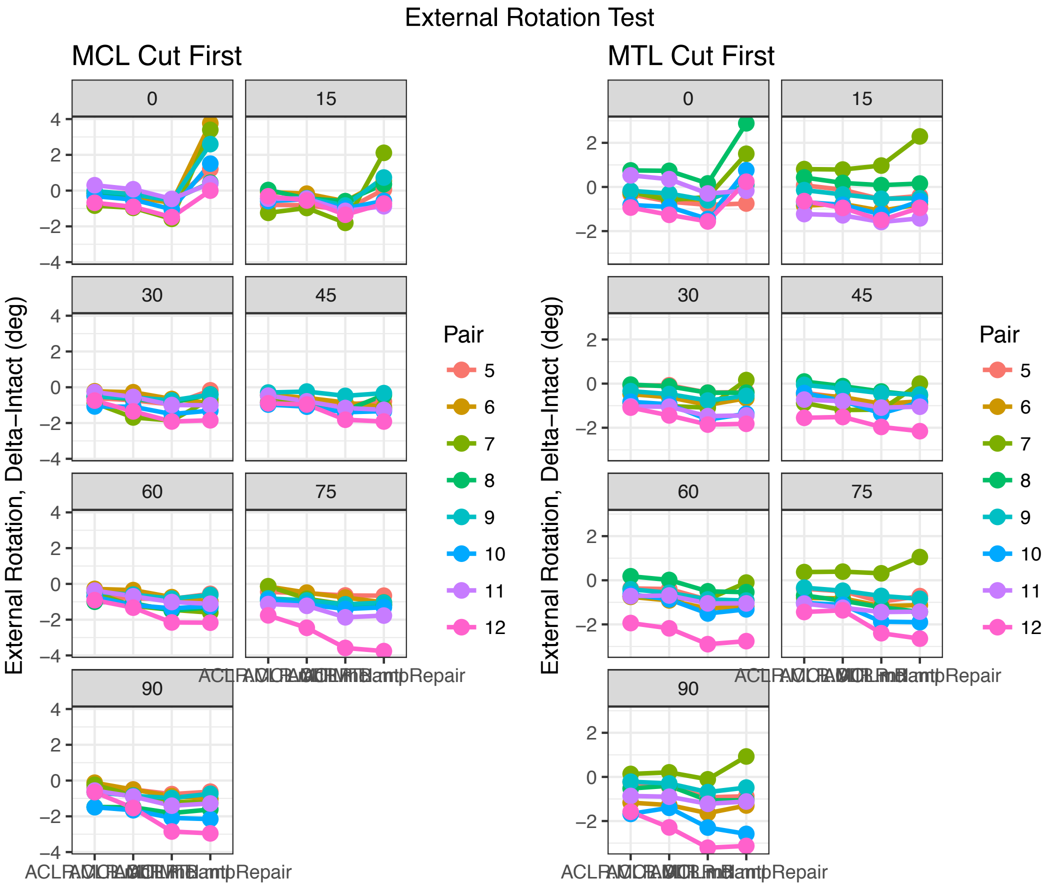
4.2.1 For Paper

Table 17: Mean ± SD External Rotation by Cut State and Flexion Angle - Non-Intact-Subtracted

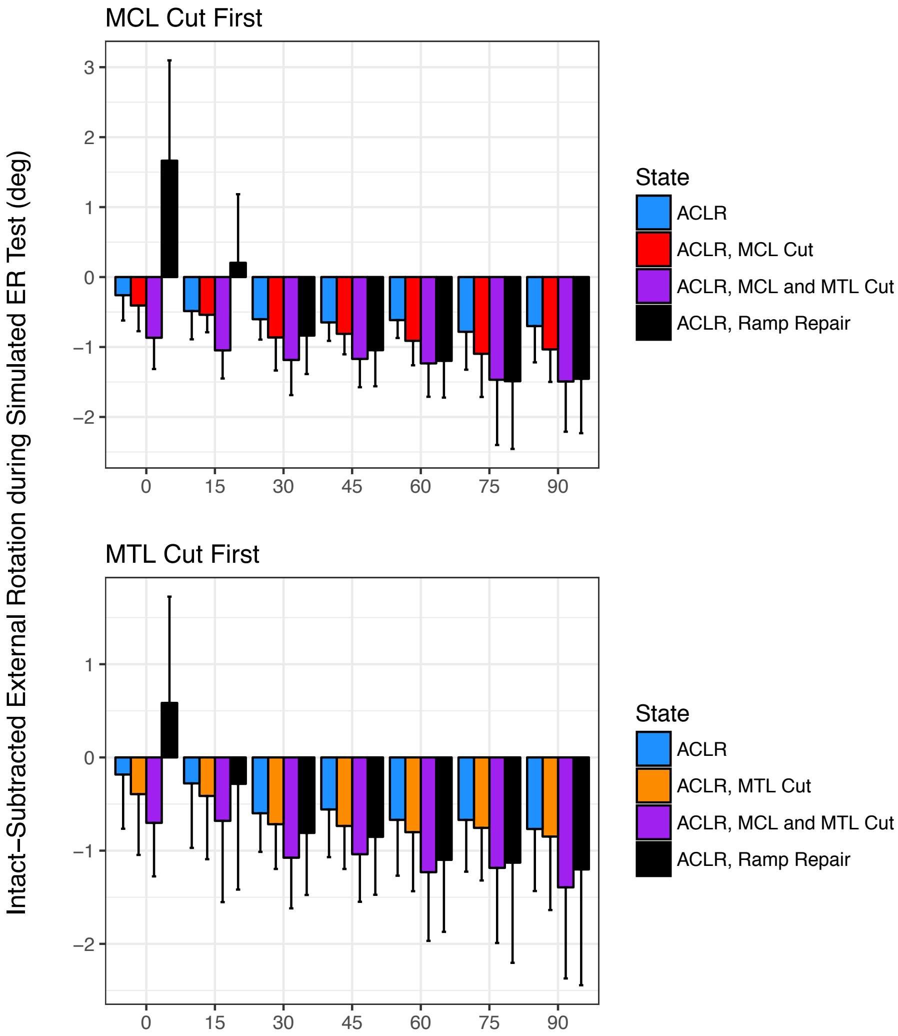
State	0	15	30	45	60	75	90
Intact	-9.7 ± 1.8	-13.2 ± 2.2	-15.6 ± 3.3	-16.9 ± 5.1	-17.9 ± 6.4	-19.1 ± 6.9	-20.4 ± 7.6
ACLR.MCL.MTL	-10 ± 1.8	-13.6 ± 2.2	-16.2 ± 3.4	-17.5 ± 5.1	-18.6 ± 6.4	-19.8 ± 7.1	-21.2 ± 7.6
ACLR.mcl.MTL	-10.8 ± 1.6	-13.9 ± 1.9	-17 ± 4.4	-18.8 ± 6.7	-20.4 ± 8.3	-21.8 ± 9	-23.3 ± 9.8
ACLR.MCL.mtl	-9.5 ± 1.9	-13.5 ± 2.7	-15.9 ± 2.6	-16.6 ± 3.2	-17.2 ± 4.2	-18.3 ± 4.5	-19.5 ± 4.6
ACLR.mcl.mtl	-10.5 ± 1.9	-14.1 ± 2.4	-16.8 ± 3.6	-18 ± 5.3	-19.2 ± 6.6	-20.4 ± 7.3	-21.9 ± 7.8
ACLR.RampRepair	-8.6 ± 1.7	-13.3 ± 2.7	-16.5 ± 3.7	-17.9 ± 5.5	-19.1 ± 6.7	-20.4 ± 7.3	-21.8 ± 7.9

