Factors Related to the Timing of Anterior Cruciate Ligament Reconstruction Failure
Among an Active Population

DISSERTATION

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Abstract

Anterior cruciate ligament (ACL) rupture is a serious event linked to detrimental sequelae such as short-term functional deficits and long-term morbidity involving osteoarthritis and degenerative, progressive disability. In most cases, highly active patients that desire to return to pre-injury activity levels require ACL reconstruction surgery (ACLR) with 75%-97% experiencing positive results with respect to knee function and stability, reduced pain, and a return to normal levels of activity. Despite this, there remain patients who experience negative outcomes such as knee pain and stiffness, restricted motion, instability, graft failure, and osteoarthritis. An increasing number of studies have focused on ACLR outcomes, with the vast majority reporting subjective data collected from validated questionnaires and objective data in the form of functional testing and radiographic results. It is estimated that between 2% and 6% of primary ACL reconstructions will fail, requiring revision ACLR (RACL) surgery. Due to the relative rarity of graft failure the collection of a sufficient number of graft failures leading to RACL in a prospective manner can be lengthy and costly. The Multicenter ACL Revision Study (MARS) was designed to prospectively assess RACL outcomes and has amassed nearly 1000 patients since 2006. The extraction of demographic and primary ACLR (PACLR) surgical data from this study allows for the calculation of time from PACLR to RACL and time from PACLR to graft failure. To date no published
study has been designed to investigate time-to-revision or time-to-failure as a dependent outcome of interest.

The goals of this study were: (1) describe patient and surgical characteristics of the largest collection of anterior cruciate ligament graft failures in the US (n=920), (2) identify factors associated with occurrence of revision surgery within 30 months of PACLR (n=653), and (3) specifically investigate the association of sex and time-to-graft failure and the modifying effects of graft type and activity level (n=193).

The main finding of this research is that among patients with confirmed ACL graft failure, factors associated with greater odds of revision within 30 months of PACLR are: age at PACLR of 18 years or less, a return to a high activity level (Marx activity score ≥ 12), allograft use in PACLR, hamstring with semitendinosis plus gracilis use in PACLR, and prior lateral meniscus surgery. Patients with a femoral tunnel position deemed too anterior or too vertical had reduced odds of revision within 30 months following PACLR when compared to a position deemed ideal. A sex difference was not observed for revision occurring within 30 months of PACLR. However, an additional finding suggests that when time-to-graft failure, rather than revision, is taken into account a significant difference between males and females exists, with female grafts failing earlier. Activity level and prior graft type modify this difference. Future, prospective studies should investigate the temporal component of graft failure and results from this study suggest age at PACLR, activity level to which the patient wishes to return, and prior graft type, graft source, and femoral tunnel position should be considered as potential factors.
Dedication

Dedicated to my wife, Bettina, and our two sons, Parker and Oliver.
Vita

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Epidemiology

Minor Field:

Environmental Health

Toxicology
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Chapter 1: Introduction

1.1 Background to the Problem

The anterior cruciate ligament (ACL) is one of the four major knee ligaments and is located at the center of the knee along with the posterior cruciate ligament. The ACL is critical to knee stability by preventing excessive forward and backward motion of the knee joint. Although the incidence of ACL injury is relatively rare in the general population, among an athletic population, the frequency is much higher. ACL injuries are primarily sports-related, but non-sports related injuries can tear, stretch, or rupture the ACL through repetitive physical stress such as frequent pivoting and twisting of the knee. These injuries often occur as a result of demands in the workplace. The nature of sports-related ACL injuries is identified as either contact or non-contact. Contact injuries result from contact with another athlete or, less frequently, sporting apparatus such as a goalpost or bench. Non-contact injuries result from movements, further referred to as dynamic sporting maneuvers, which place excessive biomechanical strain on the knee such as deceleration, cutting, pivoting, or landing. Non-contact injuries account for roughly 70% of ACL injuries and the associated risk factors have been widely studied over the last 20 years. Research has concentrated on the identification and clinical assessment of potential risk factors that may lead to an athlete sustaining an ACL injury.
Proposed risk factors are commonly separated into two categories: intrinsic or extrinsic. Intrinsic factors are those that are generally non-modifiable and include: sex, age, ligament size and strength, joint laxity, intercondylar notch size and shape, and limb alignment, and to some extent, hormonal levels. Extrinsic factors are those that are potentially modifiable and include: body movement and positioning, muscular strength, conditioning levels, activity levels, and neuromuscular coordination.

ACL injuries range from mild, such as small or partial tears, to severe, such as complete tears of the ligament or avulsions where a bone fragment tears away from the main mass of the tibia or femur. A damaged ACL will not heal on its own due to a lack of blood supply. There are, however, two treatment options, one non-surgical and one surgical. Non-surgical treatment, referred to as “conservative management,” is indicated for mild injuries or partial tears. Conservative treatment generally requires several months of rehabilitation with the goal of strengthening the surrounding muscles, the hamstring and quadriceps, in order to compensate for the weakened ACL. For patients with a severe or complete ACL tear, or among those with a partial tear who desire to return to a high level of activity involving dynamic sports maneuvers, ACL reconstruction (ACLR) surgery is indicated. For patients who experienced a complete tear and whose lifestyle involves little or no exposure to dynamic sports maneuvers, conservative management can be effective at stabilizing the knee. However, the risk of subsequent injury to other ligaments of the knee, the meniscus, and possibly osteoarthritis is greatly increased.
Patients desiring a return to an active lifestyle or those experiencing episodes of instability usually opt for ACLR. A range of surgical options exist and often involve choices regarding graft type and source. The primary graft type options are an allograft, where the graft is harvested from a cadaveric donor, and an autograft, where the graft is harvested from the patient. Allograft sources primarily consist of cadaveric patellar, anterior tibialis, or Achilles tendons. Autograft sources consist of patellar (PT) or hamstring (HT) tendons, and to a lesser extent quadriceps. ACLR is generally followed by a lengthy and rigorous rehabilitation protocol with 80-90% of patients experiencing a positive outcome regardless of graft type.

Success of ACLR can be judged in the short-term, by the restoration of functional stability to the knee, and in the long-term, by a reduction of secondary meniscal and articular cartilage injury as well as a reduction in the risk of developing degenerative joint disease, mainly osteoarthritis. Graft failure, defined as stretching or rupture of the graft leading to instability, is both a short- and long-term measure and its incidence may be higher than native ACL injury. Risk factors for ACL graft failures are not as well studied as those for native ACL injury; however, postulated reasons for ACL graft failure following ACLR are knee trauma, poor surgical technique, undiagnosed concurrent knee injuries, and failed biological incorporation of the graft. Graft failure requires additional surgery to revise the primary ACLR and will be referred to in the remainder of this study as revision ACLR (RACLR). The possibility exists that the risk of ACL graft failure may have more to do with variables associated with ACLR surgery and less to do with the underlying risk factors for the native ACL injury.
1.2 Need for the study

Several studies have investigated clinical outcomes of ACLR and have largely focused on smaller cohorts treated by individual surgeons or surgical practice groups. Most of these studies were designed to investigate objective outcome measures, such as joint laxity and knee instability, as well as subjective patient-based outcomes, such as knee pain, stiffness, and immobility. The results of these studies vary and are often conflicting. Graft failure is often reported as a secondary outcome and not the main focus of the studies with little or no interest in the timing of the failure. No study to date has specifically investigated time-to-graft failure following ACLR as the primary outcome of interest. Although risk factors for poor outcomes have been suggested, the true incidence of failed ACL reconstruction is difficult to calculate and is likely underreported. Due to the increasing number of ACLR procedures being performed annually and the high level of activity expected in an aging population, the frequency of graft failure following ACL reconstruction will likely increase. Identifying factors associated with time-to-graft failure as well as the incidence of failure can provide valuable information that can be applied to postoperative care. For example, a sex may not be a strong risk factor for graft failure incidence over a 5 year follow-up period where a similar proportion of male and female ACLR patients experience failure. However, a male/female difference may exist when the timing of failures is investigated and understanding this subtle difference can allow for more efficacious postoperative care.
1.3 Purpose of the Study

The elevated incidence of native ACL injury among female athletes remains incompletely understood. Many risk factors have been proposed during the last three decades, but only a few have garnered consensus and include: smaller femoral notch width in women, with possibly less space for the ACL; sex differences in leg alignment, with an increased rate of dynamic valgus among female athletes; and in neuromuscular control, including decreased activation of the hamstrings and gluteus muscles among female athletes. Neuromuscular training programs have been developed with the aim to minimize hazardous landing, cutting, and pivoting positions observed in female athletes. The results of these programs are encouraging and have been shown to have success in reducing the incidence of ACL injury among female athletes.

Success of ACLR can be judged in the short-term, by the restoration of functional stability to the knee, and in the long-term, by a reduction of secondary meniscal and articular cartilage injury as well as reducing the risk of developing degenerative joint disease, mainly osteoarthritis. Positive clinical outcomes of ACLR have been observed. Following ACLR, functional tests are generally favorable, indicating the stability of the knee is regained, with a large percentage of patients returning to pre-injury levels of activity. Graft type, graft source, and sex do not seem to affect functional outcomes or graft failure rates. Different surgical techniques used during ACLR, and activity level following surgery, appear to be risk factors for graft failure, suggesting modifiable intervention points. There are very little data focused on the timing of graft failure and
the resulting RACLs, and to date, no research has been published specifically investigating the time from primary ACLR (PACLs) to RACLs, or more precisely, the time from ACLR to graft failure, as the dependent variable of interest. In an attempt to fill this gap in knowledge three manuscripts will be developed that will utilize patient and surgical data collected from a large, prospective longitudinal study on RACLs. As a collective, the manuscripts will attempt to answer the questions: (1) What is the profile of an active sample population with regards to patient and surgical characteristics, (2) What factors are associated with the time from PACLs to RACLs, (3) Does activity level and graft type modify the effect of sex on time to graft failure.

1.4 Research Aims

1.4.1 Manuscript I

The specific aim of the first proposed manuscript is to provide descriptive epidemiology of the MARS study population. This study was based on the largest collection of patients with a confirmed ACLR graft failure in the US and thus a thorough description of demographic and surgical data is potentially beneficial. This population was previously described; however, this report presented data collected through April 1, 2009 and included 460 patients. The proposed study will act as an update to that report and will include data collected through December 31, 2010, involving more than 900 patients.
1.4.2 Manuscript II

The primary aim of the second proposed study was to investigate the possible effects of primary ACLR surgical techniques and patient characteristics on the timing of RACL among patients with confirmed failures. The main question is whether potentially modifiable surgical techniques affect the time between primary ACLR and RACL. Due to the design of the prospective MARS, in which the date of RACL marks the onset of follow-up, the date of graft failure leading to RACL was not available for the entire population. For the proposed manuscript the date of RACL is a proxy for the date of graft failure. Specific focus was on suspected surgical risk factors for graft failure and includes: graft type, graft source, observed meniscal damage and subsequent repair, and tibial and femoral tunnel placement. Secondary factors that may confound or modify possible associations between surgical techniques and time-to-RACL was investigated and include age at primary ACLR, activity level, smoking status, education, and BMI at the time of RACL.

1.4.3 Manuscript III

The specific aim of the third proposed study was to assess the effect sex has on time-to-graft failure, or time-to-failure (TTF), while accounting for the confounding and/or modifying effects of activity level to which the patient returned and ACLR graft type. Due to the limited sample size available for this study, full Cox proportional
hazards modeling was likely to produce unstable results. Therefore Kaplan-Meier survival analysis was conducted with stratification on activity level and graft type.

The main questions are: Do males and females experience graft failure at similar time points, and is TTF modified by activity level and graft type? The date of injury will be collected via surgeons’ notes and will more accurately reflect the date of failure. A subset of the original study population is investigated, consisting of 192 patients, of which 136 had available TTF data. Specific focus was on the difference in survival curves between males and females assessed among patients that returned to high activity level and those that returned to a lower activity level. Also, male and female survival functions were compared among patients that received an autograft and those that received and allograft in their previous ACLR.
Chapter 2: Background

2.1 Epidemiology

Anterior cruciate ligament injury and, more importantly, rupture is a calamitous event linked to detrimental sequelae such as short-term functional deficits and long-term morbidity involving osteoarthritis and degenerative, progressive disability.\(^\text{84, 103, 105, 117, 151}\)

Incidence of ACL injury is difficult to estimate with accuracy as many minor injuries occur without a physician visit, and the effects of injury can often be mitigated by reduced activity or strengthening of surrounding musculature. Also, the lack of a national knee injury registry in the United States, similar to those found in Scandinavian countries, compounds the problem. It is therefore easier to estimate the incidence of ACLR surgeries resulting from an injury severe enough to warrant such a procedure, such as a complete tear or avulsion. National estimates of ACLR surgeries in the United States vary widely, from 60,000 to 250,000 annually, and are more than a decade old.\(^\text{39, 48, 56}\)

However, recent studies involving the Kaiser Permanente Health Maintenance Organization population (>3 million)\(^\text{24}\) and the residents of New York State\(^\text{85}\) have provided incidence rate data from which Csintalan et al.\(^\text{24}\) and Lyman et al.\(^\text{85}\) extrapolated national approximations of annual incidence of ALCR surgery, which agree with earlier estimates. Despite the wide range of national estimates, annual ACLR incidence appears to be trending upward (Figures 2.1 and 2.2).\(^\text{24, 85, 85}\) This trend may be a result of an
increase in the incidence of ACL injury or an increase in the selection of ACLR as a therapeutic remedy, or both. ACLR surgery costs between $17,000 and $25,000 per patient, depending on graft choice and any concomitant injuries discovered during surgery, resulting in a conservative cost of over one billion dollars annually.

The estimated incidence of ACL injury leading to ACLR is relatively rare in the general population (< 0.1%), although it is much more common in athletic population (1.5-1.7%), and even greater in female athletes where estimates suggest 5-10% suffer an injury. ACL injury is most common among adolescents and young adults involved in various athletic activities involving frequent dynamic sports maneuvers. The estimated incidence rate of ACL injuries among this group was found to be between 36.9 and 60.9 per 100,000 person years. McNair et al. reported that 70% of ACL injuries resulted from non-contact, defined as an injury occurring without player-to-player (body-to-body) contact; 30% were found to result from contact. Boden et al. reported similar results. The consensus in the literature indicates approximately 70% of ACL injuries result from a non-contact mechanism.

It has been extensively documented that the incidence rate of knee injury among female athletes is four to six times that of male athletes competing in the same landing and cutting sports, such as soccer, basketball, and volleyball. A five- and
Figure 2.1 Anterior cruciate ligament reconstructions in New York State and US estimates. Adapted from Lyman et al. 

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ten-fold increase in collegiate and high school sport participation, respectively, has resulted in a rapid rise in the risk of ACL injuries among female athletes. The sex disparity and, to a lesser extent, the non-contact nature of a majority of injuries has fueled intense investigation. The ACL has become the most widely studied and discussed subject in sports medicine, with a particular focus on athletic female populations.
Research has covered a vast range of topics and the current review will attempt to outline areas of epidemiologic importance, such as risk factors for the first ACL injury, referred to as native ACL injury, and clinical outcomes following ACLR. Further discussion will consider risk factors for ACLR graft failure and the areas where future research is warranted.

2.2 Risk Factors for Native ACL Injury

To understand the established influence of sex on the risk of ACL injury, many studies have focused on female athletic populations in an attempt to identify additional risk factors. Risk factors for ACL injury can be divided into broad categories such as anatomical, hormonal, genetic, biomechanical, and neuromuscular. Many suggested risk factors will be discussed; special attention will be given to those that are potentially modifiable and thus amenable to intervention.

2.2.1 Anatomical Factors

Many studies have focused on anthropometric and anatomical factors. Some have argued that anatomical differences in pelvic structure and thigh and tibial alignment, known as the Q angle, may be an underlying factor for the ACL injury rate difference between male and females. However, Gray et al. and Myer et al. concluded that static Q angles were not predictive of ACL injury and did not explain the ACL injury
rate difference between male and female athletes. This supports investigation of neuromuscular factors that may affect dynamic limb alignment during dynamic sports maneuvers.

Others have hypothesized that females are predisposed to ACL injury due to a relatively small ACL and a narrower intercondylar notch width. However, when notch width was normalized to bone width no difference was found between male and female athletes. Thigh length among female skiers as well as tibia length and height have been reported to be risk factors for knee injury. These factors may very well contribute to ACL injury risk, but do not necessarily correlate with dynamic injury mechanisms. Gray et al. concluded anatomic factors, fitness, or experience could not account for the ACL injury rate differences between male and female athletes. The effect of anatomic features on ACL injury is unclear and they are, by nature, non-modifiable where the opportunity for intervention is unlikely.