4.3 Plot Data

4.3.1 Spaghetti plots to inspect subject-level data

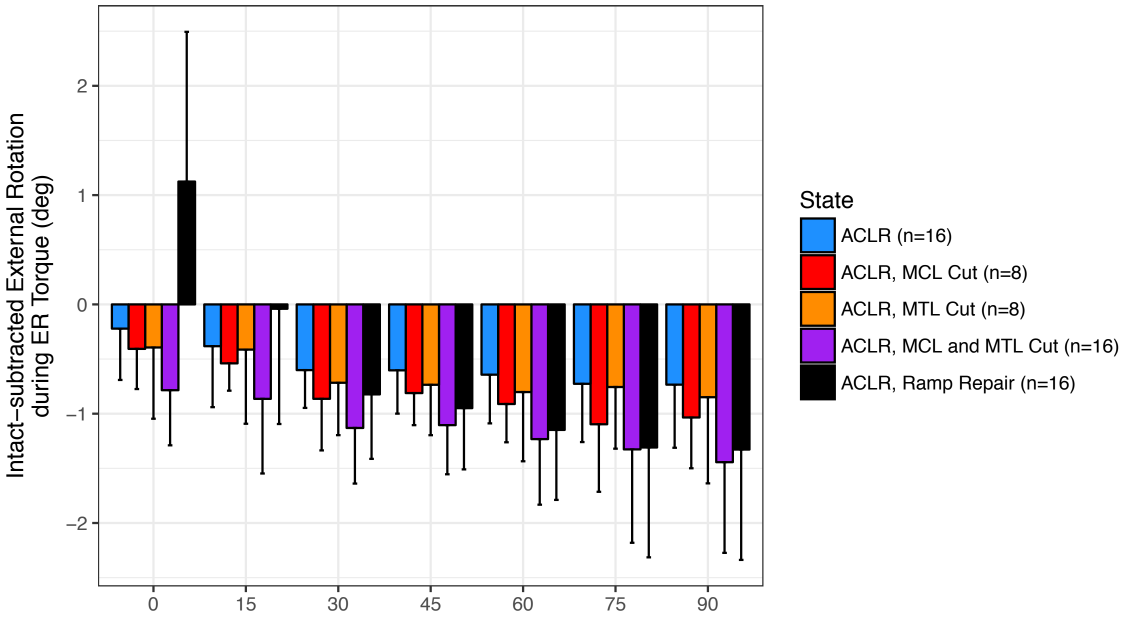


4.3.2 Bar Plot



MCL Cut First
MTL Cut First
Intact−Subtracted External Rotation during Simulated ER Test (deg)
3
2
1
0
−1
−2
0
15
30
45
60
75
90
State
ACLR
ACLR, MCL Cut
ACLR, MCL and MTL Cut
ACLR, Ramp Repair
ACLR, MTL Cut

4.3.3 New Bar Plot

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4.4 Custom set of T-tests

Table 18: T-tests for External Rotation during ER Torque (deg), intact-subtracted data

	Flexion Angle	n	Mean Diff	SD Diff	CI LB	CI UB	Holm P
Intact vs ACLR+MCL+MTL	0	16	-0.22	0.47	-0.47	0.03	0.1575
Intact vs ACLR-MCL+MTL	0	8	-0.41	0.37	-0.71	-0.10	0.0497
Intact vs ACLR+MCL-MTL	0	8	-0.39	0.65	-0.94	0.15	0.1575
Intact vs ACLR-MCL-MTL	0	16	-0.79	0.50	-1.05	-0.52	0.0001
Intact vs ACLR+RampRepair	0	16	1.12	1.37	0.39	1.85	0.0202
ACLR+MCL+MTL vs ACLR-MCL+MTL	0	8	0.15	0.07	0.09	0.21	0.0054
ACLR+MCL+MTL vs ACLR+MCL-MTL	0	8	0.21	0.13	0.10	0.32	0.0119
ACLR+MCL+MTL vs ACLR-MCL-MTL	0	16	0.56	0.18	0.47	0.66	0.0000
ACLR+MCL+MTL vs ACLR+RampRepair	0	16	-1.35	1.42	-2.10	-0.59	0.0105
ACLR-MCL-MTL vs ACL+RampRepair	0	16	-1.91	1.42	-2.67	-1.15	0.0006
Intact vs ACLR+MCL+MTL	15	16	-0.38	0.56	-0.68	-0.09	0.0910
Intact vs ACLR-MCL+MTL	15	8	-0.54	0.25	-0.75	-0.33	0.0039
Intact vs ACLR+MCL-MTL	15	8	-0.41	0.68	-0.98	0.15	0.5136
Intact vs ACLR-MCL-MTL	15	16	-0.86	0.68	-1.23	-0.50	0.0013
Intact vs ACLR+RampRepair	15	16	-0.04	1.05	-0.60	0.52	1.0000
ACLR+MCL+MTL vs ACLR-MCL+MTL	15	8	0.05	0.22	-0.13	0.24	1.0000
ACLR+MCL+MTL vs ACLR+MCL-MTL	15	8	0.13	0.13	0.03	0.24	0.1048
ACLR+MCL+MTL vs ACLR-MCL-MTL	15	16	0.48	0.27	0.34	0.63	0.0000
ACLR+MCL+MTL vs ACLR+RampRepair	15	16	-0.34	1.00	-0.88	0.19	0.5779
ACLR-MCL-MTL vs ACL+RampRepair	15	16	-0.82	0.95	-1.33	-0.32	0.0243
Intact vs ACLR+MCL+MTL	30	16	-0.60	0.35	-0.79	-0.42	0.0000
Intact vs ACLR-MCL+MTL	30	8	-0.86	0.47	-1.26	-0.47	0.0077
Intact vs ACLR+MCL-MTL	30	8	-0.72	0.48	-1.12	-0.32	0.0195
Intact vs ACLR-MCL-MTL	30	16	-1.13	0.51	-1.40	-0.86	0.0000
Intact vs ACLR+RampRepair	30	16	-0.82	0.59	-1.14	-0.51	0.0004
ACLR+MCL+MTL vs ACLR-MCL+MTL	30	8	0.26	0.29	0.02	0.50	0.0771
ACLR+MCL+MTL vs ACLR+MCL-MTL	30	8	0.12	0.11	0.02	0.21	0.0632
ACLR+MCL+MTL vs ACLR-MCL-MTL	30	16	0.53	0.28	0.38	0.68	0.0000
ACLR+MCL+MTL vs ACLR+RampRepair	30	16	0.22	0.52	-0.06	0.50	0.1094
ACLR-MCL-MTL vs ACL+RampRepair	30	16	-0.31	0.42	-0.53	-0.08	0.0443
Intact vs ACLR+MCL+MTL	45	16	-0.60	0.40	-0.81	-0.39	0.0001
Intact vs ACLR-MCL+MTL	45	8	-0.81	0.29	-1.06	-0.57	0.0006
Intact vs ACLR+MCL-MTL	45	8	-0.74	0.46	-1.12	-0.35	0.0139
Intact vs ACLR-MCL-MTL	45	16	-1.10	0.45	-1.34	-0.87	0.0000
Intact vs ACLR+RampRepair	45	16	-0.95	0.56	-1.25	-0.65	0.0001
ACLR+MCL+MTL vs ACLR-MCL+MTL	45	8	0.16	0.23	-0.03	0.35	0.1657
ACLR+MCL+MTL vs ACLR+MCL-MTL	45	8	0.18	0.13	0.07	0.28	0.0230
ACLR+MCL+MTL vs ACLR-MCL-MTL	45	16	0.50	0.24	0.37	0.63	0.0000
ACLR+MCL+MTL vs ACLR+RampRepair	45	16	0.35	0.48	0.09	0.60	0.0339
ACLR-MCL-MTL vs ACL+RampRepair	45	16	-0.16	0.39	-0.36	0.05	0.1657
Intact vs ACLR+MCL+MTL	60	16	-0.64	0.45	-0.88	-0.41	0.0003
Intact vs ACLR-MCL+MTL	60	8	-0.91	0.35	-1.20	-0.62	0.0009
Intact vs ACLR+MCL-MTL	60	8	-0.80	0.63	-1.33	-0.27	0.0269
Intact vs ACLR-MCL-MTL	60	16	-1.23	0.60	-1.55	-0.91	0.0000
Intact vs ACLR+RampRepair	60	16	-1.15	0.64	-1.49	-0.81	0.0000
ACLR+MCL+MTL vs ACLR-MCL+MTL	60	8	0.30	0.23	0.10	0.49	0.0269
ACLR+MCL+MTL vs ACLR+MCL-MTL	60	8	0.13	0.09	0.05	0.21	0.0224
ACLR+MCL+MTL vs ACLR-MCL-MTL	60	16	0.59	0.30	0.43	0.75	0.0000
ACLR+MCL+MTL vs ACLR+RampRepair	60	16	0.51	0.45	0.26	0.75	0.0023
ACLR-MCL-MTL vs ACL+RampRepair	60	16	-0.08	0.23	-0.21	0.04	0.1633
Intact vs ACLR+MCL+MTL	75	16	-0.73	0.53	-1.01	-0.44	0.0005
Intact vs ACLR-MCL+MTL	75	8	-1.10	0.62	-1.61	-0.58	0.0077
Intact vs ACLR+MCL-MTL	75	8	-0.76	0.56	-1.23	-0.28	0.0273
Intact vs ACLR-MCL-MTL	75	16	-1.33	0.85	-1.78	-0.87	0.0002

	Flexion Angle	n	Mean Diff	SD Diff	CI LB	CI UB	Holm P
Intact vs ACLR+RampRepair	75	16	-1.31	1.01	-1.84	-0.77	0.0007
ACLR+MCL+MTL vs ACLR-MCL+MTL	75	8	0.31	0.25	0.10	0.53	0.0297
ACLR+MCL+MTL vs ACLR+MCL-MTL	75	8	0.09	0.11	0.00	0.17	0.1135
ACLR+MCL+MTL vs ACLR-MCL-MTL	75	16	0.60	0.43	0.37	0.83	0.0004
ACLR+MCL+MTL vs ACLR+RampRepair	75	16	0.58	0.58	0.27	0.89	0.0065
ACLR-MCL-MTL vs ACL+RampRepair	75	16	-0.02	0.24	-0.14	0.11	0.7743
Intact vs ACLR+MCL+MTL	90	16	-0.73	0.58	-1.04	-0.43	0.0009
Intact vs ACLR-MCL+MTL	90	8	-1.03	0.46	-1.42	-0.65	0.0024
Intact vs ACLR+MCL-MTL	90	8	-0.85	0.79	-1.51	-0.19	0.0560
Intact vs ACLR-MCL-MTL	90	16	-1.44	0.83	-1.89	-1.00	0.0000
Intact vs ACLR+RampRepair	90	16	-1.33	1.01	-1.87	-0.79	0.0008
ACLR+MCL+MTL vs ACLR-MCL+MTL	90	8	0.33	0.29	0.09	0.57	0.0547
ACLR+MCL+MTL vs ACLR+MCL-MTL	90	8	0.08	0.29	-0.16	0.33	0.4576
ACLR+MCL+MTL vs ACLR-MCL-MTL	90	16	0.71	0.52	0.43	0.99	0.0006
ACLR+MCL+MTL vs ACLR+RampRepair	90	16	0.59	0.69	0.22	0.96	0.0186
ACLR-MCL-MTL vs ACL+RampRepair	90	16	-0.12	0.29	-0.27	0.04	0.2742

5 Simulated Pivot Shift Test - Anterior Displacement

5.1 Manipulate Data

```
# Create delta-intact data with dplyr gather/spread/gather
dat2.psatt.spread <- dat2.psatt %>% select(Pair, Specimen, Group,
    Flexion, State, Value) %>% spread(data = ., key = State,
    value = Value, fill = NA)
dat2.psatt.deltaintact.spread <- dat2.psatt.spread
dat2.psatt.deltaintact.spread[, 5:10] <- dat2.psatt.spread[,
    5:10] - dat2.psatt.spread[, 5]
dat2.psatt.deltaintact <- gather(dat2.psatt.deltaintact.spread,
    key = State, value = Value, Intact:ACLR.RampRepair, -(Pair:Flexion),
    factor_key = TRUE)
dat2.psatt.deltaintact <- dat2.psatt.deltaintact %>% subset(State !=
    "Intact") %>% subset(!is.na(Value)) %>% droplevels()
str(dat2.psatt.deltaintact)
```

```
~~~  'data.frame':   128 obs. of  6 variables:
~~~   $ Pair    : Factor w/ 8 levels "5","6","7","8",..: 1 1 1 1 2 2 2 2 3 3 ...
~~~   $ Specimen: num  5 5 17 17 6 6 18 18 7 7 ...
~~~   $ Group   : Factor w/ 2 levels "MCLcut","MTLcut": 1 1 2 2 1 1 2 2 1 1 ...
~~~   $ Flexion : num  15 30 15 30 15 30 15 30 15 30 ...
~~~   $ State   : Factor w/ 5 levels "ACLR.MCL.MTL",..: 1 1 1 1 1 1 1 1 1 1 ...
~~~   $ Value   : num  -0.272 0.388 -0.54 -0.333 -1.594 ...
```

```
head(dat2.psatt.deltaintact)
```

```
~~~     Pair Specimen  Group Flexion        State       Value
~~~  33    5        5 MCLcut      15 ACLR.MCL.MTL -0.27204622
~~~  34    5        5 MCLcut      30 ACLR.MCL.MTL  0.38835869
~~~  35    5       17 MTLcut      15 ACLR.MCL.MTL -0.53998350
~~~  36    5       17 MTLcut      30 ACLR.MCL.MTL -0.33349238
~~~  37    6        6 MCLcut      15 ACLR.MCL.MTL -1.59401046
~~~  38    6        6 MCLcut      30 ACLR.MCL.MTL -0.01605781
```

5.2 Summary Stats

Table 19: Anterior Translation (mm) during Simulated Pivot Shift Test

Group	State	Flexion	n	nmiss	mean	sd	min	Q1.25.	median	Q3.75.	max
MCLcut	Intact	15	8	0	13.96	4.85	8.24	10.85	12.45	16.59	21.69
MCLcut	ACLR.MCL.MTL	15	8	0	13.66	3.49	9.70	11.40	12.14	16.32	19.51
MCLcut	ACLR.mcl.MTL	15	8	0	13.68	3.57	9.97	11.40	11.82	16.35	19.81
MCLcut	ACLR.mcl.mtl	15	8	0	15.24	3.67	11.81	12.09	13.79	18.67	20.48
MCLcut	ACLR.RampRepair	15	8	0	13.29	4.21	7.91	10.64	11.61	16.82	19.92
MCLcut	Intact	30	8	0	17.27	4.62	11.99	13.81	15.54	21.75	23.49
MCLcut	ACLR.MCL.MTL	30	8	0	17.73	4.19	12.32	14.10	17.75	20.73	23.30
MCLcut	ACLR.mcl.MTL	30	8	0	18.24	4.28	12.66	14.64	18.50	21.22	24.00
MCLcut	ACLR.mcl.mtl	30	8	0	19.08	4.54	12.82	15.54	19.77	22.62	24.44
MCLcut	ACLR.RampRepair	30	8	0	18.52	4.76	12.36	14.67	19.21	21.84	24.58
MTLcut	Intact	15	8	0	13.67	3.39	9.60	12.23	13.67	14.35	20.38
MTLcut	ACLR.MCL.MTL	15	8	0	13.13	2.43	9.16	12.50	13.71	14.61	15.98
MTLcut	ACLR.MCL.mtl	15	8	0	14.88	2.92	10.31	13.55	14.49	16.64	19.04
MTLcut	ACLR.mcl.mtl	15	8	0	15.08	3.25	10.03	13.69	14.53	17.02	19.71
MTLcut	ACLR.RampRepair	15	8	0	13.74	2.77	9.60	12.41	13.76	15.41	17.97
MTLcut	Intact	30	8	0	17.29	4.96	11.72	13.08	17.00	19.67	26.67
MTLcut	ACLR.MCL.MTL	30	8	0	17.43	4.56	11.52	13.47	17.53	21.93	22.81
MTLcut	ACLR.MCL.mtl	30	8	0	18.68	5.00	11.70	15.00	18.19	22.85	25.59
MTLcut	ACLR.mcl.mtl	30	8	0	19.14	5.37	11.75	15.24	18.33	23.36	27.06
MTLcut	ACLR.RampRepair	30	8	0	18.55	5.07	11.92	14.33	18.30	22.55	26.24

Table 20: Anterior Translation (mm) during Simulated Pivot Shift Test - Version 2

State	Flexion	n	nmiss	mean	sd	min	Q1.25.	median	Q3.75.	max
Intact	15	16	0	13.82	4.05	8.24	10.85	13.29	15.26	21.69
ACLR.MCL.MTL	15	16	0	13.40	2.92	9.16	11.40	13.50	15.14	19.51
ACLR.mcl.MTL	15	8	0	13.68	3.57	9.97	11.40	11.82	16.35	19.81
ACLR.MCL.mtl	15	8	0	14.88	2.92	10.31	13.55	14.49	16.64	19.04
ACLR.mcl.mtl	15	16	0	15.16	3.35	10.03	12.21	14.53	18.57	20.48
ACLR.RampRepair	15	16	0	13.52	3.45	7.91	10.68	13.38	16.24	19.92
Intact	30	16	0	17.28	4.63	11.72	13.53	16.98	20.83	26.67
ACLR.MCL.MTL	30	16	0	17.58	4.23	11.52	13.78	17.67	21.93	23.30
ACLR.mcl.MTL	30	8	0	18.24	4.28	12.66	14.64	18.50	21.22	24.00
ACLR.MCL.mtl	30	8	0	18.68	5.00	11.70	15.00	18.19	22.85	25.59
ACLR.mcl.mtl	30	16	0	19.11	4.80	11.75	15.24	18.47	23.03	27.06
ACLR.RampRepair	30	16	0	18.53	4.75	11.92	14.33	18.58	22.55	26.24

Table 21: Anterior Translation (mm) during Simulated Pivot Shift Test, Intact-Subtracted