2.2.2 Hormonal Factors

A laboratory study conducted by Liu et al. demonstrated the ACL has estrogen, progesterone, and relaxin receptors. In vitro studies on human ACL tissue cells have shown estrogen and progesterone may also affect metabolism and collagen synthesis in the ACL. These hormones may affect the structural or functional properties of the ACL and as a result estrogen has been suggested as one of the underlying causes of the increased risk of ACL injury among female athletes. However, Warden et al.
reported that mechanical properties of the ACL are not affected by estrogen. Different phases of the menstrual cycle have been associated with increased risk of ACL injury risk.\textsuperscript{99, 100, 104, 138, 139, 159} A higher incidence of serious ACL injuries among female soccer players has been reported to occur during the luteal phase of the menstrual cycle.\textsuperscript{99, 100} Slauterbeck et al.\textsuperscript{138, 139} also found a higher incidence of ACL injury among female athletes during the luteal phase. Individual sports participation was not reported. Wojtys\textsuperscript{159} reported a decrease in incidence of non-contact ACL injuries during the follicular phase, although, Myklebust\textsuperscript{104} reported a higher incidence of ACL injuries during this phase. These findings are conflicting and to some extent controversial. It has been suggested that if the menstrual cycle was divided into “pre-ovulatory” and “post-ovulatory” phases, there would be more consistency in published reports.\textsuperscript{60} Due to the possible effect of the hormonal variation during the menstrual cycle on ACL injury risk it is has been suggested that the use of oral contraceptive pills (OCPs) may mitigate the risk.\textsuperscript{59, 75, 100} Female athletes taking OCPs have been found to have increased passive and dynamic knee stability compared to those not taking OCPs.\textsuperscript{59} Among female athletes, OCP users have also been found to be less likely to suffer injuries, in general, when compared to non-OCP users.\textsuperscript{100} Despite the suggestive nature of these studies, there is currently no available data demonstrating a decreased risk of ACL injury among OCP users. Future study on the effect of hormones on ACL injury risk is warranted, and intervention, in the form of OCPs, may have limited potential to reduce ACL injuries among female athletes.
2.2.3 Genetic Factors

By nature potential genetic risk factors are non-modifiable and thus only a brief discussion of prior research will follow. Interest in the possible genetic component of ACL injury risk has increased recently and several studies have, arguably, identified specific candidate genes. Posthumus et al. \textsuperscript{119} conducted a case-control genetic association study to compare patients with surgically diagnosed ACL ruptures with active, healthy controls with no prior ligament or tendon injuries. The authors claim to have found a variant of the gene COL1A1 that was significantly underrepresented in the ACL group compared to controls. However, the reported 95\% confidence interval (\textless 0.01 to 1.46) of the odds ratio (0.08) included one and therefore cannot be declared statistically significant. In another case-control genetic association study, \textsuperscript{121} the authors compared patients with surgically diagnosed ACL ruptures with active, healthy controls without a history of ACL injury. Among female participants, a variant of the gene COL5A1 was found to be significantly underrepresented in the ACL group compared to controls (OR=6.6, 95\% CI 1.5-29.7, \textit{p}=0.006). Posthumus et al. \textsuperscript{120} further studied a variation of the COL12A1 gene and its effect on ACL injury risk. They again compared patients with surgically diagnosed ACL ruptures with healthy, active controls. In this case-control genetic association study the authors found the gene variation was overrepresented in the ACL group compared to the healthy, active control group (OR=2.4, 95\% CI 1.0-5.5, \textit{p}=0.048). Again, the confidence interval of the odds ratio included one and should be interpreted with caution.
If a genetic component of ACL injury risk exists it is reasonable to assume that athletic family members would share a similar risk. Limited studies investigating familial tendencies toward ACL rupture have been conducted with mixed and conflicting results. Andersen et al. ² found no increased prevalence of ACL injury among family members. However, Lambert et al. ⁸⁰, Harner et al. ⁵², and Flynn et al. ³⁶ concluded a familial predisposition for ACL rupture. Hewett et al. ⁵⁸ prospectively followed a set of mature twin females involved in high risk sports, soccer and basketball, following baseline biomechanical and neuromuscular measurements and before injury. The authors found that each twin, who subsequently injured their ACLs, demonstrated increased knee abduction angles, decreased knee flexion angles, increased general joint laxity, decreased hamstring/quadriceps peak torque ratios and femoral intercondylar notch width. The findings suggest that underlying neuromuscular and biomechanical risk factors for ACL injury are maintained in a familial setting, conferring elevated risk among family members. Further study is warranted as it is unclear at this point whether familial tendencies toward ACL rupture exist.

The potential genetic component of ACL injury risk represents a new and promising area of study. Interest in this area will inevitably grow as the cost of genetic analysis decreases and has the potential to uncover underlying factors that contribute to anatomical, biomechanical, and neuromuscular deficiencies common to ACL injuries. However, these genetic factors remain non-modifiable and thus attempts at intervention are currently highly unlikely.
2.2.4 Biomechanical Factors

Several studies utilizing video analysis of ACL injuries have been conducted over the past decade. These studies have identified a common body position associated with ACL injury in which the tibia is externally rotated, the knee is close to full extension, the foot is planted, and deceleration occurs followed by valgus collapse.\textsuperscript{18, 112, 146} This body position has been termed dynamic valgus, dynamic lower extremity valgus, or simply valgus and are quite often interchangeable. Over the last 10 years dynamic valgus has been well established as a risk factor for ACL injury. Although biomechanical factors, by themselves, may be difficult to modify, the underlying neuromuscular actions that result in a valgus position allow for clear intervention points.

2.2.5 Neuromuscular Factors

The neuromuscular aspect of ACL injury is one of the most widely studied areas of ACL research. There is increasing evidence in the literature that poor or abnormal neuromuscular control of the hip, ankle, and more importantly, the knee joints during hazardous sporting maneuvers is a major contributor to ACL injury risk.\textsuperscript{56, 62, 83, 95} Sub-optimal neuromuscular control of all three of the lower extremity joints supports the dynamic valgus position observed during video analysis studies.

The quadriceps and hamstrings muscles act to extend and flex the knee, respectively, and the synergistic relationship has been the focus of many studies. Co-contraction of the
hamstrings and quadriceps acts to stabilize the knee by compressing the joint and may be protective against dynamic valgus. High rates of ACL strain occur during quadriceps contraction and lower rates of strain during hamstring contraction, suggesting hamstring activation during landing, cutting, and pivoting may be protective for ACL injury. Several studies have found significant sex-related neuromuscular imbalances where females tend to have decreased hamstrings activation and increased quadriceps activation when landing and pivoting, indicating the lack of hamstring recruitment may account for some of the elevated risk in female athletes. During knee flexion activities female athletes have been found to have increased activation of the quadriceps relative to the hamstrings and increased anterior tibial loads during stop-jump exercises. Females athletes that activate the lateral quadriceps musculature more than the medial quadriceps musculature when landing from a jump have an increased anterior shear force on the tibia and is suggestive that poor medial quadriceps activation may increase ACL injury risk. Hewett et al. measured hamstring recruitment with knee joint loading in female athletes before an athletic season. Study participants were followed through the athletic season and those with poor baseline hamstring recruitment were more likely to experience an ACL injury. Decreased activation of the hamstrings musculature may also be a result of poor proprioception. The ACL not only stabilizes the knee joint but is also highly innervated and contains specific mechanoreceptors. The ACL can sense torque and elongation, common to anterior translation of the tibia, and responds by activating the hamstrings. The available literature strongly demonstrates several relationships between altered
quadriceps and hamstring activation and increased stress on the ACL, suggesting its potential role in injury.

Dynamic stability of the body’s trunk, or core, has also been studied as a potential risk factor for injury. Insufficient neuromuscular control of the core may affect dynamic stability of the lower extremity, increasing knee abduction and strain on the knee, leading to increased injury. 11, 61, 90, 168 Zazulak et al. 167 prospectively studied 277 collegiate athletes (140 female and 137 male) over a 3-year period. They found that trunk displacement was greater in athletes with knee, ligament, and ACL injuries than in uninjured athletes. A logistic regression model, consisting of trunk displacements, proprioception, and history of low back pain, was developed and predicted knee ligament injury with 91% sensitivity and 68% specificity. The model predicted knee, ligament, and ACL injury risk in female athletes with 84%, 89%, and 91% accuracy; however only low back pain was a significant predictor in male athletes. The findings suggest factors related to core stability in female, but not male, athletes are related to ACL injury risk.

Fatigue has been proposed as a potential risk factor for ACL injury. Several studies have demonstrated that knee injuries are more likely to occur in the later portions of competitive games when compared to earlier portions. 41, 53 This suggests that fatigue and poor fitness may contribute to ACL injury by altering neuromuscular control and lower extremity mechanics during landing, cutting, deceleration, and pivoting. Wojtys et al. 160 studied anterior tibial translation in healthy knees and the effect of fatigue on neuromuscular control. They found that the neuromuscular response to anterior tibial translation was altered by fatigue. Kemozek et al. 77 found that when fatigued both male
and female athletes land and pivot with decreased knee flexion and increased dynamic valgus. McClean et al. 96 found similar results among collegiate female athletes where fatigue increased hip internal rotation, knee abduction, and knee extension, three major components of dynamic valgus. They also found a crossover effect during single-leg landings, where fatigue in one leg resulted in sub-optimal neuromuscular control in the contralateral leg. Although findings suggest fatigue may contribute to decreased neuromuscular control when attempting risky athletic maneuvers, no direct association with ACL ruptures has been reported. This area of research may provide insight into common mechanisms of ACL injury in female athletes.60 The neuromuscular factors that result in elevated stress on the ACL via dynamic valgus positioning are becoming well established and may be the most modifiable of all the risk factors of ACL injury. Markolf et al. 91 concluded that athletes can reduce their injury risk by adopting safer movement patterns during landing and pivoting or unexpected perturbations during sports movement. Hewett et al. 63 found that female athletes could land and pivot with less dynamic valgus and more knee flexion following the introduction of a plyometric training program. Many neuromuscular training programs have been developed since and continue to evolve in reaction to neuromuscular and biomechanical research. Current programs aim to change landing, cutting, and pivoting mechanics by improving hamstring strength, proprioception, and muscle endurance. These programs have demonstrated successful reduction of ACL injury incidence in female athletes.57, 63, 104

Based on neuromuscular studies it is clear that landing, cutting, and pivoting with a dynamic valgus position increase the risk of ACL injury. It is also apparent from the
literature that poor hamstring strength and activation, poor proprioception, and poor muscle endurance contributes to lower extremity dynamic valgus. The results of training programs designed to address these factors are positive and encouraging and warrant further study.

2.3 ACL Reconstruction Outcomes

Surgical options for ACLR include various autograft and allograft tissues. Autografts primarily include bone-patellar tendon-bone (BTB) and combined semitendinosus and gracilis hamstring tendons (HS [ST+Gr]), with fewer surgeons and patients selecting the quadriceps tendon. Allografts include the same tendons, usually from cadaveric donors, with the addition of Achilles and tibialis tendons.

Success of ACLR can be judged in the short-term, by the restoration of functional stability to the knee, and in the long-term, by a reduction of secondary meniscal and articular cartilage injury as well as reducing the risk of developing degenerative joint disease, mainly osteoarthritis. Subsequently, ACLR failure may also be considered within the context of objective laxity, patient perception of instability, stiffness and pain, extensor mechanism dysfunction, and infection. Due to the lengthy development of osteoarthritis, short- and mid-term prospective studies may not capture it as an outcome. Functional stability can be assessed in the short-term via objective and subjective outcome measurements. Objective measures include the pivot-shift test, which examines rotational stability of the knee; the hop test, which tests functional stability; and
the Lachman test and KT-1000/2000 arthrometer, which measure laxity. Subjective measures include; the Lysholm, International Knee Committee (IKDC), and MARX activity scores, which are patient-based, validated subjective assessments of knee function. Graft failure can be determined by MRI or surgical confirmation, a positive pivot shift test, a positive Lachman test, or a KT-1000/2000 measurement greater than 5mm.

Although risk factors for poor outcomes have been suggested, the true incidence of failed ACL reconstruction is difficult to calculate and is likely underreported. Despite the lack of an accurate estimate of ACLR graft failure incidence, the frequency of failure will almost certainly increase due in part to the increased frequency of primary ACLR and the high level of activity expected in an aging population.

The results of ALCR are favorable, with 75%-97% of ACLR patients experiencing positive results with respect to knee function and stability, reduced pain, and a return to normal levels of activity. Despite this, there remain patients that experience negative outcomes, such as knee pain and stiffness, restricted motion, instability, the development of osteoarthritis, and graft failure. Graft failure requires additional surgery to revise the primary ACLR and will be referred to in the reminder of this study as revision ACLR (RACLR).

Many studies have focused on possible factors that may contribute to poor outcomes; however, few have focused on graft failure as an outcome. Many prospective outcome studies exclude patients that experience a graft failure in an attempt to more accurately assess functional and quality of life outcomes.
The risk of subsequent ACL injury, following ACLR, has been found to be substantially higher than the risk of native ACL injury.\textsuperscript{117, 128, 135, 162} This is especially true in an active, young population.\textsuperscript{85, 135, 162} Shelbourne et al.\textsuperscript{135} reported that 17% of patients under the age of 18 sustained a second ACL injury, while 4% of those over the age of 25 sustained a second injury. The incidence of graft failure following ACLR has been reported to be between 3% and 27%.\textsuperscript{70, 71, 88, 104, 117, 164} The Multicenter Orthopaedic Outcomes Network (MOON) group\textsuperscript{162} reported that 3% of the patients experienced graft failure within the first 2 years following ACLR. At 5-year follow-up Salmon et al.\textsuperscript{128} found that 12% of their sample sustained a second ACL injury and at 10-year follow-up of the same cohort Pinczewski et al.\textsuperscript{117} reported 27% had suffered a second ACL injury. However, in a systematic review of ACL reconstructions with autografts, Spindler et al.\textsuperscript{143} estimated the incidence to be 3.6% (95% CI 2.3%-5.3%).

2.4 Sex and ACLR Outcomes

Although sex has been confirmed as a strong risk factor for native ACL injuries, a small number of studies have explored the effect of sex on ACLR outcomes. Barber-Westin et al.\textsuperscript{7} compared results and complications of ACLR experienced by men and women. Patients were matched for age, time interval from injury to surgery, preoperative activity level, condition of the articular cartilage, number of prior operative procedures on the knee, and duration of follow-up. No sex difference was found with respect to risk of graft failure, reoperation, and motion problems. Ferrarri et al.\textsuperscript{32} conducted a more
rigorous evaluation of sex and ACLR outcomes. One hundred thirty-seven men and sixty-three women were prospectively followed for an average of 59.5 months and 51.9 months, respectively. No differences were observed on Lachman, pivot shift, functional testing, mean Tegner and Lysholm scores, donor-site pain, patellofemoral pain, or problems with stair climbing. Male patients had a significantly greater mean KT-1000 maximum manual side-to-side difference (0.76 v 1.73 mm, p =0.014). However, there was no difference in the proportion of patients with KT-1000 measures greater than 5mm, defined by the authors as graft failure, with 5 men (4%) and 2 women (3%). It should be noted that at baseline significant differences existed between men and women. Specifically, men were older at the time of ALCR (p=0.018), had a longer time from clinic visit to surgery (p<0.01), and were followed for a longer period of time (p=0.046). These differences could contribute to capturing more ACL failures and thus bias the results towards the null. The effect of sex on ALCR outcomes, especially graft failure, remains unclear and future prospective studies designed to specifically address sex differences is warranted.

2.5 Graft Type and ACLR Outcomes

Many studies have prospectively investigated ACLR outcomes with a specific interest in autograft and allograft comparisons, with most lacking proper randomization, reporting on fewer than 100 patients, and follow-up less than 3 years. 29, 78, 116, 118, 136, 150 Foster et al. 37 conducted a meta-analysis of 31 manuscripts that evaluated outcomes of autograft
and allograft reconstructions. The authors found no difference between the graft types for pivot-shift results (p > 0.1), Lysholm scores (p > 0.1), the proportion of patients with KT-1000 measurements greater than 3mm (p > 0.1) or 5mm (p > 0.5), and graft failures (p > 0.1). Mean laxity was found to be greater in the autograft group (p < 0.02) while the proportion of patients with IKDC A scores (normal knee) was greater in the allograft group (P < 0.02). Krych et al. 79 conducted a meta-analysis of six prospective studies comparing PT autografts and allografts. They found that allograft patients were five times more likely to suffer a graft rupture than autograft patients (OR=5.3, p=0.01). However, when irradiated and chemically processed grafts were removed from the analysis (sterilization techniques no longer used), no significant differences were found between PT and HT groups with respect to graft rupture, Lachman exam, pivot-shift exam, rate of reoperation, normal/near normal IKDC scores, return to sport, or graft rupture.