Group	State	Flexion	n	nmiss	mean	sd	min	Q1.25.	median	Q3.75.	max
MCLcut	ACLR.MCL.MTL	15	8	0	-0.31	2.63	-4.44	-1.74	-0.41	0.79	4.23
MCLcut	ACLR.mcl.MTL	15	8	0	-0.28	2.45	-4.46	-1.54	-0.24	0.79	3.52
MCLcut	ACLR.mcl.mtl	15	8	0	1.27	2.59	-1.21	-0.64	0.68	2.15	6.60
MCLcut	ACLR.RampRepair	15	8	0	-0.67	2.71	-4.65	-2.30	-0.50	1.15	2.87
MCLcut	ACLR.MCL.MTL	30	8	0	0.46	2.21	-2.67	-0.53	0.16	0.76	4.92
MCLcut	ACLR.mcl.MTL	30	8	0	0.97	2.40	-2.10	-0.10	0.35	1.47	5.91
MCLcut	ACLR.mcl.mtl	30	8	0	1.80	2.79	-0.37	0.21	0.61	2.41	8.09
MCLcut	ACLR.RampRepair	30	8	0	1.25	2.75	-1.43	-0.27	0.51	1.89	6.99
MTLcut	ACLR.MCL.MTL	15	8	0	-0.54	2.42	-5.85	-0.75	-0.19	0.61	2.15
MTLcut	ACLR.MCL.mtl	15	8	0	1.21	2.21	-1.99	-0.01	0.80	2.57	5.21
MTLcut	ACLR.mcl.mtl	15	8	0	1.41	2.04	-0.75	0.15	0.82	2.62	5.26
MTLcut	ACLR.RampRepair	15	8	0	0.07	1.61	-2.41	-1.12	0.32	1.03	2.30
MTLcut	ACLR.MCL.MTL	30	8	0	0.15	1.93	-3.87	-0.35	0.21	1.35	2.58
MTLcut	ACLR.MCL.mtl	30	8	0	1.39	1.79	-1.08	0.16	1.34	2.27	4.60
MTLcut	ACLR.mcl.mtl	30	8	0	1.85	1.76	0.03	0.46	1.71	2.39	5.42
MTLcut	ACLR.RampRepair	30	8	0	1.26	1.31	-0.43	0.19	1.18	1.96	3.54

Table 22: Anterior Translation (mm) during Simulated Pivot Shift Test, Intact-Subtracted - Version 2

State	Flexion	n	nmiss	mean	sd	min	Q1.25.	median	Q3.75.	max
ACLR.MCL.MTL	15	16	0	-0.42	2.44	-5.85	-1.45	-0.38	0.64	4.23
ACLR.mcl.MTL	15	8	0	-0.28	2.45	-4.46	-1.54	-0.24	0.79	3.52
ACLR.MCL.mtl	15	8	0	1.21	2.21	-1.99	-0.01	0.80	2.57	5.21
ACLR.mcl.mtl	15	16	0	1.34	2.25	-1.21	-0.57	0.75	2.62	6.60
ACLR.RampRepair	15	16	0	-0.30	2.19	-4.65	-1.53	-0.12	1.03	2.87
ACLR.MCL.MTL	30	16	0	0.30	2.01	-3.87	-0.42	0.16	1.35	4.92
ACLR.mcl.MTL	30	8	0	0.97	2.40	-2.10	-0.10	0.35	1.47	5.91
ACLR.MCL.mtl	30	8	0	1.39	1.79	-1.08	0.16	1.34	2.27	4.60
ACLR.mcl.mtl	30	16	0	1.83	2.25	-0.37	0.36	1.03	2.39	8.09
ACLR.RampRepair	30	16	0	1.25	2.08	-1.43	0.15	0.86	1.96	6.99

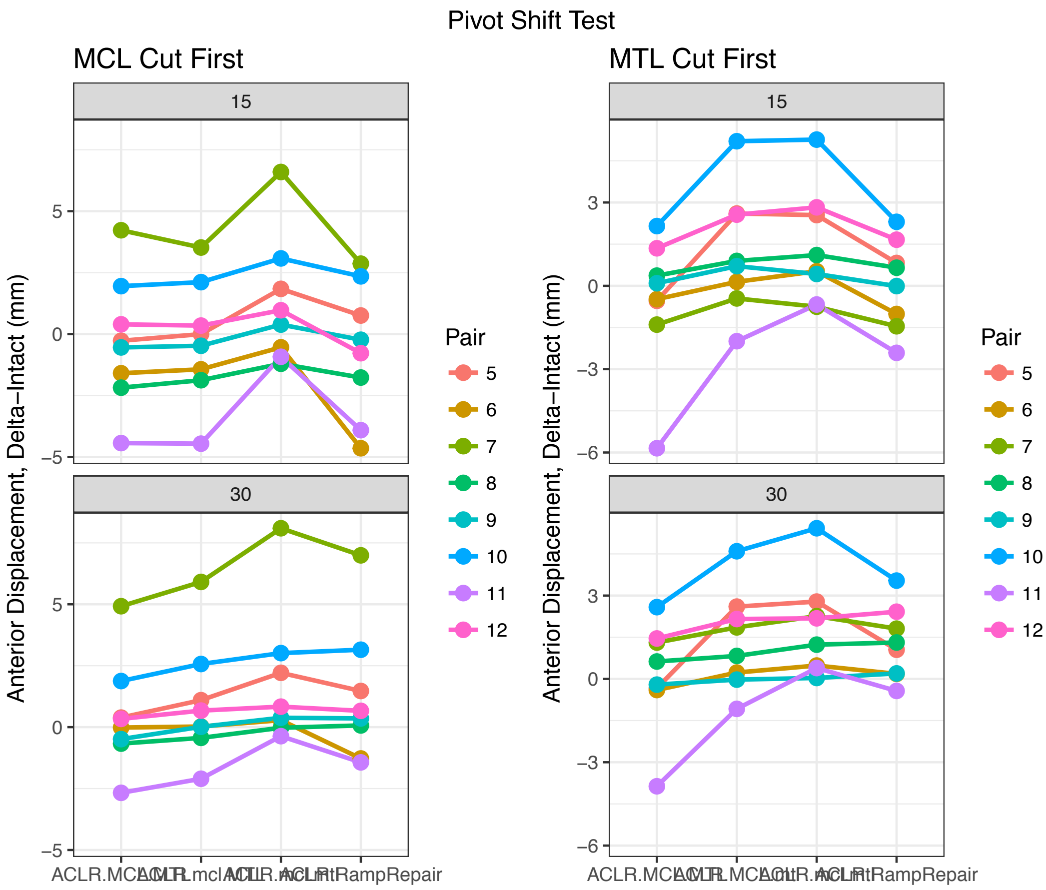
5.2.1 For Paper

Table 23: Mean ± SD Anterior Tibial Translation by Cut State and Flexion Angle - Non-Intact-Subtracted

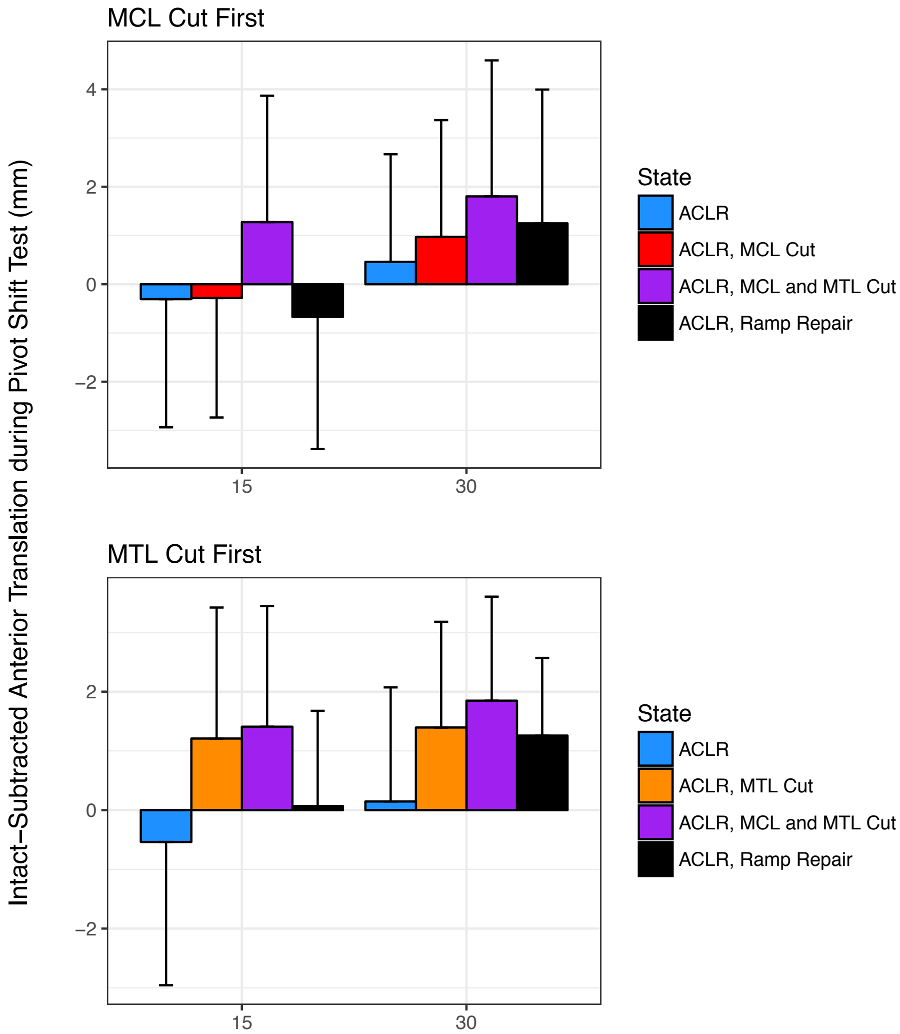
State	15	30
Intact	13.8 ± 4	17.3 ± 4.6
ACLR.MCL.MTL	13.4 ± 2.9	17.6 ± 4.2
ACLR.mcl.MTL	13.7 ± 3.6	18.2 ± 4.3
ACLR.MCL.mtl	14.9 ± 2.9	18.7 ± 5
ACLR.mcl.mtl	15.2 ± 3.3	19.1 ± 4.8
ACLR.RampRepair	13.5 ± 3.4	18.5 ± 4.8

5.3 Plot Data

5.3.1 Spaghetti plots to inspect subject-level data

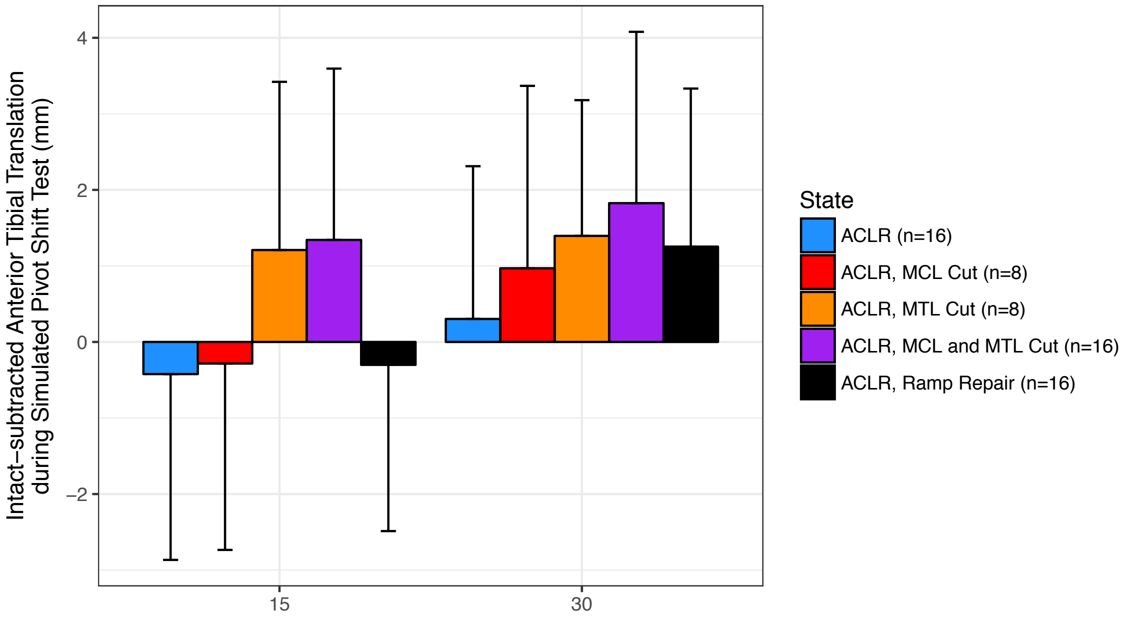


5.3.2 Bar Plot



MCL Cut First
MTL Cut First
Intact−Subtracted Anterior Translation during Pivot Shift Test (mm)
4
2
0
−2
15
30
State
ACLR
ACLR, MCL Cut
ACLR, MCL and MTL Cut
ACLR, Ramp Repair
2
0
−2
15
30
State
ACLR
ACLR, MTL Cut
ACLR, MCL and MTL Cut
ACLR, Ramp Repair

5.3.3 New Bar Plot




```
~~~  pdf
~~~    2
```

```
~~~  pdf
~~~    2
```

```
~~~  pdf
~~~    2
```

5.4 Custom set of T-tests

Table 24: T-tests for Anterior Displacement during Pivot Shift Test (mm), intact-subtracted data

	Flexion Angle	n	Mean Diff	SD Diff	CI LB	CI UB	Holm P
Intact vs ACLR+MCL+MTL	15	16	-0.42	2.44	-1.72	0.88	1.0000
Intact vs ACLR-MCL+MTL	15	8	-0.28	2.45	-2.33	1.77	1.0000
Intact vs ACLR+MCL-MTL	15	8	1.21	2.21	-0.64	3.06	0.9962
Intact vs ACLR-MCL-MTL	15	16	1.34	2.25	0.14	2.54	0.2163
Intact vs ACLR+RampRepair	15	16	-0.30	2.19	-1.47	0.86	1.0000
ACLR+MCL+MTL vs ACLR-MCL+MTL	15	8	-0.02	0.32	-0.29	0.24	1.0000
ACLR+MCL+MTL vs ACLR+MCL-MTL	15	8	-1.75	1.37	-2.89	-0.61	0.0683
ACLR+MCL+MTL vs ACLR-MCL-MTL	15	16	-1.76	1.35	-2.48	-1.04	0.0009
ACLR+MCL+MTL vs ACLR+RampRepair	15	16	-0.12	1.37	-0.85	0.61	1.0000
ACLR-MCL-MTL vs ACL+RampRepair	15	16	1.64	1.19	1.01	2.28	0.0006
Intact vs ACLR+MCL+MTL	30	16	0.30	2.01	-0.77	1.37	0.5814
Intact vs ACLR-MCL+MTL	30	8	0.97	2.40	-1.04	2.97	0.5814
Intact vs ACLR+MCL-MTL	30	8	1.39	1.79	-0.10	2.89	0.1884
Intact vs ACLR-MCL-MTL	30	16	1.83	2.25	0.62	3.03	0.0384
Intact vs ACLR+RampRepair	30	16	1.25	2.08	0.15	2.36	0.1162
ACLR+MCL+MTL vs ACLR-MCL+MTL	30	8	-0.51	0.30	-0.76	-0.26	0.0157
ACLR+MCL+MTL vs ACLR+MCL-MTL	30	8	-1.25	1.15	-2.21	-0.29	0.0891
ACLR+MCL+MTL vs ACLR-MCL-MTL	30	16	-1.52	1.24	-2.18	-0.86	0.0018
ACLR+MCL+MTL vs ACLR+RampRepair	30	16	-0.95	0.96	-1.46	-0.44	0.0113
ACLR-MCL-MTL vs ACL+RampRepair	30	16	0.57	0.72	0.19	0.96	0.0384

6 Simulated Pivot Shift Test - Internal Rotation

6.1 Manipulate Data

```
# Create delta-intact data with dplyr gather/spread/gather
dat2.psir.spread <- dat2.psir %>% select(Pair, Specimen, Group,
    Flexion, State, Value) %>% spread(data = ., key = State,
    value = Value, fill = NA)
dat2.psir.deltaintact.spread <- dat2.psir.spread
dat2.psir.deltaintact.spread[, 5:10] <- dat2.psir.spread[, 5:10] -
    dat2.psir.spread[, 5]
dat2.psir.deltaintact <- gather(dat2.psir.deltaintact.spread,
    key = State, value = Value, Intact:ACLR.RampRepair, -(Pair:Flexion),
    factor_key = TRUE)
dat2.psir.deltaintact <- dat2.psir.deltaintact %>% subset(State !=
    "Intact") %>% subset(!is.na(Value)) %>% droplevels()
str(dat2.psir.deltaintact)
```

```
~~~ 'data.frame':   128 obs. of  6 variables:
~~~  $ Pair    : Factor w/ 8 levels "5","6","7","8",..: 1 1 1 1 2 2 2 2 3 3 ...
~~~  $ Specimen: num  5 5 17 17 6 6 18 18 7 7 ...
~~~  $ Group   : Factor w/ 2 levels "MCLcut","MTLcut": 1 1 2 2 1 1 2 2 1 1 ...
~~~  $ Flexion : num  15 30 15 30 15 30 15 30 15 30 ...
~~~  $ State   : Factor w/ 5 levels "ACLR.MCL.MTL",..: 1 1 1 1 1 1 1 1 1 1 ...
~~~  $ Value   : num  -0.086 0.2635 -0.2482 0.0727 -0.5437 ...
```