2.6 Graft Source and ACLR Outcomes

Several systematic reviews and meta-analyses have been conducted to analyze studies investigating the two most popular graft choices, PT and HT. 16, 47, 55, 143 Biau et al. 16 conducted a meta-analysis of fourteen randomized, controlled trials comparing PT and HT grafts with the reported outcome measures: the final overall IKDC score and return to pre-injury level of activity. The authors found no difference between the PT group and the HT group with respect to the final overall IKDC score or in the number of
patients returning to full activity. Spindler et al.\textsuperscript{143} conducted a systematic review of 9 randomized controlled trials comparing PT and HT autografts. The authors found similar results between the PT and HT groups with respect to anterior–posterior laxity, isokinetic quadriceps and hamstring strength, anterior knee pain, and clinical outcome or rating scores. However, four trials found a greater degree of pain when kneeling in the PT group compared to the HT group. Goldblatt et al.\textsuperscript{47} meta-analyzed 11 manuscripts comparing PT and HT grafts. They concluded incidence of instability was not significantly different between the PT and HT grafts. However, patients in the PT group were more likely to have a normal Lachman, normal pivot-shift, KT-1000 <3 mm, and fewer results with significant flexion loss. In contrast, HT grafts were less likely to experience kneeling pain, and extension loss. Biau et al.\textsuperscript{15} conducted another meta-analysis of individual patient data with knee instability, defined as a positive pivot-shift test result, as the primary outcome, and knee laxity, defined as a positive Lachman test, as the secondary outcome data. Six randomized control trials (RCTs) investigating PT and HT autographs were included in the analysis. The authors concluded the ACLR with patellar tendon autograft was significantly associated with a decreased risk of a positive pivot-shift test result (adjusted OR= 0.46; 95% CI 0.24-0.86; p = 0.016). The risk of having a positive Lachman test result was not significantly different between the 2 groups. It appears that current available data suggests that graft source has a minimal effect on ACLR outcomes.

The foci of the reviews mentioned above are functional outcomes with little or no attention paid to graft failure, which is an important and often overlooked outcome.
Reinhardt et al.\textsuperscript{123} conducted a thorough systematic literature review of ACLR studies comparing PT and HT grafts, with a minimum 2-yr follow-up. Initial inclusion criteria included prospective RCTs, meta-analyses of RCTs, studies comparing PT and HT, and studies investigating allografts and/or autografts. No restriction was placed on publication date. Twenty-eight studies published during the period 1991-2009 met the initial inclusion criteria. In an attempt to improve the validity of their conclusions the authors further restricted inclusion to RCTs with proper randomization, 80\% follow-up at a minimum 2-yr follow-up, and comparing PT with either 2- or 4-strand HT grafts. Of the 28 previously identified studies, only 6 met the additional inclusion criteria and reported on functional clinical outcomes, ACLR graft failure rates, and objective parameters following ACLR.\textsuperscript{2, 14, 31, 87, 145, 154} The authors found no difference between PT and HT groups for knee range of motion, patellofemoral pain, or activity level. Higher absolute values of laxity were found in the HT groups compared to the PT groups. The overall ACLR graft failure rate was found to be 11/153 reconstructions in the PT group (7.2\%) compared to 23/165 reconstructions in the HT group (15.8\%), representing a significant difference (p=0.02).

2.7 Femoral and Tibial Tunnel Position and ACLR Outcomes

Recent studies have suggested that, at the time of revision reconstruction, technical error is a contributing factor in 22\% to 79\% of failures.\textsuperscript{9, 26, 27, 33, 38, 42, 50, 109, 110, 113, 129, 147, 155} The most commonly cited technical error is incorrect tunnel position.
Improper placement of the femoral and/or tibial tunnel resulting in a departure from the native ACL anatomical footprint increases graft stress and can lead to excessive laxity. Femoral tunnel placement that is anterior of the native ACL footprint increases graft tension in flexion, resulting in loss of flexion or graft stretching leading to graft laxity. Posterior femoral tunnel placement produces graft tension in extension and laxity in flexion. A vertically placed femoral tunnel will not provide rotational stability.

Anatomically incorrect tibial tunnel placement also contributes to knee stability. A tibial tunnel placement that is too far anterior will lead to impingement against the intercondylar notch, reducing extension. A tunnel placed too far posterior may result in impingement against the posterior cruciate ligament resulting in decreased flexion and diminished control of anterior translation of the tibia. Medial or lateral tunnel placement can result in intercondylar notch graft impingement and possible injury to the tibial plateau cartilage. As a result of inaccurate surgical technique, excessive graft forces and strain may lead to inadequate incorporation and result in early failure.

2.8 Time-to-failure Research

An increasing number of studies have focused on ACLR outcomes, the vast majority report subjective data collected from validated questionnaires, and objective data in the form of functional testing and radiographic results. Several studies have reported results with graft failure as an outcome measure, and fewer have reported statistics on the time to failure. None of these studies were designed
with time-to-failure as the dependent variable of interest and merely report mean and median time-to-failure. To date, no study has investigated the time from PACLR to RACLR or time from PACLR to graft failure as the dependent outcome of interest. The lack of research in this area may be due to the rarity of the event and the difficulty in obtaining data on a sufficient number of subjects. At 6 years of follow-up of patients with unilateral ACLR enrolled in the Multicenter Orthopedic Outcomes Network (MOON) ACLR study, the largest prospective ACLR outcomes study in the US, 21 of 378 (5.6%) patients experienced graft failure. The low failure rate in this large multicenter prospective study highlights the difficulty in acquiring a sufficient sample of graft failures. To address this, MARS patient demographic and primary ACLR surgical data will be utilized to analyze and identify factors associated with early RA CLR among the nearly 1,000 cases of graft failures. Understanding the risk of graft failure in a temporal framework has important clinical ramifications. For instance, it would be valuable to know that the mean time to graft failure for females is different from that of males or that the risk of graft failure 6-12 months post-ACL R is different than 13-24 months post-ACL R. The proposed research will utilize multivariable linear and logistic regression analysis as appropriate methods for investigating these potential differences.
Chapter 3: General Methodology

Due to the rarity of ACLR graft failure and subsequent revision surgery, as well as the paucity of revision surgeries performed by any single surgeon, the Multicenter Anterior Cruciate Ligament Revision Study (MARS) was created as a multicenter group of surgeons involved in a prospective longitudinal cohort analysis of RACL surgery. This group is comprised of academic and private practice physicians and has been supported and endorsed by the American Orthopedic Society for Sports Medicine (AOSSM). For a complete list of participating centers see Appendix A.

MARS has focused on the predictors for RACL outcomes at two-year follow-up. The study has three specific aims: (1) to identify independent predictors of patient-reported quality of life, which will be accomplished by the use of a general (SF-36) and knee-specific (Knee Injury and Osteoarthritis Outcome Score - KOOS) validated outcome instrument; (2) to identify independent predictors of sports function using validated outcome instruments such as the Marx activity level, International Knee Documentation Committee Subjective form (IKDC), and the KOOS sports and recreation subscale; and (3) to identify those independent and modifiable predictors measured at the time of the revision ACL reconstruction associated with symptoms of early osteoarthritis at 2 years post-surgery. Symptoms are quantified using the Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC), a validated survey instrument...
that assesses the pain, joint stiffness, physical, social & emotional function of a person with osteoarthritis.

3.1 Study population

Study inclusion criteria were: All patients, aged 12-65, with a prior ACLR presenting to a participating MARS surgeon, identified with a failed ACLR and scheduled for RACL. Failure of the primary ACLR was defined by either MRI, knee laxity (KT > 5mm), a positive pivot shift or Lachman's, functional instability, and/or by arthroscopic confirmation. Patients seeking a RACL with either partial (Grade I or II) and/or complete (Grade III) simultaneous ligamentous injuries to the collateral ligaments (MCL or LCL) and/or the posterior cruciate ligament (PCL) were also included. Patients with ACLR failure treated non-operatively are also eligible for inclusion in the study. The following graft types used in the primary ACLR were accepted: any autograft, fresh-frozen allografts from a single donor source (Musculoskeletal Transplant Foundation (MTF); Edison, NJ) consisting of either bone-patellar tendon-bone, tibialis anterior/posterior, or Achilles tendon. Patients were excluded if they presented with prior infection, arthrofibrosis, regional pain syndrome, their allograft source was not obtained from MTF, or they were unwilling or unable to complete their repeat questionnaire two years after their initial surgery.
3.2 Data Collection

The current study utilized data collected from all MARS patients during the period May 1, 2006 to July 31, 2010. Data collected from patient questionnaires (Appendix B) at the time of the first clinic visit and from surgeon questionnaires (Appendix C) at the time of revision surgery were analyzed. Roughly 75% of all patients presented with graft failure at participating MARS facilities agreed to enroll in the study. Data collected from the two questionnaires are baseline data for the prospective study; it can also provide endpoint data for a time-to-event. Entry into the sample was therefore a result of a terminating event (ACLR failure) and information regarding the initiating event (primary ACLR surgery) is obtained retrospectively. Surgical information involving previous ACL surgeries included the date of primary surgery and surgical techniques used such as graft type, graft source, and medial and lateral meniscus damage and repair. Time from primary surgery to revision surgery can thus be constructed.

Due to the design and goals of the MARS the date of initial injury that resulted in ACLR failure is not collected. The second proposed study utilized the date of the first revision surgery as a proxy for the date of initial injury, with the assumption that most physically active patients generally opt to have revision surgery shortly after their first ACL injury. In order to obtain a more accurate time point for graft failure, the third proposed study involved patient and surgical data from a subsample collected from the top three contributing institutions (OSU, Washington University, and Vanderbilt University). Surgeons’ notes will be reviewed in order to identify the date of injury
resulting in a confirmed failure. It is assumed that the reported date of injury is a very close approximation of the date of failure. All data, including the subsample, will be compiled and distributed by Vanderbilt University Medical Center.

3.3 Analysis

The primary goal of the first manuscript was to provide an updated description of the MARS population. This population was previously described following three years of enrollment and included 460 participants. The current study included 920 patients after 4 years of enrollment. Descriptive statistics included mean, median, and standard deviation for all continuous variables and proportions percentage for all categorical variables.

The primary focus of the second manuscript was the time from primary ACLR to first RACL and from primary ACLR to injury resulting in graft failure, respectively. Binary logistic regression was performed to investigate the effects of covariates on a dichotomized time-to-revision.

Initial univariate analyses were performed on demographic and surgical variables deemed important with regards to time-to-revision and time-to-injury. Patient demographic variables included age, sex, race, and activity level. Primary ACLR surgical variables included graft type, graft source, surgical technique (1-incision vs. 2-incision), femoral tunnel position and size, tibial tunnel position and size, and concomitant medial and lateral meniscal surgery. Variables were added into and removed from a multivariable model based on level of statistical significance and
confounding influence using purposeful forward selection methods described by Hosmer and Lemeshow. All variables found significant from univariate analyses were included, as a block, into a multivariable model. The criterion for initial entry into the multivariable model was set at Wald $\chi^2$ p-value < 0.25, a value recommended by Hosmer and Lemeshow. The use of 0.25 as a screening criterion is based on the work of Bendel and Afifi\textsuperscript{10} on linear regression and Mickey and Greenland\textsuperscript{98} on logistic regression. The authors showed that the use of the traditional level of 0.05 often fails to identify variables known to be important. Hosmer and Lemeshow\textsuperscript{64} point out that any univariable approach ignores the possibility that a group of variables, that are individually weakly associated with the outcome, can become important predictors when taken together and that a significance level should be large enough to allow for these variables to become candidates for inclusion into the multivariable model.

Removal from the multivariable model was based on two criteria; (1) an examination of the Wald $\chi^2$ statistic for each variable (p-value > 0.05) and (2) a comparison of the estimated coefficient with the coefficient from the univariable model (greater than a 20% change). All variables that did not contribute to the model based on these criteria were eliminated and a reduced model was fit. All model comparisons were made using the Likelihood Ratio (LR) test with a P-value < 0.05 indicating significant model improvement with regards to parsimony. The formula for the LR test using log likelihood (LL) is: $[-2 \times \text{LL of larger model}] - [-2 \times \text{LL of smaller model}] \sim \chi^2$ with degrees of freedom equal to the difference in the number of variables between the two models. The above process of deletion, refitting, and verification continued until all
important variables were included and those excluded were clinically and/or statistically unimportant. Variables not initially selected for inclusion in the multivariable model were added back into the model, one at a time, in order to identify any variable that, by itself, was not significantly related to the outcome but may make an important contribution in the presence of other variables.

Linearity of the logit for continuous variables was assessed using fractional polynomials and quartile design plots. Additionally, each justifiable interaction term (effect modifier) was tested for statistical significance using the Wald $\chi^2$ p-value < 0.01. This strict inclusion criterion reduces the needless inflation of standard errors and complexity of interpretation of the model. Confounding was assessed as a variable that changed the coefficient of a variable already in the model by $\geq 15-20\%$. Any significant interaction terms (effect modifiers) or appreciable confounders remained in the final model. Fit of the final model was assessed using the Hosmer-Lemeshow goodness of fit test. Results were expressed as a ratio of odds (estimating relative risks) between varying levels of independent variables, while controlling for the other variables in the model.

Once the model was complete, diagnostics were performed in order to identify covariate patterns that may have had undue influence. Model diagnostics consisted of visual assessment of various plots including $\Delta \chi^2$ versus estimated logistic probability, $\Delta$Deviance versus logistic probability, and Pregibon’s $\Delta\beta$ versus logistic probability. Covariate patterns found to have the most extreme effect on the model were assessed for
clinical and biologic plausibility. Despite their effect, patterns deemed plausible were retained in the model.

The goal of the third manuscript was to determine the effect of activity level and ACLR graft type on the relationship between sex and time-to-graft failure. Descriptive statistics were used to provide overall study population characteristics by sex. Differences between females and males were assessed using Fisher’s Exact Test for categorical variables and independent 2-sample t-tests for continuous variables. Survival functions of male and female patients were assessed using Kaplan-Meier (K-M) survival plots. It was established *a priori*, that the activity level to which the patient returned following ACLR and graft type could potentially modify the sex-TTF association; therefore associations were stratified on Marx activity level and graft type separately. All survival function comparisons were assessed using the Tarone-Ware test for equality. Tarone-Ware was preferred over the long-rank test as it assigns more weight to early differences between observed and expected number of failures.

All analyses were conducted using SPSS version 19 (SPSS for Windows, Rel. 19.0.0. 2010. Chicago: SPSS Inc.) and STATA IC version 9.2 (Intercooled Stata for Windows, Rel. 19.2. 2006. College Station: StataCorp LP). All p-values are 2-sided.
Chapter 4: Descriptive Epidemiology of the Multicenter ACL Revision Study (MARS)

Cohort: An update

4.1 Introduction

Anterior cruciate ligament (ACL) rupture is a serious event linked to detrimental sequelae such as short-term functional deficits and long-term morbidity involving osteoarthritis and degenerative, progressive disability.\(^ {84, 103, 105, 117, 151}\) In most cases, highly active patients whom desire to return to pre-injury activity levels require ACL reconstruction surgery (ACLR) with 75%-97% experiencing positive results with respect to knee function and stability, reduced pain, and a return to normal levels of activity.\(^ {5, 6, 16, 17, 40, 143}\) Despite this, there remain patients who experience negative outcomes such as knee pain and stiffness, restricted motion, instability, graft failure, and osteoarthritis.\(^ {84, 103, 104, 117, 151}\) No strict definition of graft failure exists, although common definitions in previous research include: knee laxity (with a KT1000/2000 measurement > 5mm), a positive pivot shift test, positive Lachman's test, functional instability, MRI and/or arthroscopic confirmation. The incidence of graft failure following ACLR has been reported to be between 3% and 27%.\(^ {117, 70, 71, 88, 104, 164}\) However, in a systematic review of ACL reconstructions with autografts, Spindler et al.\(^ {143}\) estimated the incidence to be 3.6% (95% CI 2.3%-5.3%).
Graft failure generally results in revision ACLR (RACL), a complicated and delicate surgical procedure whose outcomes have been shown to be inferior to primary ACLR. Spindler cites the less favorable results of RACL as one of the compelling reasons for the creation of the Multicenter ACL Revision Study (MARS). MARS was created as a multicenter, multi-surgeon group for the purpose of prospective longitudinal cohort analysis of RACL outcomes and currently represents the largest collection of confirmed ACLR graft failures in the US. This population has previously been described; however, this report presented data collected from May 1, 2006 through April 1, 2009 and included 460 patients. The present study will act as an update to that report and will include data collected through July 31, 2010, involving 920 patients.

4.2 Methods

4.2.1 Study Design

The MARS study has been described in detail previously. Briefly, MARS is a longitudinal, cohort design involving multiple sites and multiple surgeons with a specific focus on RACL prognosis and predictors of prognosis. It was designed to recruit and retain enough subjects with longitudinal follow-up to allow multivariable analyses of factors affecting outcome. All American Orthopaedic Society for Sports Medicine (AOSSM) members were informed of MARS and given the opportunity to participate. Participating surgeons were required to attend 1 of 4 surgeon training sessions held in
2006-2008 where the manual of operating and data collection procedures were reviewed. Following the training sessions, surgeons were required to obtain institutional review board approval, complete a trial surgeon form, and sign a surgeon’s agreement to follow the manual of operating procedures before patient enrollment. Institutional Review Board approval is required for each participating site. Study coordinators were made available for guidance during the study. MARS patient enrollment began May 1, 2006. The current study includes enrollment through July 31, 2010.