```
head(dat2.psir.deltaintact)
```

```
~~~    Pair Specimen  Group Flexion        State     Value
~~~ 33    5        5 MCLcut      15 ACLR.MCL.MTL -0.086001
~~~ 34    5        5 MCLcut      30 ACLR.MCL.MTL  0.263462
~~~ 35    5       17 MTLcut      15 ACLR.MCL.MTL -0.248156
~~~ 36    5       17 MTLcut      30 ACLR.MCL.MTL  0.072676
~~~ 37    6        6 MCLcut      15 ACLR.MCL.MTL -0.543706
~~~ 38    6        6 MCLcut      30 ACLR.MCL.MTL  0.634655
```

6.2 Summary Stats

Table 25: Internal Rotation (deg) during Simulated Pivot Shift Test

Group	State	Flexion	n	nmiss	mean	sd	min	Q1.25.	median	Q3.75.	max
MCLcut	Intact	15	8	0	14.24	4.82	9.13	10.55	12.62	18.18	22.15
MCLcut	ACLR.MCL.MTL	15	8	0	14.47	4.50	10.27	10.78	13.00	16.99	21.75
MCLcut	ACLR.mcl.MTL	15	8	0	14.53	4.59	10.19	10.89	12.91	17.04	22.04
MCLcut	ACLR.mcl.mtl	15	8	0	16.32	4.63	10.79	12.99	14.98	20.37	22.94
MCLcut	ACLR.RampRepair	15	8	0	14.80	4.88	8.95	11.74	13.31	18.28	22.03
MCLcut	Intact	30	8	0	17.65	5.74	9.89	14.02	16.74	21.12	26.34
MCLcut	ACLR.MCL.MTL	30	8	0	18.55	5.93	10.76	14.38	18.35	20.84	28.21
MCLcut	ACLR.mcl.MTL	30	8	0	18.93	6.00	10.98	14.68	19.01	21.17	28.78
MCLcut	ACLR.mcl.mtl	30	8	0	20.12	6.14	11.22	16.18	20.49	23.38	29.51
MCLcut	ACLR.RampRepair	30	8	0	19.65	6.21	11.17	15.46	20.05	22.49	29.46
MTLcut	Intact	15	8	0	13.74	3.17	9.33	11.88	13.54	15.55	19.19
MTLcut	ACLR.MCL.MTL	15	8	0	13.45	2.63	9.09	12.29	13.78	14.74	17.17
MTLcut	ACLR.MCL.mtl	15	8	0	15.56	3.28	11.39	13.58	14.73	16.93	20.45
MTLcut	ACLR.mcl.mtl	15	8	0	15.91	3.47	11.38	14.06	14.90	17.32	21.46
MTLcut	ACLR.RampRepair	15	8	0	14.72	2.97	11.11	12.94	14.05	16.16	19.60
MTLcut	Intact	30	8	0	17.51	5.18	12.11	12.46	16.86	21.83	25.67
MTLcut	ACLR.MCL.MTL	30	8	0	17.87	4.93	12.35	13.03	17.42	22.31	24.14
MTLcut	ACLR.MCL.mtl	30	8	0	19.52	5.51	13.38	15.81	18.11	23.45	27.81
MTLcut	ACLR.mcl.mtl	30	8	0	20.09	5.78	13.55	16.29	18.44	24.15	28.97
MTLcut	ACLR.RampRepair	30	8	0	19.39	5.46	13.59	14.76	18.31	23.35	27.96

Table 26: Internal Rotation (deg) during Simulated Pivot Shift Test
- Version 2

State	Flexion	n	nmiss	mean	sd	min	Q1.25.	median	Q3.75.	max
Intact	15	16	0	13.99	3.95	9.13	10.70	13.54	16.60	22.15
ACLR.MCL.MTL	15	16	0	13.96	3.60	9.09	10.78	13.72	15.88	21.75
ACLR.mcl.MTL	15	8	0	14.53	4.59	10.19	10.89	12.91	17.04	22.04
ACLR.MCL.mtl	15	8	0	15.56	3.28	11.39	13.58	14.73	16.93	20.45
ACLR.mcl.mtl	15	16	0	16.12	3.96	10.79	13.52	14.97	20.08	22.94
ACLR.RampRepair	15	16	0	14.76	3.90	8.95	12.19	13.94	17.59	22.03
Intact	30	16	0	17.58	5.28	9.89	12.58	16.86	21.83	26.34
ACLR.MCL.MTL	30	16	0	18.21	5.28	10.76	13.18	18.01	22.31	28.21
ACLR.mcl.MTL	30	8	0	18.93	6.00	10.98	14.68	19.01	21.17	28.78
ACLR.MCL.mtl	30	8	0	19.52	5.51	13.38	15.81	18.11	23.45	27.81
ACLR.mcl.mtl	30	16	0	20.11	5.76	11.22	16.29	19.59	23.93	29.51
ACLR.RampRepair	30	16	0	19.52	5.65	11.17	14.76	19.65	23.35	29.46

Table 27: Internal Rotation (deg) during Simulated Pivot Shift Test, Intact-Subtracted

Group	State	Flexion	n	nmiss	mean	sd	min	Q1.25.	median	Q3.75.	max
MCLcut	ACLR.MCL.MTL	15	8	0	0.24	1.53	-2.14	-0.43	-0.04	0.73	2.99
MCLcut	ACLR.mcl.MTL	15	8	0	0.29	1.47	-2.12	-0.19	0.03	0.70	2.78
MCLcut	ACLR.mcl.mtl	15	8	0	2.09	1.85	0.45	0.86	1.42	2.72	6.05
MCLcut	ACLR.RampRepair	15	8	0	0.57	1.78	-2.40	-0.25	0.30	1.71	3.27
MCLcut	ACLR.MCL.MTL	30	8	0	0.90	1.09	-0.74	0.34	0.75	1.29	2.86
MCLcut	ACLR.mcl.MTL	30	8	0	1.28	1.25	-0.35	0.66	0.96	1.53	3.72
MCLcut	ACLR.mcl.mtl	30	8	0	2.47	1.77	0.95	1.27	2.12	2.71	6.40
MCLcut	ACLR.RampRepair	30	8	0	2.00	1.62	0.20	1.25	1.46	2.17	5.47
MTLcut	ACLR.MCL.MTL	15	8	0	-0.29	1.63	-3.20	-0.72	0.05	0.58	1.82
MTLcut	ACLR.MCL.mtl	15	8	0	1.82	1.93	-1.00	0.85	1.29	2.75	5.06
MTLcut	ACLR.mcl.mtl	15	8	0	2.17	1.98	-0.99	0.98	2.07	3.14	5.31
MTLcut	ACLR.RampRepair	15	8	0	0.98	1.56	-1.69	0.22	0.97	2.14	2.99
MTLcut	ACLR.MCL.MTL	30	8	0	0.36	1.04	-1.54	0.00	0.37	0.86	2.06
MTLcut	ACLR.MCL.mtl	30	8	0	2.01	1.58	0.50	0.82	1.53	2.69	4.48
MTLcut	ACLR.mcl.mtl	30	8	0	2.58	1.70	1.02	1.13	2.03	3.66	5.32
MTLcut	ACLR.RampRepair	30	8	0	1.88	1.06	0.65	0.97	1.96	2.41	3.64

Table 28: Internal Rotation (deg) during Simulated Pivot Shift Test, Intact-Subtracted - Version 2

State	Flexion	n	nmiss	mean	sd	min	Q1.25.	median	Q3.75.	max
ACLR.MCL.MTL	15	16	0	-0.03	1.55	-3.20	-0.43	-0.04	0.58	2.99
ACLR.mcl.MTL	15	8	0	0.29	1.47	-2.12	-0.19	0.03	0.70	2.78
ACLR.MCL.mtl	15	8	0	1.82	1.93	-1.00	0.85	1.29	2.75	5.06
ACLR.mcl.mtl	15	16	0	2.13	1.86	-0.99	0.90	1.89	2.85	6.05
ACLR.RampRepair	15	16	0	0.77	1.63	-2.40	-0.18	0.53	2.08	3.27
ACLR.MCL.MTL	30	16	0	0.63	1.06	-1.54	0.17	0.58	0.97	2.86
ACLR.mcl.MTL	30	8	0	1.28	1.25	-0.35	0.66	0.96	1.53	3.72
ACLR.MCL.mtl	30	8	0	2.01	1.58	0.50	0.82	1.53	2.69	4.48
ACLR.mcl.mtl	30	16	0	2.52	1.68	0.95	1.15	2.03	3.20	6.40
ACLR.RampRepair	30	16	0	1.94	1.32	0.20	1.14	1.68	2.41	5.47