4.2.2 Study Population

Inclusion and exclusion criteria for MARS have previously been reported\textsuperscript{92} and are given in Table 4.1. Failure of the primary ACLR is confirmed by either: MRI, knee laxity (KT1000/2000 > 5mm), a positive pivot shift or Lachman test, functional instability, and/or by arthroscopic confirmation. Patients scheduled for RACLRR with either partial (Grade I or II) and/or complete (Grade III) simultaneous ligamentous injuries to the collateral ligaments and/or the posterior cruciate ligament were included. Patients with ACLR failure treated non-operatively are also eligible for inclusion in the study.
<table>
<thead>
<tr>
<th>Inclusion Criteria</th>
<th>Exclusion Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>All patients, aged 12-65, with a prior</td>
<td>Prior intra-articular infection</td>
</tr>
<tr>
<td>ACLR presenting to a participating</td>
<td>Arthrofibrosis</td>
</tr>
<tr>
<td>MARS surgeon, identified with a failed</td>
<td>Regional pain syndrome</td>
</tr>
<tr>
<td>ACLR and scheduled for RACLR</td>
<td>Allograft source not obtained from the</td>
</tr>
<tr>
<td></td>
<td>Musculoskeletal Transplant Foundation (MTF)</td>
</tr>
<tr>
<td></td>
<td>Unwilling or unable to complete repeat</td>
</tr>
<tr>
<td></td>
<td>questionnaire at 2yr follow-up</td>
</tr>
</tbody>
</table>

4.2.3 Treatment

Study participants presented to MARS surgeons with one or more ACL graft failures where graft type and source could vary; as a result the revising surgeon’s graft choice may have been limited by the previous reconstruction technique and may not reflect their first choice. The following graft types used in the RACLR were accepted: (1) any autograft, contralateral autografts included; and (2) non-irradiated, fresh-frozen allografts from a single donor source (Musculoskeletal Transplant Foundation (MTF); Edison, NJ) consisting of bone-patellar tendon-bone, tibialis anterior/posterior, semitendinosis, gracilis, or Achilles tendon. Radiographic requirements for the study include bilateral standing anterior-posterior and full-extension lateral views. Bilateral, 45° bent knee weight bearing (Rosenberg), patellofemoral, and standing alignment views were also recommended.
4.2.4 Data Collection

Data collection methods have been previously detailed. Briefly, data were collected from patients and surgeons via questionnaires. The patient questionnaire was a self-administered 13-page questionnaire containing the validated outcome instruments of the Short Form-36 (SF36, version 2), Western Ontario and McMaster Osteoarthritis Index (WOMAC), Knee injury Osteoarthritis Outcome Score (KOOS), International Knee Documentation Committee subjective form (IKDC), and Marx activity scale. The patient questionnaire was provided following informed consent.

The surgeon questionnaire was completed prior to and shortly after surgery and included sections on the history of knee injury and/or surgery on both knees, the results of the general knee examination done under anesthesia, recording of all previous and new intra-articular injuries and treatments to the meniscus and articular cartilage, as well as surgical technique used for the revision ACL reconstruction. Findings of the general knee examination are classified according to the updated 1999 International Knee Documentation Committee guidelines. Articular cartilage injury is documented by the revising surgeon using the modified Outerbridge classification, and is based on a multi-rater agreement study that indicated moderate agreement (Kappa=0.47). Meniscal injuries are classified by size, location, and partial versus complete tears with treatment categories of none, repair, or extent of resection. These classifications are based on a previous interrater agreement study. Rehabilitation aspects are also reported.
and include postoperative and functional bracing, timing of initiating weightbearing, passive motion, and active motion.

Each participating site submits, via mail, completed data forms to the central data collection site (Vanderbilt University). To avoid potential errors common during manual data entry, patient and surgeon data were scanned with TeleForm software (Cardiff Software, Inc, Vista, California) using optical character recognition. Upon verification, the data were exported to a database. A matched, barcoded identification number is printed on each page of the patient and surgeon questionnaires allowing for de-identification and database merging.

4.2.5 Statistical Design

MARS was designed to recruit and retain enough subjects for longitudinal follow-up to allow multivariable analyses of potential factors affecting outcome, such as graft choice and femoral and tibial tunnel placement. Due to the multivariable analytic approach, sample size estimates were based on estimating the number of variables of interest and allowing a 10:1 patient to variable ratio. Sample size was therefore based on multivariable model complexity. An estimated 900 to 1000 patients was determined to be sufficient in order to assure adequate power with 80% follow-up at 2 years. The current study presents descriptive data of the MARS cohort as of August 1, 2010 and includes 920 patients.
4.3 Results

As of July 31, 2010, 87 surgeons had enrolled 920 patients with confirmed ACL graft failure across 52 sites in 28 states and 2 Canadian provinces; with a near equal distribution of academic (54%) and private practice (46%) sites. Enrollment began March 23, 2006. Previous ACLR was performed by the revising surgeon in 27% of the cases. The median age of the patient cohort was 26 years (interquartile range [25%-75%] 20-35 years; males 27 years [21-35 years], females 24 years [18-34 years]), with 58% male patients (Figure 4.1). Revision ACLR most frequently occurred in the third (20-29 years) and second (10-19 years) decade of life for males and females respectively. High activity level within the 12 months prior to revision, reported as a Marx Activity Score 12-16, was most frequently reported (overall 47.8%; males 52.3%, females 41.5%, Figure 4.2). The cohort predominately reported never having smoked (overall 77.0%; males 75.0%, females 79.6%). Most commonly, males were overweight and females were normal weight. The most common races reported were white (84%) and black or African American (5%) (Table 4.2). Completed educational level ranged from 6th grade to 20 years of education. Nearly every adult completed high school (98%) with 48% completing 16 years or more of education (Table 4.3). Non-contact injury was reported by a majority of the cohort (54%) (Table 4.4).
Figure 4.1 Age at revision surgery
Figure 4.2 Marx activity score within 1 year prior to revision ACL surgery. Marx: 0-3, no or low activity; 4-7, low/moderate activity; 8-11, moderate/high activity; 12-16, high/very high activity
Table 4.2 Distribution of race by sex, MARS population 2006-2010

<table>
<thead>
<tr>
<th>Race</th>
<th>Female No. (%)</th>
<th>Male No. (%)</th>
<th>Total Cohort No. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>White</td>
<td>327 (84.9)</td>
<td>444 (83.0)</td>
<td>771 (83.8)</td>
</tr>
<tr>
<td>Black/African American</td>
<td>18 (4.7)</td>
<td>25 (4.7)</td>
<td>43 (4.7)</td>
</tr>
<tr>
<td>Hispanic</td>
<td>8 (2.1)</td>
<td>16 (3.0)</td>
<td>24 (2.6)</td>
</tr>
<tr>
<td>Asian</td>
<td>5 (1.3)</td>
<td>16 (3.0)</td>
<td>21 (2.3)</td>
</tr>
<tr>
<td>Native Hawaiian/Pacific Islander</td>
<td>2 (0.5)</td>
<td>2 (0.4)</td>
<td>4 (0.4)</td>
</tr>
<tr>
<td>American Indian/Alaskan Native</td>
<td>1 (0.3)</td>
<td>2 (0.4)</td>
<td>3 (0.3)</td>
</tr>
<tr>
<td>Other</td>
<td>5 (1.3)</td>
<td>12 (2.2)</td>
<td>17 (1.8)</td>
</tr>
<tr>
<td>More than one race</td>
<td>13 (3.4)</td>
<td>15 (2.8)</td>
<td>28 (3.0)</td>
</tr>
<tr>
<td>Unknown/not reported</td>
<td>6 (1.6)</td>
<td>3 (0.6)</td>
<td>9 (1.0)</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>385 (100)</strong></td>
<td><strong>535 (100)</strong></td>
<td><strong>920 (100)</strong></td>
</tr>
</tbody>
</table>

Table 4.3 Completed education level by sex

<table>
<thead>
<tr>
<th>Years of school completed&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Female No. (%)</th>
<th>Male No. (%)</th>
<th>Total Cohort No. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 9</td>
<td>9 (2.3)</td>
<td>6 (1.1)</td>
<td>15 (1.6)</td>
</tr>
<tr>
<td>9-11</td>
<td>57 (14.8)</td>
<td>45 (8.4)</td>
<td>102 (11.1)</td>
</tr>
<tr>
<td>12-15</td>
<td>156 (40.5)</td>
<td>257 (48.0)</td>
<td>413 (44.9)</td>
</tr>
<tr>
<td>16-19</td>
<td>134 (34.8)</td>
<td>199 (37.2)</td>
<td>333 (36.2)</td>
</tr>
<tr>
<td>&gt; 20</td>
<td>27 (7.0)</td>
<td>24 (4.5)</td>
<td>51 (5.5)</td>
</tr>
<tr>
<td>Unknown/not reported</td>
<td>2 (0.5)</td>
<td>4 (0.7)</td>
<td>6 (0.7)</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>385 (100)</strong></td>
<td><strong>535 (100)</strong></td>
<td><strong>920 (100)</strong></td>
</tr>
</tbody>
</table>

<sup>a</sup>For example; 12=high school graduate, 16=college graduate
For 88% of the patients this was the first revision, the second for 10%, the third for 2%, and the fourth or more for less than 1% (Table 4.5). The median time from last reconstruction (n=738) was 30 months (males 30.5 months, females 29 months) with less than 1 year in 21% of patients, between 1 and 2 years for 22%, and greater than 2 years for 57%. Thirteen percent had a time from last reconstruction of 10 years or more (Figure 4.3). Among first revision patients (n=653) the median time from last reconstruction was 30 months (males 35 months, females 29 months) with less than 1 year in 22% of patients, between 1 and 2 years for 21%, and greater than 2 years for 57%. Fourteen percent of first revisions occurred 10 years or more after primary ACLR. Among patients with 1 or more previous revisions (n=85), the median time was 27 months (males 27 months, females 30 months) with less than 1 year in 15% of patients, between 1 and 2 years in 30%, and greater than 2 years in 55%. Among patients with 1 or more previous revisions, 11% occurred 10 years or more after previous reconstruction.

Table 4.4 Mechanism of injury by sex

<table>
<thead>
<tr>
<th>Mechanism</th>
<th>Females No. (%)</th>
<th>Male No. (%)</th>
<th>Total Cohort No. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Traumatic</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>non-contact onset</td>
<td>205 (53.2)</td>
<td>295 (55.1)</td>
<td>500 (54.3)</td>
</tr>
<tr>
<td>contact onset</td>
<td>35 (9.1)</td>
<td>65 (12.2)</td>
<td>100 (10.9)</td>
</tr>
<tr>
<td><strong>Non-traumatic</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>gradual onset</td>
<td>116 (30.2)</td>
<td>143 (26.7)</td>
<td>259 (28.2)</td>
</tr>
<tr>
<td>sudden onset</td>
<td>29 (7.5)</td>
<td>31 (5.8)</td>
<td>60 (6.5)</td>
</tr>
<tr>
<td><strong>Missing/Unknown</strong></td>
<td>0 (0.0)</td>
<td>1 (0.2)</td>
<td>1 (0.1)</td>
</tr>
<tr>
<td>Total</td>
<td>385 (100)</td>
<td>535 (100)</td>
<td>920 (100.0)</td>
</tr>
</tbody>
</table>
Intraoperative visualization of the graft found: 31% absent; 44% present, with the majority torn; 25% present, but elongated; and less than 1% not reported. Mode of failure, as deemed by the revising surgeon, was traumatic for 33% (n=303); technical (n=211), 23%; biologic (n=75), 8%; combination, 35% (surgeons marked all that applied); other, less than %1; infection, less than 1%, and no response, less than 1% (Figure 4.4). Biologic failure was previously defined in this cohort as “lack of incorporation of the graft as evidenced by early failure without a significant traumatic episode or obvious significant technical problems with the previous reconstruction.”

Table 4.5  Number of revisions by sex

<table>
<thead>
<tr>
<th>Revision Number</th>
<th>Females No. (%)</th>
<th>Male No. (%)</th>
<th>Total Cohort No. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>345 (89.6)</td>
<td>460 (86.0)</td>
<td>805 (87.5)</td>
</tr>
<tr>
<td>2</td>
<td>31 (8.1)</td>
<td>64 (12.0)</td>
<td>95 (10.3)</td>
</tr>
<tr>
<td>3</td>
<td>7 (1.8)</td>
<td>8 (1.5)</td>
<td>15 (1.6)</td>
</tr>
<tr>
<td>4+</td>
<td>1 (0.25)</td>
<td>3 (0.5)</td>
<td>4 (0.4)</td>
</tr>
<tr>
<td>Missing/unreported</td>
<td>1 (0.25)</td>
<td>0 (0.0)</td>
<td>1 (0.1)</td>
</tr>
<tr>
<td>Total</td>
<td>385 (100)</td>
<td>535 (100)</td>
<td>920 (100.0)</td>
</tr>
</tbody>
</table>
Figure 4.3 Time from Last Reconstruction (Years). n=738, Missing/Unknown n=182. Median time from last reconstruction, 30 months (males 30.5 years, females 29 years).
Figure 4.4 Mode of graft failure

Technical failure was determined at the time of revision by the surgeon. Patient history, physical examination, radiographs, and arthroscopic evaluation were used to determine technical error. Surgeons were allowed to indicate more than one type of technical error. The most common technical error reported was femoral tunnel
malposition (78%), followed by tibial tunnel malposition (32%) (Table 4.6). Prior femoral tunnel surgical technique was single tunnel 97%, double tunnel 3%, and unreported 2%. Among patients with available data on previous femoral tunnel position and size (n=900), 34% were deemed ideal and 66% compromised (Table 4.6). The single most common aspect of a compromised femoral tunnel was a position deemed too vertical (33%) (Table 4.7). Among patients with available data on prior tibial tunnel position and size (n=909), 64% were deemed ideal and 35% were compromised (Table 4.8). The most common aspect of a compromised tibial tunnel was a position deemed too anterior or too posterior (22%).

Table 4.6  Technical cause of failure\textsuperscript{a,b}

<table>
<thead>
<tr>
<th>Cause</th>
<th>No.</th>
<th>Technical (%)</th>
<th>Cohort (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Femoral tunnel malposition</td>
<td>461</td>
<td>(77.7)</td>
<td>(50.4)</td>
</tr>
<tr>
<td>Tibial tunnel malposition</td>
<td>187</td>
<td>(31.5)</td>
<td>(20.3)</td>
</tr>
<tr>
<td>Allograft source</td>
<td>50</td>
<td>(8.4)</td>
<td>(5.4)</td>
</tr>
<tr>
<td>Autograft source</td>
<td>10</td>
<td>(1.7)</td>
<td>(1.1)</td>
</tr>
<tr>
<td>Malalignment</td>
<td>21</td>
<td>(3.5)</td>
<td>(2.2)</td>
</tr>
<tr>
<td>Femoral fixation</td>
<td>21</td>
<td>(3.5)</td>
<td>(2.2)</td>
</tr>
<tr>
<td>Tibial fixation</td>
<td>8</td>
<td>(1.3)</td>
<td>(&lt;1.0)</td>
</tr>
<tr>
<td>Posteromedial laxity</td>
<td>11</td>
<td>(1.9)</td>
<td>(1.2)</td>
</tr>
<tr>
<td>Posterolateral laxity</td>
<td>4</td>
<td>(&lt;1.0)</td>
<td>(&lt;1.0)</td>
</tr>
<tr>
<td>Other</td>
<td>17</td>
<td>(2.9)</td>
<td>(1.8)</td>
</tr>
</tbody>
</table>

\textsuperscript{a} Note the denominator is >100% due to the multiple choice option of this question (surgeons were instructed to “check all that apply”).
\textsuperscript{b} Number of patients where cause of failure was deemed non-technical n=327 (35.5% of 920)
Table 4.7 Femoral tunnel position and size from previous ACL reconstruction

<table>
<thead>
<tr>
<th></th>
<th>Female (No. (%)</th>
<th>Male (No. %)</th>
<th>Total Cohort (No. (%))</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Ideal</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Both position &amp; size</td>
<td>136 (35.3)</td>
<td>151 (28.2)</td>
<td>287 (31.2)</td>
</tr>
<tr>
<td>Both position &amp; size, but enlarged tunnel</td>
<td>10 (2.6)</td>
<td>12 (2.3)</td>
<td>22 (2.4)</td>
</tr>
<tr>
<td><strong>Compromised</strong></td>
<td>235 (61.0)</td>
<td>356 (66.5)</td>
<td>591 (64.2)</td>
</tr>
<tr>
<td>Position</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Too anterior</td>
<td>42 (10.9)</td>
<td>80 (15.0)</td>
<td>122 (13.3)</td>
</tr>
<tr>
<td>Too vertical</td>
<td>128 (33.2)</td>
<td>172 (32.1)</td>
<td>300 (32.6)</td>
</tr>
<tr>
<td>Too anterior &amp; too vertical</td>
<td>42 (10.9)</td>
<td>64 (11.9)</td>
<td>106 (11.5)</td>
</tr>
<tr>
<td><strong>Size (enlarged aperture)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Both position &amp; size</td>
<td>17 (4.4)</td>
<td>29 (5.4)</td>
<td>46 (5.0)</td>
</tr>
<tr>
<td><strong>Missing/not reported</strong></td>
<td>4 (1.0)</td>
<td>16 (3.0)</td>
<td>20 (2.2)</td>
</tr>
<tr>
<td>Total</td>
<td>385 (100)</td>
<td>535 (100)</td>
<td>920 (100)</td>
</tr>
</tbody>
</table>

Table 4.8 Tibial tunnel position and size from previous ACL reconstruction

<table>
<thead>
<tr>
<th></th>
<th>Female (No. (%))</th>
<th>Male (No. (%))</th>
<th>Total Cohort (No. (%))</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Ideal</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Both position &amp; size</td>
<td>222 (57.7)</td>
<td>307 (57.4)</td>
<td>529 (57.5)</td>
</tr>
<tr>
<td>Both position &amp; size, but enlarged tunnel</td>
<td>32 (8.3)</td>
<td>26 (4.8)</td>
<td>58 (6.3)</td>
</tr>
<tr>
<td><strong>Compromised</strong></td>
<td>129 (333.5)</td>
<td>193 (36.1)</td>
<td>322 (35.0)</td>
</tr>
<tr>
<td>Position</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Too anterior or posterior</td>
<td>102 (26.5)</td>
<td>168 (31.4)</td>
<td>270 (29.3)</td>
</tr>
<tr>
<td>Too medial or lateral</td>
<td>69 (17.9)</td>
<td>132 (24.7)</td>
<td>201 (21.8)</td>
</tr>
<tr>
<td>Too medial/lateral &amp; too anterior/posterior</td>
<td>28 (7.3)</td>
<td>29 (5.4)</td>
<td>57 (6.2)</td>
</tr>
<tr>
<td><strong>Size (enlarged aperture)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Both position &amp; size</td>
<td>15 (3.9)</td>
<td>14 (2.6)</td>
<td>29 (3.2)</td>
</tr>
<tr>
<td><strong>Missing/not reported</strong></td>
<td>2 (0.5)</td>
<td>9 (1.7)</td>
<td>11 (1.2)</td>
</tr>
<tr>
<td>Total</td>
<td>385 (100)</td>
<td>535 (100)</td>
<td>920 (100)</td>
</tr>
</tbody>
</table>
Graft type for the prior reconstruction was autograft 68%, allograft 29%, allograft and autograft 2%, combination autograft or allograft with prosthetic < 1%, prosthetic < 1%, and unknown < 1%. Overall, the most common graft was an autograft bone-patellar tendon-bone (42%), followed by autograft hamstring (semitendinosus + gracilis) (22%) and allograft bone-patellar tendon-bone (12%) (Table 4.9). Prior surgical approach was arthroscopic single incision in 81%, arthroscopic rear entry 2-incision in 17%, traditional arthrotomy in 1%, miniarthrotomy in less than 1%, and less than 1% was not recorded.

Previous meniscal surgery was noted in 48% of patients; prior surgery involving solely the medial meniscus 30%, solely the lateral meniscus 10%, and both 8%. Excision accounted for 79% of previous medial meniscus surgeries and 75% of lateral meniscus surgeries (Table 4.10). Baseline patient-based outcome measures were recorded (Table 4.11).
Table 4.9 Graft source of previous ACL reconstruction

<table>
<thead>
<tr>
<th>Source</th>
<th>Autograft No. (%)</th>
<th>Allograft No. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bone-patellar tendon-bone</td>
<td>386 (61.9)</td>
<td>108 (40.9)</td>
</tr>
<tr>
<td>Hamstring (semitendinosus [ST] + gracilis)</td>
<td>200 (32.1)</td>
<td>11 (4.2)</td>
</tr>
<tr>
<td>Hamstring (ST)</td>
<td>23 (3.7)</td>
<td>1 (&lt;1.0)</td>
</tr>
<tr>
<td>Quadriceps tendon bone</td>
<td>3 (&lt;1.0)</td>
<td></td>
</tr>
<tr>
<td>Iliotibial band</td>
<td>1 (&lt;1.0)</td>
<td></td>
</tr>
<tr>
<td>Achilles tendon</td>
<td></td>
<td>32 (12.1)</td>
</tr>
<tr>
<td>Tibialis anterior</td>
<td></td>
<td>46 (17.4)</td>
</tr>
<tr>
<td>Tibialis posterior</td>
<td></td>
<td>8 (3.0)</td>
</tr>
<tr>
<td>Multiple prior sources</td>
<td>6 (1.0)</td>
<td>5 (1.9)</td>
</tr>
<tr>
<td>Other/unknown</td>
<td>5 (&lt;1.0)</td>
<td>52 (19.6)</td>
</tr>
<tr>
<td>Blank/unanswered</td>
<td></td>
<td>1 (&lt;1.0)</td>
</tr>
<tr>
<td>Total</td>
<td>624&lt;sup&gt;a&lt;/sup&gt; (100)</td>
<td>264&lt;sup&gt;b&lt;/sup&gt; (100)</td>
</tr>
</tbody>
</table>

<sup>a</sup> Represents 67.8% of total cohort  
<sup>b</sup> Represents 28.7% of total cohort

Table 4.10 Observation of previous meniscal surgery

<table>
<thead>
<tr>
<th>Previous Surgery</th>
<th>Medial Meniscus&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Lateral Meniscus&lt;sup&gt;b&lt;/sup&gt;</th>
<th>Both&lt;sup&gt;c&lt;/sup&gt;</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Excision</td>
<td>219 (78.8%)</td>
<td>72 (75.0%)</td>
<td>54 (76.1%)</td>
<td>345 (77.5%)</td>
</tr>
<tr>
<td>Repair healed / Stable</td>
<td>20 (7.2%)</td>
<td>13 (13.5%)</td>
<td>4 (5.6%)</td>
<td>37 (8.3%)</td>
</tr>
<tr>
<td>Repair not healed / Unstable</td>
<td>39 (14.0%)</td>
<td>11 (11.5%)</td>
<td>13 (18.3%)</td>
<td>63 (14.2%)</td>
</tr>
<tr>
<td>Total</td>
<td>278 (100%)</td>
<td>96 (100%)</td>
<td>71 (100%)</td>
<td>445* (100%)</td>
</tr>
</tbody>
</table>

<sup>a</sup> 30.2% of the cohort had prior medial meniscus surgery  
<sup>b</sup> 10.4% of the cohort had prior lateral meniscus  
<sup>c</sup> 7.7% of the cohort had prior surgery of both medial and lateral meniscus  
* Total represents 48.4% of the cohort. 475 patients (51.6% of cohort) had no indications of previous meniscal surgery at the time of revision.
Table 4.11 Patient-based baseline outcome measures

<table>
<thead>
<tr>
<th>Outcome Instrument</th>
<th>Scale</th>
<th>F Median (25%,75%)</th>
<th>M Median (25%,75%)</th>
<th>Total Median (25%,75%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Marx activity level</td>
<td>0-16</td>
<td>10 (4,16)</td>
<td>12 (4,16)</td>
<td>11 (4,16)</td>
</tr>
<tr>
<td>IKDC</td>
<td>0-100</td>
<td>51 (37,61)</td>
<td>52 (39,63)</td>
<td>51 (39,62)</td>
</tr>
<tr>
<td>KOOS</td>
<td>0-100</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Symptoms</td>
<td></td>
<td>68 (50,82)</td>
<td>68 (56,82)</td>
<td>68 (54,82)</td>
</tr>
<tr>
<td>Pain</td>
<td></td>
<td>72 (56,84)</td>
<td>75 (61,86)</td>
<td>75 (58,86)</td>
</tr>
<tr>
<td>ADL</td>
<td></td>
<td>85 (68,96)</td>
<td>86 (69,96)</td>
<td>85 (69,96)</td>
</tr>
<tr>
<td>Sports/recreation</td>
<td></td>
<td>40 (20,65)</td>
<td>45 (25,65)</td>
<td>45 (25,65)</td>
</tr>
<tr>
<td>Knee-related QOL</td>
<td></td>
<td>31 (19,50)</td>
<td>31 (19,44)</td>
<td>31 (19,44)</td>
</tr>
<tr>
<td>WOMAC</td>
<td>0-100</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stiffness</td>
<td></td>
<td>75 (50,88)</td>
<td>75 (50,88)</td>
<td>75 (50,88)</td>
</tr>
<tr>
<td>Pain</td>
<td></td>
<td>80 (65,95)</td>
<td>85 (70,95)</td>
<td>85 (65,95)</td>
</tr>
<tr>
<td>ADL</td>
<td></td>
<td>85 (68,96)</td>
<td>86 (69,96)</td>
<td>85 (69,96)</td>
</tr>
</tbody>
</table>

IKDC, International Knee Documentation Committee “subjective” form; KOOS, Knee Osteoarthritis Outcome Score; WOMAC, Western Ontario and McMaster Osteoarthritis Index; ADL, activities of daily living; QOL, quality of life.

4.4 Discussion

MARS is the largest multicenter, multi-surgeon group assembled to investigate revision ACLR outcomes. It has enrolled nearly 1000 patients and represents the largest series of revision patients reported in the literature. The primary purpose of this report was to provide a descriptive analysis of patient demographics and clinical features for the 920 enrolled patients in this prospective cohort, acting as an update to previously published data involving the initial 460 MARS patients. Multivariable predictive analysis of patient outcomes is a primary goal of MARS and the data presented here will
assist in forming the basis of that analysis. The ultimate goal is to identify modifiable predictors of outcomes in order to better counsel surgeons and patients.

Graft failure, much like native ACL rupture, most likely results from multiple factors. The most common modes of failure found in this cohort were determined to be traumatic injury followed by technical error. Several previous studies have indicated that technical aspects were the most common cause of graft failure suggesting that more than half of failures were due to technical factors.\textsuperscript{21, 27, 72, 137} These studies included technical failure as a broad category, not allowing for specific details on the type of technical failure. In the current study the reporting surgeon was provided the option of indicating multiple modes of failure, resulting in combinations of factors which may explain the differences. In the current study a combination of factors was found to be the most common overall cause in this cohort, representing nearly 35% of failures. This is larger than the traumatic (33%) and technical failure group (23%) and may further suggest the complex nature of graft failure. Femoral and tibial tunnel malposition were found to be the most common technical errors in this cohort and are in general agreement with previous studies with identified aspects of technical error.\textsuperscript{42, 144} The present study offers a detailed description of femoral and tibial tunnel position and size, setting it apart from other studies investigating tunnel placement. The current findings indicate the most commonly cited femoral malposition is one that is placed too anterior and the most common tibial malposition is one that is too anterior or posterior.

The time from last reconstruction was less than 1 year in 21% of patients, between 1 and 2 years for 22%, greater than 2 years for 57%. Nearly 14% of the total cohort had a
time from last reconstruction of 10 years or more. Among patients without prior revision, the time from last reconstruction was less than 1 year in 22%, between 1 and 2 years for 21%, greater than 2 years for 57%. Fourteen percent of 1st revisions occurred 10 years or more after primary ACLR. Among patients with 1 or more prior revisions, time from last reconstruction was less than 1 year in 15%, between 1 and 2 years in 30%, and greater than 2 years in 55%. Eleven percent of this sub-group had revision surgery 10 years or more after previous reconstruction. The high percentage of revisions that occurred 10 years or more after the last reconstruction suggests longer follow-up times may be needed in primary ACLR outcome studies. A common belief is that if graft failure occurs it will occur within a short time period (24-36 months) following ACLR, in which time the individual presumably regains full stability and returns to pre-injury activity levels. However, an increase in ACL re-injury rate has been reported with longer follow-up. At a 5-year follow-up, Salmon et al.\textsuperscript{128} reported that 1 in 8.3 (12%) individuals sustained a second ACL injury and at a 10-year follow-up\textsuperscript{117} of the same cohort 27% had sustained a second ACL injury. The high percentage of failures occurring 10 or more years after reconstruction warrants further study with the goal of answering the question: are there differentiating factors among those that have a revision 10 or more years after ACLR and those that have an earlier revision?

Limitations of the current study include the descriptive nature of the study, which require a minimal follow-up of 2 years in order to properly assess the effects of potential predictors on RAclr outcome. Lack of agreement between study surgeons, with regard to intraoperative findings, is another potential limitation. However, this was mitigated
by the required training of all participating surgeons as well as annual meetings outlining expectations and research findings. Despite the wide geographic range, practice settings, and insurance plans (Medicaid included) represented by the 52 study sites in this study, a small number of minority patients are represented. The MARS group has previously stated that MARS participants may represent the racial distribution of revision ACLR currently performed in North America. This may be inaccurate, as the study did not incorporate proper sampling methodology designed to capture a representative sample of North American revision ACL reconstructions. However, this cohort does represent the largest collection of ACL revisions in North America and thus substantially advances our understanding of factors associated with revision ACLR outcomes.
Chapter 5: Factors Associated with Early Revision Anterior Cruciate Ligament Reconstruction Surgery

5.1 Introduction

A number of studies have focused on anterior cruciate ligament reconstruction (ACLR) surgery outcomes, with the vast majority reporting subjective data collected from validated questionnaires and objective data in the form of functional testing and radiographic results. Several studies have reported results with graft failure as an outcome measure, presenting incidence and prevalence data; fewer have reported statistics on time-to-failure or time-to-revision, only presenting mean and/or median times. It is estimated that between 2% and 6% of primary ACL reconstructions will fail, requiring revision ACLR (RACL) surgery. Due to the relative rarity of graft failure the collection of a sufficient number of graft failures leading to revision ACLR (RACL) in a prospective manner can be lengthy and costly. At 2 years of follow-up of patients enrolled in the Multicenter Orthopedic Outcomes Network (MOON) ACLR study, the largest prospective ACLR outcomes study in the US, 19 of 322 (5.9%) patients suffered graft failure. In order to study potential risk factors associated with the timing of graft failure and subsequent revision, a higher number of graft failures must be captured. The Multicenter ACL Revision Study (MARS) was designed to prospectively assess RACL outcomes and has amassed nearly
1000 patients since 2006. The collection of demographic and primary ACLR (PACL) surgical data is feasible and would include the date of PACLR, allowing for the calculation and use of time-to-RACL as the dependent variable. To date no published study has been designed to investigate time-to-revision as a dependent outcome of interest.

The goals of the present study were to (1) discuss the use of baseline data from a prospective cohort study that included patients with confirmed ALCR graft failure (MARS) as outcome data in a cross-sectional study with particular focus on time from PACLR to RACL, and (2) describe demographic and primary ACLR surgical factors associated with early first RACL (< 30 months). Identification of predictors of early revision within a temporal construct can provide important information from which the surgeon, patient, and post-operative therapist can determine a more efficacious course of care. The identification of factors associated with early revision among patients with confirmed graft failure may provide support for their inclusion in future prospective studies.

5.2 Methods

5.2.1 Study Design

The current study is cross-sectional and involves secondary analysis of patient data enrolled in MARS. All patients were confirmed ACLR graft failures and scheduled for their first RACL at MARS member sites at the time of data collection. The
dependent variable was early revision ACLR, defined as less than or equal to 30 months following primary ACLR.

5.2.2 Study population

The current study includes patients enrolled in MARS. Inclusion and exclusion criteria for this study have previously been reported\(^92\) and are summarized in Table 5.1, with the additional restriction of patients with no previous RACLR (1\(^{st}\) revisions). Failure of the primary ACLR is defined by either MRI, knee laxity (KT1000/2000 > 5mm), a positive pivot shift test, a positive Lachman test, functional instability, and/or by arthroscopic confirmation. Patients scheduled for RACLR with either partial (Grade I or II) and/or complete (Grade III) simultaneous ligamentous injuries to the collateral ligaments and/or the posterior cruciate ligament were also included. Patients with ACLR failure treated non-operatively were also eligible for inclusion in MARS; however, none were included in the current study as the focus was on time from PACLR to RACLR and thus all patients had a PACLR.

The current study reports on data collected on MARS patients enrolled from March 23, 2006 to July 31, 2010 and includes 920 patients across 52 sites in 28 states and 2 Canadian provinces, with a nearly equal distribution of academic (54%) and private practice (46%) sites. The primary goal of the analysis was the identification of factors associated with early revision ACLR and is restricted to first revisions. 805 were first revisions, of which 653 had available PACLR to RACLR time, referred to in this report.
as the 1\textsuperscript{st} revision subset. Complete data were available for 453, representing the analytic subset in this report (Figure 5.1).