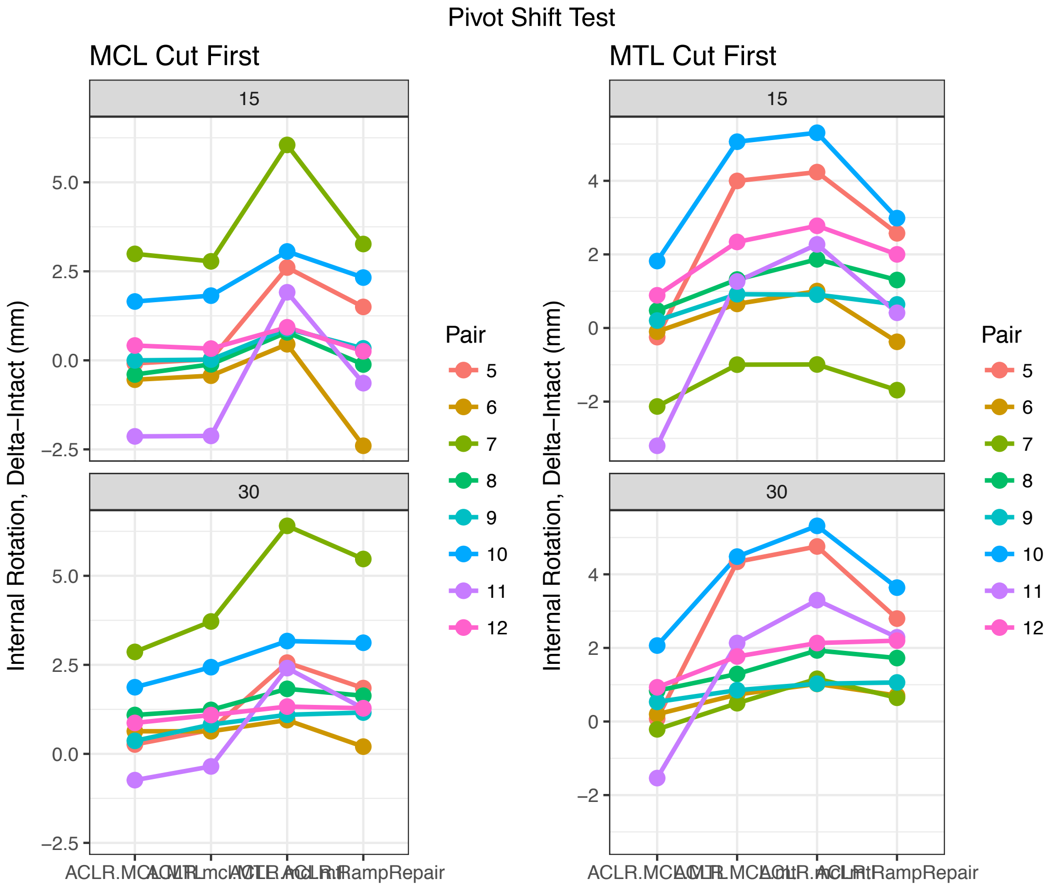
6.2.1 For Paper

Table 29: Mean ± SD Internal Rotation (deg) by Cut State and Flexion Angle - Non-Intact-Subtracted

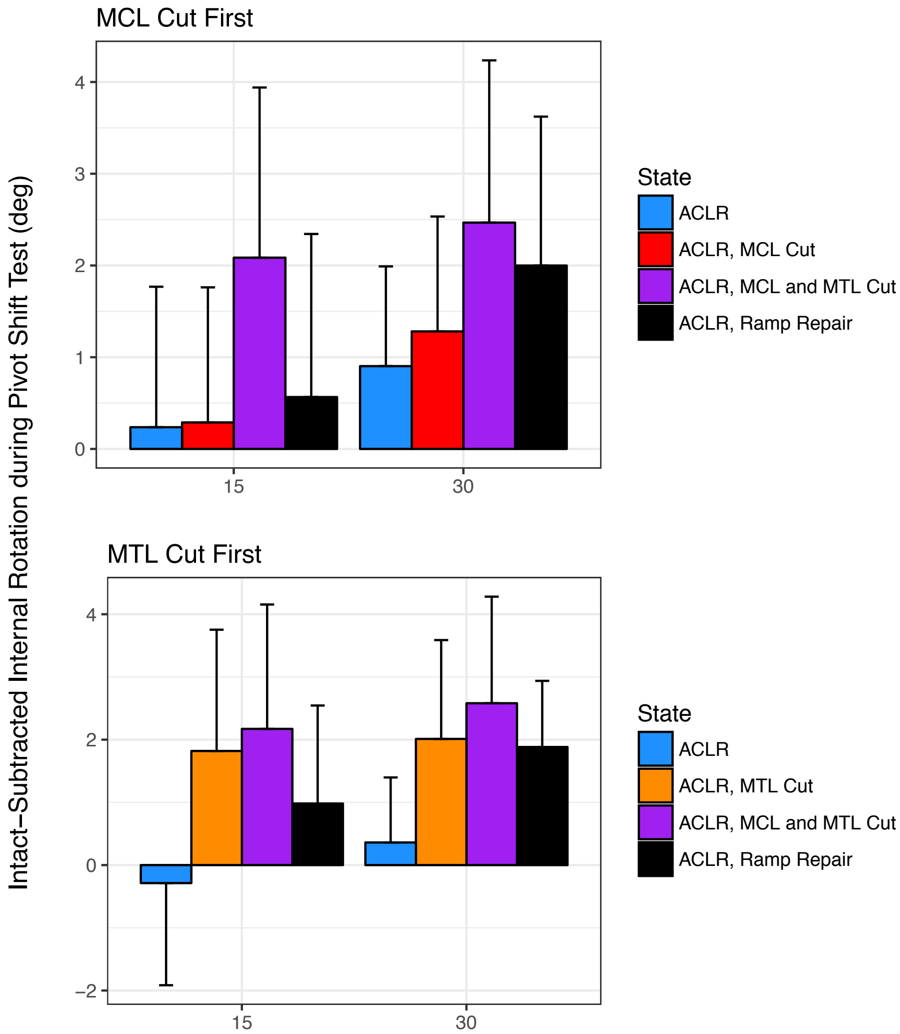
State	15	30
Intact	14 ± 3.9	17.6 ± 5.3
ACLR.MCL.MTL	14 ± 3.6	18.2 ± 5.3
ACLR.mcl.MTL	14.5 ± 4.6	18.9 ± 6
ACLR.MCL.mtl	15.6 ± 3.3	19.5 ± 5.5
ACLR.mcl.mtl	16.1 ± 4	20.1 ± 5.8
ACLR.RampRepair	14.8 ± 3.9	19.5 ± 5.7

6.3 Plot Data

6.3.1 Spaghetti plots to inspect subject-level data

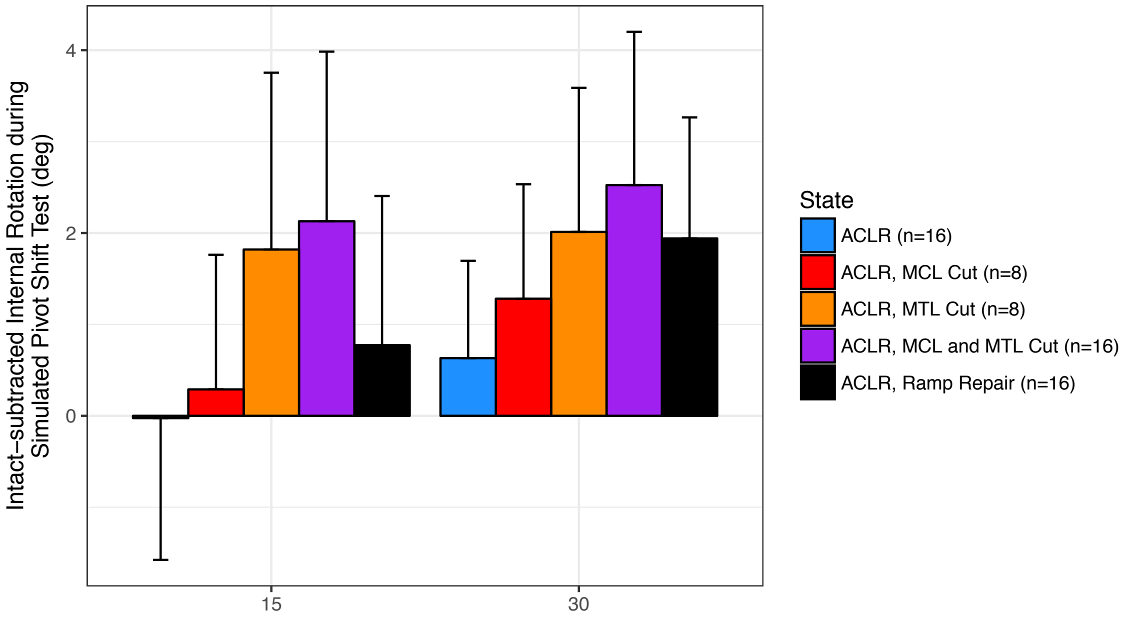


6.3.2 Bar Plot



MCL Cut First
MTL Cut First
Intact–Subtracted Internal Rotation during Pivot Shift Test (deg)
State
ACLR
ACLR, MCL Cut
ACLR, MCL and MTL Cut
ACLR, Ramp Repair
State
ACLR
ACLR, MTL Cut
ACLR, MCL and MTL Cut
ACLR, Ramp Repair
15
30

6.3.3 New Bar Plot




```
~~~  pdf
~~~    2

~~~  pdf
~~~    2

~~~  pdf
~~~    2
```

6.4 Custom set of T-tests

Table 30: T-tests for Anterior Displacement during Pivot Shift Test (mm), intact-subtracted data

	Flexion Angle	n	Mean Diff	SD Diff	CI LB	CI UB	Holm P
Intact vs ACLR+MCL+MTL	15	16	-0.03	1.55	-0.85	0.80	1.0000
Intact vs ACLR-MCL+MTL	15	8	0.29	1.47	-0.94	1.52	1.0000
Intact vs ACLR+MCL-MTL	15	8	1.82	1.93	0.20	3.44	0.1622
Intact vs ACLR-MCL-MTL	15	16	2.13	1.86	1.14	3.12	0.0028
Intact vs ACLR+RampRepair	15	16	0.77	1.63	-0.10	1.64	0.3091
ACLR+MCL+MTL vs ACLR-MCL+MTL	15	8	-0.05	0.15	-0.18	0.08	1.0000
ACLR+MCL+MTL vs ACLR+MCL-MTL	15	8	-2.11	1.61	-3.45	-0.76	0.0536
ACLR+MCL+MTL vs ACLR-MCL-MTL	15	16	-2.15	1.53	-2.97	-1.34	0.0004
ACLR+MCL+MTL vs ACLR+RampRepair	15	16	-0.80	1.25	-1.47	-0.13	0.1326
ACLR-MCL-MTL vs ACL+RampRepair	15	16	1.35	0.87	0.89	1.82	0.0002
Intact vs ACLR+MCL+MTL	30	16	0.63	1.06	0.06	1.20	0.0639
Intact vs ACLR-MCL+MTL	30	8	1.28	1.25	0.23	2.33	0.0639
Intact vs ACLR+MCL-MTL	30	8	2.01	1.58	0.69	3.33	0.0345
Intact vs ACLR-MCL-MTL	30	16	2.52	1.68	1.63	3.42	0.0002
Intact vs ACLR+RampRepair	30	16	1.94	1.32	1.24	2.65	0.0003
ACLR+MCL+MTL vs ACLR-MCL+MTL	30	8	-0.38	0.27	-0.60	-0.16	0.0247
ACLR+MCL+MTL vs ACLR+MCL-MTL	30	8	-1.65	1.58	-2.97	-0.33	0.0639
ACLR+MCL+MTL vs ACLR-MCL-MTL	30	16	-1.89	1.52	-2.70	-1.08	0.0013
ACLR+MCL+MTL vs ACLR+RampRepair	30	16	-1.31	1.06	-1.88	-0.74	0.0013
ACLR-MCL-MTL vs ACL+RampRepair	30	16	0.58	0.63	0.25	0.92	0.0124

7 Statistical Software

```
lapply(c("base", pkgs), citation)
```

```
~~~ [[1]]
~~~
~~~ To cite R in publications use:
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~~~   statistical computing. R Foundation for Statistical Computing,
~~~   Vienna, Austria. URL https://www.R-project.org/.
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~~~ A BibTeX entry for LaTeX users is
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~~~   @Manual{,
~~~     title = {R: A Language and Environment for Statistical Computing},
~~~     author = {{R Core Team}},
~~~     organization = {R Foundation for Statistical Computing},
~~~     address = {Vienna, Austria},
~~~     year = {2017},
~~~     url = {https://www.R-project.org/},
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~~~   https://CRAN.R-project.org/package=gridExtra
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~~~   @Manual{,
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~~~     year = {2016},
~~~     note = {R package version 2.2.1},
~~~     url = {https://CRAN.R-project.org/package=gridExtra},
~~~   }
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~~~ To cite ggplot2 in publications, please use:
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~~~   Springer-Verlag New York, 2009.
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~~~   @Book{,
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~~~     title = {ggplot2: Elegant Graphics for Data Analysis},
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~~~      year = {2009},
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~~~      url = {http://ggplot2.org},
~~~    }
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~~~  Pinheiro J, Bates D, DebRoy S, Sarkar D and R Core Team (2017).
~~~  _nlme: Linear and Nonlinear Mixed Effects Models_. R package
~~~  version 3.1-131, <URL: https://CRAN.R-project.org/package=nlme>.
~~~
~~~  A BibTeX entry for LaTeX users is
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~~~      url = {https://CRAN.R-project.org/package=nlme},
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~~~  To cite lme4 in publications use:
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~~~    Fitting Linear Mixed-Effects Models Using lme4. Journal of
~~~    Statistical Software, 67(1), 1-48. doi:10.18637/jss.v067.i01.
~~~
~~~  A BibTeX entry for LaTeX users is
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~~~    @Article{,
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~~~  To cite package 'languageR' in publications use:
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~~~    "Analyzing Linguistic Data: A practical introduction to
~~~    statistics".. R package version 1.4.1.
~~~    https://CRAN.R-project.org/package=languageR
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~~~    Journal 50(3), 346--363.
~~~
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~~~      year = {2008},
~~~      volume = {50},
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~~~      pages = {346--363},
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~~~  To cite sandwich in publications use:
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~~~    Covariance Matrix Estimators. Journal of Statistical Software
~~~    11(10), 1-17. URL http://www.jstatsoft.org/v11/i10/.
~~~
~~~  If sandwich is applied to models other than lm() also cite:
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~~~    Estimators. Journal of Statistical Software 16(9), 1-16. URL
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~~~    R package version 5.1-1. https://CRAN.R-project.org/package=rms
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~~~    https://CRAN.R-project.org/package=xlsx
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~~~    0.7.1. https://CRAN.R-project.org/package=tidyr
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~~~  To cite package 'dplyr' in publications use:
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~~~    0.7.2. https://CRAN.R-project.org/package=dplyr
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~~~  To cite reshape in publications, please use:
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~~~    H. Wickham. Reshaping data with the reshape package. Journal of
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~~~      author = {Hadley Wickham},
~~~      journal = {Journal of Statistical Software},
~~~      number = {12},
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~~~      url = {http://www.jstatsoft.org/v21/i12/paper},
~~~      volume = {21},
~~~      year = {2007},
~~~    }
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~~~  [[14]]
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~~~  To cite effects in publications use:
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~~~    John Fox (2003). Effect Displays in R for Generalised Linear
~~~    Models. Journal of Statistical Software, 8(15), 1-27. URL
~~~    http://www.jstatsoft.org/v08/i15/.
~~~
~~~  For usage in multinomial and proportional-odds logit models also
~~~  cite:
~~~
~~~    John Fox, Jangman Hong (2009). Effect Displays in R for
~~~    Multinomial and Proportional-Odds Logit Models: Extensions to
~~~    the effects Package. Journal of Statistical Software, 32(1),
~~~    1-24. URL http://www.jstatsoft.org/v32/i01/.
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~~~    Models. R package version 2.0-33.
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~~~     url = {https://CRAN.R-project.org/package=lmerTest},
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~~~
~~~    Yihui Xie (2015) Dynamic Documents with R and knitr. 2nd
~~~    edition. Chapman and Hall/CRC. ISBN 978-1498716963
~~~
~~~    Yihui Xie (2014) knitr: A Comprehensive Tool for Reproducible
~~~    Research in R. In Victoria Stodden, Friedrich Leisch and Roger
~~~    D. Peng, editors, Implementing Reproducible Computational
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~~~  To cite the car package in publications use:
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~~~    John Fox and Sanford Weisberg (2011). An {R} Companion to
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~~~    http://socserv.socsci.mcmaster.ca/jfox/Books/Companion
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