Table 5.1  Inclusion and exclusion criteria for the multicenter ACL revision study (MARS)

<table>
<thead>
<tr>
<th>Inclusion Criteria</th>
<th>Exclusion Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aged 12-65</td>
<td>Prior intra-articular infection</td>
</tr>
<tr>
<td>Prior ACLR presenting to a participating MARS surgeon</td>
<td>Arthrofibrosis</td>
</tr>
<tr>
<td>Identified with a failed ACLR</td>
<td>Regional pain syndrome</td>
</tr>
<tr>
<td>Scheduled for 1\textsuperscript{st} RACLR</td>
<td>Allograft source for RACLR not obtained from the Musculoskeletal Transplant Foundation (MTF)</td>
</tr>
<tr>
<td></td>
<td>Unwilling/unable to complete repeat questionnaire at 2yr follow-up</td>
</tr>
</tbody>
</table>
Data collection methods for MARS have been previously detailed. Briefly, data collection involved the completion of a patient and surgeon questionnaire. The patient questionnaire is a self-administered 13-page questionnaire containing the validated outcome items of the Short Form-36 (SF36, version 2), Western Ontario and McMaster Osteoarthritis Index (WOMAC), Knee injury Osteoarthritis Outcome Score (KOOS),
International Knee Documentation Committee subjective form (IKDC), and Marx activity scale. The patient questionnaire is administered following informed consent.

The surgeon questionnaire is completed just prior to and shortly after surgery and includes sections on the history of knee injury and/or surgery on both knees, the results of the general knee examination done under anesthesia, recording of all previous and new intra-articular injuries and treatments to the meniscus and articular cartilage, and the surgical technique used for the revision ACL reconstruction. Findings of the general knee examination are classified according to the updated 1999 International Knee Documentation Committee guidelines. Articular cartilage injury is documented by the revising surgeon using the modified Outerbridge classification, and is based on an inter-observer agreement study. Meniscal injuries were classified by size, location, and partial versus complete tears with treatment categories of none, repair, or extent of resection. These classifications are based on a previous inter-rater agreement study.

Each participating site submits, via mail, completed data forms to the central data collection site (Vanderbilt University). To avoid potential errors common during manual data entry, patient and surgeon data are scanned with TeleForm software (Cardiff Software, Inc, Vista, California) using optical character recognition. Upon verification, the data are exported to a database. A matched, barcoded identification number is printed on each page of the patient and surgeon questionnaires allowing for de-identification and database merging.
5.2.3 Covariates and Outcomes

The main outcome of interest is the time from PACLR to RACL (time-to-revision). Revisions were considered “early” if they occurred within 30 months following primary ACLR, dichotomized as less than or equal to 30 months and greater than 30 months. Thirty months was chosen as a dichotomization cut point for 2 reasons. First, while there is no clear definition of “early” graft failure or revision, anecdotal evidence suggests many orthopedic surgeons deem graft failures that occur within 24 months as early. Results from an unpublished report on a subset of the MARS population indicates an average 6 month lag between graft failure and RACL, therefore 6 months was added, resulting in a 30 month cut point. Secondly, 30 months was subsequently found to be the median time to revision for this population, allowing for nearly equal proportions for comparison. To date there is no clearly defined timeframe in which graft failure and subsequent revision is deemed early or late. Kamath et al.\textsuperscript{74} have suggested that early (<6 months) laxity of the graft following ACLR is typically associated with sub-optimal surgical techniques as well as poor biologic incorporation of the graft, however a clearly defined “early” timeframe, with regards to revision, is absent. Magnussen et al.\textsuperscript{86} suggest 14 months as a timeframe for “early” RACL and found graft size and age at the time of PACLR to be contributing factors to revision within this timeframe. Despite the lack of a precise definition for “early” revisions, the need for identification of factors associated with graft failure and subsequent revision within a
temporal construct is a potentially valuable addition to understanding post-operative risks and prospective care.

Demographic covariates investigated were age at PACLR, sex, race (white, black, other), and Marx activity score. Due to the cross-sectional nature of the study, time-varying patient demographic variables were excluded from analysis as they were collected at the time of revision and may not accurately reflect the characteristic at the time of PACLR. These include education, smoking status, and marital status. Marx activity score, while a time-varying variable, was included for the following reason. The Marx activity score attempts to quantify activity level within the year prior to revision and was dichotomized (≥12 vs <12) in the current study in order to distinguish highly active and less active patients. The Marx score serves as an estimate of the level of activity to which the patient returned and was deemed a priori a potential confounder/effect modifier of the relationship between age at primary and early revision.

Primary ACLR surgical covariates were also investigated and included graft type (allograft vs autograft), graft source (bone-patellar tendon-bone (BTB) vs hamstring [semitendonosis + gracilis]), surgical technique (1-incision vs. 2-incision), femoral tunnel position, tibial tunnel position, and previous medial and lateral meniscal surgery (yes/no).

5.2.4 Statistical analysis

Descriptive statistics were used to summarize overall population characteristics and are presented for both the 1st revision subset and analytic subset. Relationships between
time-to-revision and individual baseline characteristics were assessed using univariable logistic regression models where the likelihood ratio (LR) $\chi^2$ test for the significance of the coefficients is asymptotically equivalent to the Pearson $\chi^2$ test often used in contingency table analysis.

A multivariable logistic regression model was developed to assess the simultaneous association of several independent variables and early revisions ($\leq 30$ months) while controlling for potentially confounding and/or effect modifying variables. Initial univariable analyses were performed on demographic and surgical variables deemed important with regards to early revision in order to identify candidates for inclusion into a multivariable model.

Variables were added into and removed from a multivariable model based on level of statistical significance and confounding influence using purposeful forward selection methods described by Hosmer and Lemeshow. All variables found significant from univariable analyses were included, as a block, into a multivariable model. The criterion for initial entry into the multivariable model was set at LR $\chi^2$ p-value < 0.25, as recommended by Hosmer and Lemeshow and based on the work of Bendel and Afifi on linear regression and Mickey and Greenland on logistic regression. The authors showed that the use of the traditional level of 0.05 often fails to identify variables known to be important. Hosmer and Lemeshow point out that any univariable approach ignores the possibility that a group of variables that are individually weakly associated with the outcome can become important predictors when taken
together and that a significance level should be large enough to allow for these variables to become candidates for inclusion into the multivariable model.

Removal from the multivariable model was based on two criteria: (1) an examination of the Wald $\chi^2$ statistic for each variable ($p$-value > 0.05) and (2) a comparison of the estimated coefficient with the coefficient from the univariable model with less than a 20% change indicating minimal confounding. All variables that did not contribute to the model based on these criteria were eliminated and a reduced model was fit. All model comparisons were made using the LR $\chi^2$ test with a $p$-value < 0.05 indicating a significantly improved model fit. The formula for the LR test using log likelihood (LL) is: 

$$-2 \times \text{LL of larger model} - [-2 \times \text{LL of smaller model}] \sim \chi^2$$

with degrees of freedom equal to the difference in the number of variables between the two models. All $p$-values were two-sided.

The above process of deletion, refitting, and verification continued until all important variables were included and those excluded were clinically and/or statistically unimportant. Variables not initially selected for inclusion in the multivariable model were added back into the model, one at a time, in order to identify any variable that, by itself, was not significantly related to the outcome but have made an important contribution in the presence of other variables.

Linearity of the logit for continuous variables was assessed using fractional polynomials and quartile design plots. Additionally, each justifiable interaction term (effect modifier) was tested for statistical significance using the Wald $\chi^2$ $p$-value < 0.01. Fit of the final model was assessed using the Hosmer-Lemeshow goodness of fit test.
Results were expressed as a ratio of odds (estimating relative risks) between varying levels of independent variables, while controlling for the other variables in the model.

Diagnostics were performed on the final model in order to identify extreme covariate patterns that may have had undue influence on model coefficients. Diagnostics consisted of visual assessment of various plots including $\Delta \chi^2$ versus estimated logistic probability, $\Delta$Deviance versus estimated logistic probability, and Pregibon’s $\Delta \beta$ versus logistic probability. The effect on model coefficients following the deletion of each pattern was also assessed.

5.3 Results

Nine hundred and twenty patients were enrolled in MARS from March 23, 2006 to July 31, 2010. Six hundred fifty three patients were first revisions with available time-to-revision data. Due to missing data for several variables of interest, complete data were available for 453, representing the analytic subset on which logistic regression was performed. Demographics of the analytic population, those not in the analysis, and the total population of first revisions with time-to-revision data are presented in table 5.2.
Table 5.2  Demographic characteristics of MARS enrollees

<table>
<thead>
<tr>
<th>Variables of interest</th>
<th>Analytic sample (n=453)</th>
<th>Not included in analysis (n=200)</th>
<th>Total (n=653)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>n (%)</td>
<td>n (%)</td>
<td>n (%)</td>
</tr>
<tr>
<td>Demographic characteristics</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PACLR-to-RACL R (months)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>mean (sd)</td>
<td>56.29 (57.4)</td>
<td>53.61 (63.8)</td>
<td>55.47 (59.4)</td>
</tr>
<tr>
<td>median</td>
<td>32</td>
<td>27.5</td>
<td>30</td>
</tr>
<tr>
<td>&gt; 30 months</td>
<td>232 (51.2)</td>
<td>93 (46.5)</td>
<td>325 (49.8)</td>
</tr>
<tr>
<td>≤ 30 months</td>
<td>221 (48.8)</td>
<td>107 (53.5)</td>
<td>328 (50.2)</td>
</tr>
<tr>
<td>Sex</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Male</td>
<td>250 (55.2)</td>
<td>121 (60.5)</td>
<td>371 (56.8)</td>
</tr>
<tr>
<td>Female</td>
<td>203 (44.8)</td>
<td>79 (39.5)</td>
<td>282 (43.2)</td>
</tr>
<tr>
<td>Age</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean (SD)</td>
<td>20.69 (7.52)</td>
<td>23.36 (9.92)</td>
<td>21.50 (8.41)</td>
</tr>
<tr>
<td>Median</td>
<td>18</td>
<td>20</td>
<td>19</td>
</tr>
<tr>
<td>&gt; 18 yrs</td>
<td>209 (46.1)</td>
<td>119 (59.8)</td>
<td>328 (50.2)</td>
</tr>
<tr>
<td>≤ 18 yrs</td>
<td>244 (53.9)</td>
<td>80 (40.2)</td>
<td>324 (49.6)</td>
</tr>
<tr>
<td>Race†</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>White</td>
<td>381 (84.7)</td>
<td>154 (78.2)</td>
<td>535 (81.9)</td>
</tr>
<tr>
<td>Black</td>
<td>20 (4.4)</td>
<td>16 (8.1)</td>
<td>36 (5.5)</td>
</tr>
<tr>
<td>Other</td>
<td>49 (10.9)</td>
<td>27 (13.7)</td>
<td>76 (11.6)</td>
</tr>
<tr>
<td>Marx activity score</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&lt;12</td>
<td>205 (45.3)</td>
<td>105 (53.3)</td>
<td>310 (47.5)</td>
</tr>
<tr>
<td>≥12</td>
<td>248 (54.7)</td>
<td>92 (46.7)</td>
<td>340 (52.1)</td>
</tr>
<tr>
<td>Surgical characteristics (PACL R)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Graft Type</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Autograft</td>
<td>392 (86.5)</td>
<td>79 (40.9)</td>
<td>471 (72.1)</td>
</tr>
<tr>
<td>Allograft</td>
<td>61 (13.5)</td>
<td>114 (59.1)</td>
<td>175 (26.8)</td>
</tr>
<tr>
<td>Graft Source</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BTB</td>
<td>302 (66.7)</td>
<td>43 (67.2)</td>
<td>345 (52.8)</td>
</tr>
<tr>
<td>HS (ST+Gr)</td>
<td>151 (33.3)</td>
<td>21 (32.8)</td>
<td>172 (26.3)</td>
</tr>
<tr>
<td>Surgical Technique</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Arthroscopic 2-incision</td>
<td>72 (15.9)</td>
<td>26 (13.7)</td>
<td>98 (15.0)</td>
</tr>
<tr>
<td>Arthroscopic 1-incision</td>
<td>381 (84.1)</td>
<td>164 (86.3)</td>
<td>545 (83.5)</td>
</tr>
<tr>
<td>Prior Medial Meniscus Surgery</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>No</td>
<td>286 (63.1)</td>
<td>141 (70.5)</td>
<td>427 (65.4)</td>
</tr>
<tr>
<td>Yes</td>
<td>167 (36.9)</td>
<td>59 (29.5)</td>
<td>226 (34.6)</td>
</tr>
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<td>Prior Lateral Meniscus Surgery</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No</td>
<td>366 (80.8)</td>
<td>156 (81.3)</td>
<td>522 (79.9)</td>
</tr>
<tr>
<td>Yes</td>
<td>87 (19.2)</td>
<td>36 (18.8)</td>
<td>123 (18.8)</td>
</tr>
</tbody>
</table>

Continued
Table 5.2 continued

<table>
<thead>
<tr>
<th>Femoral Tunnel Position</th>
<th>Ideal</th>
<th>Too anterior</th>
<th>Too vertical</th>
<th>Too anterior &amp; vertical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ideal</td>
<td>182 (40.2)</td>
<td>56 (38.6)</td>
<td>238 (36.4)</td>
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<tr>
<td>Too anterior</td>
<td>57 (12.6)</td>
<td>21 (14.5)</td>
<td>78 (11.9)</td>
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<tr>
<td>Too vertical</td>
<td>162 (35.8)</td>
<td>51 (35.2)</td>
<td>213 (32.6)</td>
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</tr>
<tr>
<td>Too anterior &amp; vertical</td>
<td>52 (11.5)</td>
<td>17 (11.7)</td>
<td>69 (10.6)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Tibial Tunnel Position</th>
<th>Ideal</th>
<th>Too anterior/posterior</th>
<th>Too medial/lateral</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ideal</td>
<td>322 (71.1)</td>
<td>121 (76.1)</td>
<td>443 (67.8)</td>
</tr>
<tr>
<td>Too anterior/posterior</td>
<td>92 (20.3)</td>
<td>34 (21.4)</td>
<td>126 (19.3)</td>
</tr>
<tr>
<td>Too medial/lateral</td>
<td>39 (8.6)</td>
<td>4 (2.5)</td>
<td>43 (6.6)</td>
</tr>
</tbody>
</table>

† 3 patients in the analytic population did not report race
PACLRR - primary ACL reconstruction; RACLRR - revision ACL reconstruction; HS - Hamstring; ST - semitendinosis; Gr - gracilis; BTB - bone-patellar tendon-bone

5.3.1 First Revision Subset (n=653)

Primary ACLR was performed by the revising surgeon in 33% of the cases. Males accounted for 55% of this cohort. Primary ACLR most often occurred in the second decade of life (61%), while RACLRR most often occurred during the third and second (36% and 33%, respectively) (Figure 5.2). The median age at the time of the PACLR and RACLRR, was 18 years (range, 10-54 years) and 23 years (range, 12-60 years), respectively. High activity level within the 12 months prior to revision, indicated by a patient-reported Marx Activity Score of 12 or greater, was most frequently reported (55%). The cohort predominately reported never having smoked (80%) and was most commonly normal weight (48%) at the time of revision. The predominately reported race was white (85%) followed by patients that identified their race as neither white nor African-American (11%). African-American patients comprised 4% of the analytic
population. A non-contact injury mechanism was reported by a majority of the cohort (59%).

Figure 5.2 Age at primary ACL reconstruction

The median time from last reconstruction was 32 months. The time from PACLR to RACLR was less than 1 year in 22% of patients, between 1 and 2 years for 19%, and greater than 2 years for 59%. Fourteen percent had a time from last reconstruction of 10
years or more (Figure 5.3). Intraoperative visualization of the graft at the time of revision found: 49% present, with the majority torn; 28% absent; 23% present, but elongated. Mode of failure, as deemed by the revising surgeon, was traumatic for 40%; technical, 20%; biologic, 6%; combination, 33% (surgeons marked all that applied); and unreported or missing, less than 1%. Biologic failure was previously defined in this cohort as “lack of incorporation of the graft as evidenced by early failure without a significant traumatic episode or obvious significant technical problems with the previous reconstruction.”
Technical failure, or failure associated with surgical techniques, was determined at the time of revision by the surgeon. Patient history, physical examination, radiographs, and arthroscopic evaluation were used to determine technical error. Surgeons were allowed to indicate more than one type of technical error. The most common technical error reported was femoral tunnel malposition (48%, as sole reason 29%, in combination with other factors 19%), followed by tibial tunnel malposition (32%). Prior femoral tunnel surgical technique was single tunnel 99%, double tunnel less than 1%, and

Figure 5.3  Time from primary ACL reconstruction to revision ACL reconstruction.
unreported less than 1%. Prior femoral tunnel position was deemed ideal in 40% of the patients and compromised in 60%. The single most common aspect of a compromised femoral tunnel was a position deemed too vertical (36%). Prior tibial tunnel position was deemed ideal in 71% of patients and compromised in 29%. The most common aspect of a compromised tibial tunnel was a position deemed too anterior or too posterior (20%).

Primary ACLR graft type was autograft (86%) and allograft (14%) and graft source was BTB (67%) and hamstring (semitendinosis + gracilis) (33%). Prior surgical approach was arthroscopic single incision in 84% and rear entry 2-incision in 16%. Previous meniscal surgery was noted in 48% of patients; prior surgery involving solely the medial meniscus 29%, solely the lateral meniscus 11%, and both 8%. Excision accounted for 73% of previous medial meniscus surgeries and 71% of lateral meniscus surgeries.

5.3.2 Analytic Subset (n=453)

Binary logistic regression was used to identify and model variables associated with early revision. The results of the univariable logistic regression analysis (Table 5.3) indicate age at PACLR, Marx activity score, prior graft type, prior graft source, prior medial meniscus surgery, prior lateral meniscus surgery, prior femoral tunnel position, and prior tibial tunnel position should be candidates for inclusion into the initial multivariable model. Multivariable model inclusion criterion was set at Wald $\chi^2$ p-value $\leq 0.25$.  

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All PACLR surgical variables were forced into the initial multivariable model and the results suggested the removal of prior surgical technique, medial meniscus surgery, and tibial tunnel position (Tables 5.4). A reduced model was fit and found to provide a better fit (LR $\chi^2 = 4.512, p=0.341$), representing the preliminary main effects model (Table 5.5).

Table 5.3  Univariable binary logistic regression for early revision (< 30 months)

<table>
<thead>
<tr>
<th>Independent Variable</th>
<th>$\beta$ (SE)</th>
<th>OR (95% CI)</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Demographic Characteristics</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Age at PACLR (Continuous)</td>
<td>-0.045</td>
<td>0.96 (0.93, 0.98)</td>
<td>0.001</td>
</tr>
<tr>
<td>Age at PACLR (in years)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&gt;18</td>
<td>1.00 (reference)</td>
<td>1.00 (reference)</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>$\leq$18</td>
<td>1.055</td>
<td>2.87 (1.96, 4.21)</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Sex</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Male</td>
<td>1.00 (reference)</td>
<td>1.00 (reference)</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Female</td>
<td>0.249</td>
<td>1.28 (0.89, 1.86)</td>
<td>0.188</td>
</tr>
<tr>
<td>Race</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>White</td>
<td>1.00 (reference)</td>
<td>1.00 (reference)</td>
<td>0.94†</td>
</tr>
<tr>
<td>Black</td>
<td>-0.164</td>
<td>0.85 (0.34, 2.10)</td>
<td>0.722</td>
</tr>
<tr>
<td>Other</td>
<td>-0.004</td>
<td>1.00 (0.55, 1.81)</td>
<td>0.989</td>
</tr>
<tr>
<td>Marx Activity</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0-3</td>
<td>1.00 (reference)</td>
<td>1.00 (reference)</td>
<td>&lt;0.001†</td>
</tr>
<tr>
<td>4-7</td>
<td>0.127</td>
<td>1.14 (0.56, 2.310)</td>
<td>0.726</td>
</tr>
<tr>
<td>8-1</td>
<td>0.032</td>
<td>1.03 (0.53, 2.03)</td>
<td>0.925</td>
</tr>
<tr>
<td>12-16</td>
<td>1.067</td>
<td>2.91 (1.74, 4.87)</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Marx Activity Score</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$&lt; 12$</td>
<td>1.00 (reference)</td>
<td>1.00 (reference)</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>$\geq 12$</td>
<td>1.023</td>
<td>2.78 (1.90, 4.08)</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Surgical Characteristics (PACLRA)‡</td>
<td></td>
<td></td>
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<tr>
<td>Graft Type</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Autograft</td>
<td>1.00 (reference)</td>
<td>1.00 (reference)</td>
<td>0.372</td>
</tr>
<tr>
<td>Allograft</td>
<td>0.246</td>
<td>1.28 (0.74, 2.20)</td>
<td>0.372</td>
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<tr>
<td>Graft Source</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>BTB</td>
<td>1.00 (reference)</td>
<td>1.00 (reference)</td>
<td>0.372</td>
</tr>
<tr>
<td>HS (ST+Gr)</td>
<td>0.863</td>
<td>2.37 (1.59, 3.54)</td>
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</tr>
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</table>

Continued
Table 5.3 continued

<table>
<thead>
<tr>
<th>Surgical Technique</th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Arthroscopic 2-incision</td>
<td>1.00 (reference)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Arthroscopic 1-incision</td>
<td>0.342</td>
<td>1.41 (0.85, 2.34)</td>
<td>0.189</td>
</tr>
<tr>
<td>Prior Medial Meniscus Surgery</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No</td>
<td>1.00 (reference)</td>
<td></td>
<td></td>
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<tr>
<td>Yes</td>
<td>-0.516</td>
<td>0.60 (0.41, 0.88)</td>
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<td>Prior Lateral Meniscus Surgery</td>
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<tr>
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<td></td>
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<td>Femoral Tunnel Position</td>
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<td></td>
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</tr>
<tr>
<td>Ideal (reference)</td>
<td>1.00 (reference)</td>
<td></td>
<td>&lt;0.001†</td>
</tr>
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<td>Too Anterior</td>
<td>-1.109</td>
<td>0.33 (0.18, 0.61)</td>
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</tr>
<tr>
<td>Too Vertical</td>
<td>-0.945</td>
<td>0.39 (0.25, 0.60)</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Too Anterior &amp; Vertical</td>
<td>-0.570</td>
<td>0.57 (0.30, 1.05)</td>
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<tr>
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</tr>
<tr>
<td>Ideal (reference)</td>
<td>1.00 (reference)</td>
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<td>0.002†</td>
</tr>
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<td>Too Anterior/Posterior</td>
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<td>0.52 (0.32, 0.84)</td>
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<tr>
<td>Too Medial/Lateral</td>
<td>-0.973</td>
<td>0.38 (0.19, 0.77)</td>
<td>0.008</td>
</tr>
</tbody>
</table>

† p-value is from Wald $\chi^2$ test for entire polytomous term
‡ All primary ACL reconstruction variables were included in the first multivariable model regardless of univariable significance
PACLRR-primary ACL reconstruction; RACLR-revision ACL reconstruction; BTB-bone-patellar tendon-bone; HS-Hamstring; ST-semitendinosus; Gr-gracilis.
Table 5.4  First multivariable model (full model) including all significant (p <0.25) demographic variables from univariable analyses.

<table>
<thead>
<tr>
<th>Independent Variable</th>
<th>β</th>
<th>S.E.</th>
<th>OR (95% C.I.)</th>
<th>p-value</th>
<th>Candidate for removal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age at PACLR</td>
<td>-0.030</td>
<td>0.016</td>
<td>0.97 (0.94, 1.00)</td>
<td>0.053‡</td>
<td></td>
</tr>
<tr>
<td>Marx Activity Score</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>&lt; 12</td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>≥ 12</td>
<td>0.804</td>
<td>0.221</td>
<td>2.24 (1.45, 3.44)</td>
<td>&lt;0.001</td>
<td></td>
</tr>
<tr>
<td>Graft Type (PACLR)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Autograft</td>
<td>1.00</td>
<td></td>
<td>(reference)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Allograft</td>
<td>0.878</td>
<td>0.321</td>
<td>2.41 (1.28, 4.51)</td>
<td>0.006</td>
<td></td>
</tr>
<tr>
<td>Graft Source</td>
<td></td>
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<td>BTB</td>
<td>1.00</td>
<td></td>
<td>(reference)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HS (ST+Gr)</td>
<td>0.638</td>
<td>0.234</td>
<td>1.89 (1.20, 3.00)</td>
<td>0.006</td>
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<tr>
<td>Surgical Technique</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Arthroscopic 2-incision</td>
<td>1.00</td>
<td></td>
<td>(reference)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Arthroscopic 1-incision</td>
<td>0.341</td>
<td>0.307</td>
<td>1.41 (0.77, 2.57)</td>
<td>0.267</td>
<td>x</td>
</tr>
<tr>
<td>Prior Medial Meniscus Surgery</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>No</td>
<td>1.00</td>
<td></td>
<td>(reference)</td>
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<tr>
<td>Yes</td>
<td>-0.246</td>
<td>0.223</td>
<td>0.78 (0.51, 1.21)</td>
<td>0.270</td>
<td>x</td>
</tr>
<tr>
<td>Prior Lateral Meniscus Surgery</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No</td>
<td>1.00</td>
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<td>(reference)</td>
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<tr>
<td>Yes</td>
<td>0.558</td>
<td>0.265</td>
<td>1.75 (1.04, 2.94)</td>
<td>0.035</td>
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<td>Femoral Tunnel Position (PACLR)</td>
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<td></td>
<td></td>
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</tr>
<tr>
<td>Ideal</td>
<td>1.00</td>
<td></td>
<td>(reference)</td>
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<tr>
<td>Too Anterior</td>
<td>-0.791</td>
<td>0.343</td>
<td>0.45 (0.23, 0.89)</td>
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<tr>
<td>Too Vertical</td>
<td>-0.913</td>
<td>0.254</td>
<td>0.40 (0.24, 0.66)</td>
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<td>Too Anterior &amp; Vertical</td>
<td>-0.357</td>
<td>0.361</td>
<td>0.70 (0.34, 1.42)</td>
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<tr>
<td>Tibial Tunnel Position (PACLR)</td>
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<td></td>
</tr>
<tr>
<td>Ideal</td>
<td>1.00</td>
<td></td>
<td>(reference)</td>
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<td></td>
</tr>
<tr>
<td>Too Anterior/Posterior</td>
<td>-0.289</td>
<td>0.274</td>
<td>0.75 (0.44, 1.28)</td>
<td>0.292</td>
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<td>Too Medial/Lateral</td>
<td>-0.249</td>
<td>0.395</td>
<td>0.78 (0.36, 1.69)</td>
<td>0.529</td>
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</tr>
</tbody>
</table>

† p-value is from Wald $\chi^2$ test for entire polytomous term.
‡ Age was retained due to its known association with graft failure incidence
PACLRT-primary ACL reconstruction; RACLR-revision ACL reconstruction; BTB-bone-patellar
tendon-bone ; HS-Hamstring; ST-semitendinosis; Gr-gracilis.

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Table 5.5 Second multivariable model (reduced model) following the removal of non-significant (p > 0.05) variables from the full model.

<table>
<thead>
<tr>
<th>Independent Variable</th>
<th>β</th>
<th>S.E.</th>
<th>OR (95% C.I.)</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age at PACLR</td>
<td>-0.031</td>
<td>0.015</td>
<td>0.970 (0.94, 1.00)</td>
<td>0.046</td>
</tr>
<tr>
<td>Marx Activity Score</td>
<td></td>
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</tr>
<tr>
<td>&lt; 12</td>
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</tr>
<tr>
<td>≥ 12</td>
<td>0.882</td>
<td>0.215</td>
<td>2.415 (1.58, 3.68)</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Graft Type (PACLRS)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Autograft</td>
<td>1.00</td>
<td></td>
<td>(reference)</td>
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</tr>
<tr>
<td>Allograft</td>
<td>-0.861</td>
<td>0.316</td>
<td>2.54 (1.38, 4.68)</td>
<td>0.003</td>
</tr>
<tr>
<td>Graft Source</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>BTB</td>
<td>1.00</td>
<td></td>
<td>(reference)</td>
<td></td>
</tr>
<tr>
<td>HS (ST+Gr)</td>
<td>-0.708</td>
<td>0.226</td>
<td>1.99 (1.27, 3.12)</td>
<td>0.003</td>
</tr>
<tr>
<td>Prior Lateral Meniscus Surgery</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No</td>
<td>1.00</td>
<td></td>
<td>(reference)</td>
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</tr>
<tr>
<td>Yes</td>
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<td>0.260</td>
<td>1.703 (1.02, 2.84)</td>
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<tr>
<td>Femoral Tunnel Position (PACLRS)</td>
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</tr>
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<td>Ideal</td>
<td>1.00</td>
<td></td>
<td>(reference)</td>
<td>0.001†</td>
</tr>
<tr>
<td>Too Anterior</td>
<td>-0.830</td>
<td>0.336</td>
<td>0.436 (0.23, 0.84)</td>
<td>0.014</td>
</tr>
<tr>
<td>Too Vertical</td>
<td>-0.943</td>
<td>0.237</td>
<td>0.389 (0.25, 0.62)</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Too Anterior &amp; Vertical</td>
<td>-0.388</td>
<td>0.338</td>
<td>0.678 (0.35, 1.32)</td>
<td>0.251</td>
</tr>
</tbody>
</table>

† p-value is from Wald χ² test for entire polytomous term
PACLRS-primary ACL reconstruction; RACLRS-revision ACL reconstruction; BTB-bone-patellar tendon-bone; HS-Hamstring; ST-semitendinosus; Gr-gracilis.

Due to the inclusion of age at PACRL as a continuous variable, linearity in the logit was assessed via quartile design and fractional polynomial methods. In brief, the quartile design method includes: The creation of a new variable (primageQ) taking levels 1-4 corresponding to each quartile; replacing the suspect continuous variable with the new variable in the model, using Q1 (25th percentile) as the referent group; and plotting the estimated coefficients of the new variable against the quintile midpoint. The underlying theory and use of fractional polynomials to select the scale of a continuous variable in logistic regression has been detailed previously. Despite the indication from the fractional polynomial analysis that age at PACR remain as a linear, continuous
variable (Table 5.6; Figures 5.2); the quartile design analysis strongly suggests a binary shift in age, suggesting a dichotomization point at or near the median (18 years) (Table 5.7, Figure 5.3). The continuous age at PACLR variable was replaced with a dichotomized age variable. No appreciable effect on model coefficients was observed.

Table 5.6  Fractional polynomial method for scale selection of the continuous variable; age at primary ACL reconstruction.

<table>
<thead>
<tr>
<th>Age at PACLR</th>
<th>df</th>
<th>Deviance</th>
<th>Gain</th>
<th>p-value</th>
<th>Powers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Not in Model</td>
<td>0</td>
<td>559.396</td>
<td>--</td>
<td>--</td>
<td></td>
</tr>
<tr>
<td>Linear</td>
<td>1</td>
<td>555.275</td>
<td>0.000</td>
<td>0.042\textsuperscript{a}</td>
<td>1</td>
</tr>
<tr>
<td>m=1</td>
<td>2</td>
<td>552.983</td>
<td>2.293</td>
<td>0.130\textsuperscript{b}</td>
<td>-1</td>
</tr>
<tr>
<td>m=2</td>
<td>4</td>
<td>551.738</td>
<td>3.538</td>
<td>0.537\textsuperscript{c}</td>
<td>0.5</td>
</tr>
</tbody>
</table>

\textsuperscript{a} p-value comparing the linear model of age at PACLR to the model without age at PACLR, indicating the inclusion of age at primary ACL reconstruction as a continuous provides a better fit than a model without age.

\textsuperscript{b} p-value comparing the best m=1 model (1/age) to the linear model, indicating an inverse scale does not provide a better fit than the continuous scale.

\textsuperscript{c} p-value comparing the best m=2 model [(\sqrt{age}), (\sqrt{age})] to the best m=1 model.
Figure 5.4 Fractional polynomial fit: Age at primary ACL reconstruction as a continuous (linear) variable.

Table 5.7 Model with age at primary ACL reconstruction quartile variables

<table>
<thead>
<tr>
<th>Independent Variable</th>
<th>β</th>
<th>S.E.</th>
<th>OR</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>primageQ reference</td>
<td></td>
<td></td>
<td></td>
<td>&lt;0.001†</td>
</tr>
<tr>
<td>primageQ(1)</td>
<td>0.269</td>
<td>.309</td>
<td>1.308</td>
<td>0.385</td>
</tr>
<tr>
<td>primageQ(2)</td>
<td>-0.983</td>
<td>.290</td>
<td>.374</td>
<td>0.001‡</td>
</tr>
<tr>
<td>primageQ(3)</td>
<td>-0.631</td>
<td>.286</td>
<td>.532</td>
<td>0.027‡</td>
</tr>
<tr>
<td>Marx Activity Score</td>
<td>0.833</td>
<td>.217</td>
<td>2.301</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Graft Type (PACLAR)</td>
<td>-0.901</td>
<td>.315</td>
<td>2.463</td>
<td>0.004</td>
</tr>
<tr>
<td>Graft Source (PACLAR)</td>
<td>-0.707</td>
<td>.230</td>
<td>2.028</td>
<td>0.002</td>
</tr>
<tr>
<td>Prior Lateral Meniscus Surgery</td>
<td>0.586</td>
<td>.266</td>
<td>1.797</td>
<td>0.028</td>
</tr>
<tr>
<td>Femoral Tunnel Position (PACLAR)</td>
<td></td>
<td></td>
<td></td>
<td>0.002</td>
</tr>
<tr>
<td>femtunnel4(1)</td>
<td>-0.749</td>
<td>.344</td>
<td>.473</td>
<td>0.029</td>
</tr>
<tr>
<td>femtunnel4(2)</td>
<td>-0.913</td>
<td>.242</td>
<td>.401</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>femtunnel4(3)</td>
<td>-0.423</td>
<td>.344</td>
<td>.655</td>
<td>0.219</td>
</tr>
</tbody>
</table>

† p-value is from Wald $\chi^2$ test for entire polytomous term
‡Suggests quartile 2 and 3 can be collapsed resulting in a dichotomized age variable ($\leq 18$ and $> 18$ years).
Figure 5.5 Quartile design: age at primary ACL reconstruction quartile vs. age at primary ACL reconstruction quartile midpoint. Suggests a binary shift in the continuous age variable at the median (18 years).

The model including the dichotomized age variable represents the main effects model. The significance of possible main effect interactions were assessed by their addition, one at a time, to the main effects model. The inclusion criterion was set, \textit{a priori}, at Wald $\chi^2$ p-value $< 0.01$. The narrow inclusion criterion has been recommended\textsuperscript{64} in order to avoid inclusion of marginally significant interactions that may inflate estimated standard errors and complicate model interpretation. No interactions
were added to the model, representing the preliminary final model. The final model (Table 5.8) showed no signs of lack of fit (Hosmer-Lemeshow Goodness of Fit $\chi^2$: 6.11, p-value=0.635) nor did any cells in the 10 x 2 table contain fewer than 5 patients. The power of the final model’s predicted values to discriminate between positive and negative cases ($\leq 30$ vs $>30$ months, respectively) was assessed using the area under the ROC curve (0.74, 95% CI: 0.69, 0.78)(Figure 5.4), indicating moderate to good discrimination.

Among the demographic variables in the final model, only age at PACLR and Marx activity score at the time of revision remained in the final model. Among the PACLR surgical variables; graft type, graft source, prior lateral meniscus surgery, and femoral tunnel placement were retained. While all predictors in the final model were found to be significant, the strongest predictors of early revision ($\leq 30$ months) were age at primary ACLR (OR:2.44, p<0.001), level of activity within the year of revision (Marx activity score, OR:2.23, p<0.001). A femoral tunnel position deemed to be too vertical (OR:0.40, p<0.001) or too anterior (OR: 0.46, p=0.024) decreased the odds of early graft failure. No effect was found when femoral tunnel position was deemed both too vertical and too anterior (OR: 67, p=0.236).
Table 5.8  Final binary logistic regression model for early revision (< 30 months)

<table>
<thead>
<tr>
<th>Independent Variable</th>
<th>β</th>
<th>OR (95% CI)</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age at PACLR (in years)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&gt;18</td>
<td></td>
<td>1.00 (reference)</td>
<td></td>
</tr>
<tr>
<td>≤18</td>
<td>0.891</td>
<td>2.44 (1.58, 3.76)</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Marx Activity Score</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&lt; 12</td>
<td></td>
<td>1.00 (reference)</td>
<td></td>
</tr>
<tr>
<td>≥12</td>
<td>0.804</td>
<td>2.23 (1.46, 3.41)</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Graft Type</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Autograft</td>
<td></td>
<td>1.00 (reference)</td>
<td></td>
</tr>
<tr>
<td>Allograft</td>
<td>0.931</td>
<td>2.54 (1.38, 4.68)</td>
<td>0.003</td>
</tr>
<tr>
<td>Graft Source</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BTB</td>
<td></td>
<td>1.00 (reference)</td>
<td></td>
</tr>
<tr>
<td>HS (ST+Gr)</td>
<td>0.689</td>
<td>1.99 (1.27, 3.12)</td>
<td>0.003</td>
</tr>
<tr>
<td>Prior Lateral Meniscus Surgery</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No</td>
<td></td>
<td>1.00 (reference)</td>
<td></td>
</tr>
<tr>
<td>Yes</td>
<td>0.579</td>
<td>1.78 (1.07, 2.99)</td>
<td>0.028</td>
</tr>
<tr>
<td>Femoral Tunnel Position</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ideal (reference)</td>
<td></td>
<td>1.00 (reference)</td>
<td></td>
</tr>
<tr>
<td>Too Anterior</td>
<td>-0.770</td>
<td>0.46 (0.24, 0.91)</td>
<td>0.024</td>
</tr>
<tr>
<td>Too Vertical</td>
<td>-0.909</td>
<td>0.40 (0.25, 0.65)</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Too Anterior &amp; Vertical</td>
<td>-0.407</td>
<td>0.67 (0.34, 1.30)</td>
<td>0.236</td>
</tr>
</tbody>
</table>

† p-value is from Wald χ² test for entire polytomous term.

PACLAR-primary ACL reconstruction; RACLAR-revision ACL reconstruction; BTB-bone-patellar tendon-bone; HS-Hamstring; ST-semitendinosus; Gr-gracilis.
Diagnostics were performed to identify covariate patterns that may have had undue influence on model coefficients. Suspect covariate patterns were identified through visual assessment of various plots including $\Delta \chi^2$ versus estimated logistic probability (Figure 5.7) and $\Delta$Deviance versus logistic probability (Figure 5.8) where the size of each covariate pattern marker is relative to its Pregibon’s $\Delta \beta$ value. Four extreme covariate patterns were identified (Table 5.9) and it was determined that each of the patterns were clinically and biologically plausible, and therefore all were retained. Despite this, the effect on model coefficients following the deletion of each pattern was assessed (Table 5.10). It is clear that the effect covariate pattern 2 has on the estimated coefficient of a femoral tunnel position deemed too anterior is quite large (a 53%
decrease, however, as mentioned above, the covariate pattern that produces this effect is well within the range of plausibility.

Figure 5.7 Change in $\chi^2$ versus estimated probability of early revision. Size weighted by Pregibon’s $\Delta\beta$ value
Figure 5.8 Change in deviance versus estimated probability of early revision. Size weighted by Pregibon’s $\Delta \beta$ value.
Table 5.9 Extreme covariate patterns

<table>
<thead>
<tr>
<th>Time -to- RACLR (Months)</th>
<th>Age at PACLR (Yrs)</th>
<th>Marx Activity Score</th>
<th>Graft Type (PACLAR)</th>
<th>Graft Source (PACLAR)</th>
<th>Prior LM Surgery</th>
<th>Femoral Tunnel Position (PACLAR)</th>
<th>p</th>
<th>Δχ²</th>
<th>ΔD</th>
<th>Δβ</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>&gt; 30 ≤ 18 ≥ 12</td>
<td>Autograft BTB</td>
<td>No</td>
<td>Too Ant.</td>
<td>0.49</td>
<td>4.03</td>
<td>4.25</td>
<td>1.29</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>&gt; 30 ≤ 18 ≥ 12</td>
<td>Autograft BTB</td>
<td>No</td>
<td>Too Ant.</td>
<td>0.49</td>
<td>4.03</td>
<td>4.25</td>
<td>1.29</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>≤ 30 ≤ 18 ≥ 12</td>
<td>Autograft BTB</td>
<td>No</td>
<td>Too Ant.</td>
<td>0.49</td>
<td>4.03</td>
<td>4.25</td>
<td>1.29</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>≤ 30 ≤ 18 ≥ 12</td>
<td>Autograft BTB</td>
<td>No</td>
<td>Too Ant.</td>
<td>0.49</td>
<td>4.03</td>
<td>4.25</td>
<td>1.29</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>≤ 30 ≤ 18 ≥ 12</td>
<td>Autograft BTB</td>
<td>No</td>
<td>Too Ant.</td>
<td>0.49</td>
<td>4.03</td>
<td>4.25</td>
<td>1.29</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>≤ 30 ≤ 18 ≥ 12</td>
<td>Autograft BTB</td>
<td>No</td>
<td>Too Ant.</td>
<td>0.49</td>
<td>4.03</td>
<td>4.25</td>
<td>1.29</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>&gt; 30 ≤ 18 &lt; 12</td>
<td>Autograft HS</td>
<td>Yes</td>
<td>Too Vert.</td>
<td>0.57</td>
<td>0.44</td>
<td>4.34</td>
<td>5.54</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>&gt; 30 ≤ 18 &lt; 12</td>
<td>Autograft HS</td>
<td>Yes</td>
<td>Too Vert.</td>
<td>0.57</td>
<td>0.44</td>
<td>4.34</td>
<td>5.54</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>&gt; 30 ≤ 18 &lt; 12</td>
<td>Autograft HS</td>
<td>Yes</td>
<td>Too Vert.</td>
<td>0.57</td>
<td>0.44</td>
<td>4.34</td>
<td>5.54</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>≥ 18 ≥ 12</td>
<td>Autograft HS</td>
<td>No</td>
<td>Too Vert.</td>
<td>0.81</td>
<td>0.44</td>
<td>8.75</td>
<td>6.90</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>≥ 18 ≥ 12</td>
<td>Autograft HS</td>
<td>No</td>
<td>Too Vert.</td>
<td>0.81</td>
<td>0.44</td>
<td>8.75</td>
<td>6.90</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

PACLAR - primary anterior cruciate ligament reconstruction, RACLR - revision anterior cruciate ligament reconstruction, LM - lateral meniscus, BTB - bone-patellar tendon-bone, HS - hamstring (semitendinosus+gracilis), p - logistic probability of time-to-RACLR ≤ 30; Δχ² - change in model LR χ² if covariate pattern were deleted; ΔD - change in model deviance if covariate pattern were deleted; Δβ - change in estimated model coefficients if covariate pattern were deleted.

Table 5.10 The effect of individual extreme covariate pattern deletion on model coefficients

<table>
<thead>
<tr>
<th>Variable</th>
<th>All Data (n=453)</th>
<th>Pattern 1 deleted</th>
<th>Pattern 2 deleted</th>
<th>Pattern 3 deleted</th>
<th>Pattern 4 deleted</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>β</td>
<td>β (%Δ)</td>
<td>β (%Δ)</td>
<td>β (%Δ)</td>
<td>β (%Δ)</td>
</tr>
<tr>
<td>Age at PACLR</td>
<td>0.891</td>
<td>0.909 (2.02)</td>
<td>0.818 (-8.19)</td>
<td>0.944 (5.95)</td>
<td>0.941 (5.61)</td>
</tr>
<tr>
<td>Marx Activity Score</td>
<td>0.804</td>
<td>0.821 (2.11)</td>
<td>0.731 (-9.08)</td>
<td>0.747 (-7.09)</td>
<td>0.829 (3.11)</td>
</tr>
<tr>
<td>Graft Type (PACLAR)</td>
<td>0.931</td>
<td>0.926 (-0.54)</td>
<td>0.959 (3.01)</td>
<td>0.922 (-0.97)</td>
<td>1.093 (17.40)</td>
</tr>
<tr>
<td>Graft Source (PACLAR)</td>
<td>0.689</td>
<td>0.677 (-1.74)</td>
<td>0.743 (7.84)</td>
<td>0.746 (8.27)</td>
<td>0.762 (10.60)</td>
</tr>
<tr>
<td>Prior LM Surgery</td>
<td>0.579</td>
<td>0.572 (-1.21)</td>
<td>0.612 (5.70)</td>
<td>0.683 (17.96)</td>
<td>0.565 (-2.42)</td>
</tr>
<tr>
<td>Femoral Tunnel Position</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Too Anterior</td>
<td>-0.77</td>
<td>-0.682 (11.43)</td>
<td>-1.176 (-52.73)</td>
<td>-0.752 (2.34)</td>
<td>-0.754 (-2.08)</td>
</tr>
<tr>
<td>Too Vertical</td>
<td>-0.909</td>
<td>-0.909 (0.00)</td>
<td>-0.911 (-0.22)</td>
<td>-0.845 (7.04)</td>
<td>-0.873 (-3.96)</td>
</tr>
<tr>
<td>Too Anterior &amp; Vertical</td>
<td>-0.407</td>
<td>-0.406 (0.25)</td>
<td>-0.409 (-0.49)</td>
<td>-0.405 (0.49)</td>
<td>-0.400 (-1.72)</td>
</tr>
</tbody>
</table>

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Anterior cruciate ligament injury is one of the most common within an athletic population, frequently leading to reconstructive surgery. While most ACL reconstructions are successful, subsequent graft failure occurs. Several studies have investigated factors associated with incidence of graft failure; however no study has analyzed time-to-revision as the dependent outcome. This study investigates factors associated with early revision ACL reconstruction among revision patients. The primary goal was to identify factors associated with early revision (less than 30 months) when compared to revisions occurring later.

The effect of graft type on a wide range of outcomes has been investigated. In a meta-analysis involving 256 autograft and 278 allograft patients with at least 2 years of follow-up, the odds of graft failure were significantly higher for allografts compared to autografts (OR, 5.03; p=0.01). In a 5-year prospective cohort study comparing outcomes for allograft and autograft reconstructions, Poehling et al. found that within the first 3 months following ACLR, the autograft group experienced increased pain and decreased knee function when compared to the allograft group. Over the entire 5-year period, the allograft group had significantly more knee laxity. These findings suggest that allograft patients may be more likely to return to high level activity early in the post-operative period because they have less pain and more knee function, placing them at higher risk for graft failure than autograft patients. These findings are consistent
with the results of our study where allograft patients had higher odds of revision within the 30 months of PACLR.

Activity level has also been studied as a risk factor for ACL graft failure. Athletes that return to a high activity level have been shown to have a greater risk of ACL graft failure. Borchers et al.\textsuperscript{19} found high activity level and allograft use to be strong predictors of graft failure. While their finding of increased risk of failure due to a return to high activity is consistent with our study, it differs with respect to allograft use. Although their study was not designed to analyze when failures occurred, the reported median time from primary ACLR to failure was greater among allograft patients compared to autograft patients (12 and 9 months, respectively). This is counter to findings in the current study where median time to revision among allograft and autograft was 28 and 33 months, respectively, and allograft patients had nearly two and half times the odds of revision within 30 months of PACLR. This discrepancy may be due to the different outcomes, failure and revision, and additional studies investigating the effect of graft choice on the time from failure to revision may be needed.

Previous studies have also shown an association between a younger age at PACLR and subsequent re-injury. Shelbourne et al.\textsuperscript{135} found patients less than 18 years of age at the time of ACLR had the highest risk of graft failure when compared to those aged 18-25 and older than 25. They also found that among this younger age group, 72% returned to full activity before 6 months post-ACLR (mean, 4.6±1.9 months), a standard time frame for ACLR post-operative rehabilitation. This additional finding may partially explain the greater incidence of failure. Younger age at the time of ACLR has also been
proposed as a predictor for revision ACLR within 24 months. Results from the current study indicate that among a population of graft failures, a younger age at PACLR is also associated with revision within 30 months post-ACL.

Results of our study also indicate increased odds of revision within 30 months of PACLR for hamstring with semitendinosis plus gracilis and prior lateral meniscus surgery. A decreased odds of early revision was found among femoral tunnel positions deemed too anterior or too vertical. These additional factors should be considered in future studies investigating time-to-revision or time-to-graft failure.

The current study does have limitations. Information regarding activity level prior to PACLR was unavailable for this study, restricting the ability to investigate potential changes that may have occurred following PACLR. Activity exposure rates were not available; however, the Marx activity score, which is a validated activity score used to assess the frequency of running, cutting, decelerating and pivoting, provided information on the level to which the patient returned before graft failure and subsequent revision. A binary finding of meniscal tear or no meniscal tear is potentially misleading, as small posterior horn lateral meniscal tears usually require little or no treatment, compared with large complex lateral meniscal tears that require repair or debridement. Also, data on post-operative rehabilitation protocol following primary ACLR were not available and could affect the timing of RACLR. The size of the meniscectomy was not included in the current analysis. Also, in large multicenter cohorts such as the one utilized in this study, there is the potential for missing data and misclassification of data.
to affect the results. Standardized surgeon data collection methods used in the MARS study greatly reduces this potential problem.

5.5 Conclusion

Results indicate increased odds of revision within 30 months following PACLR for patients: aged 18 or younger; returning to a higher level of activity; with prior lateral meniscus surgery; that received an allograft versus autograft; and a hamstring (semitendinosis + gracilis) versus bone-patellar tendon-bone. Femoral tunnel positions deemed to be too anterior or too vertical had decreased odds of revision within 30 months of PACLR. Interestingly, a femoral tunnel with both malpositions was not associated with early revision.

These factors should be considered in future, prospective study of the temporal aspects of graft failure allowing for a greater understanding of the dynamic risk profile within various post-operative time-periods.
Chapter 6: The Effects of Sex, Graft Type, and Activity Level on Time to Graft Failure

6.1 Introduction

An increasing number of studies have focused on anterior cruciate ligament (ACL) reconstructive outcomes, the vast majority of which report subjective data collected from validated questionnaires, and objective data in the form of functional testing and radiographic results. Several studies have reported graft failure as an outcome, primarily presenting incidence rates. Far fewer studies have reported statistics on time-to-failure, only presenting mean and/or median times. It is estimated that between 3% and 15% of primary ACL reconstructions will fail, requiring revision ACL (RACLR) surgery. Due to the uncommon nature of graft failure, the collection of a sufficient number of graft failures in a prospective manner can be lengthy and costly. At the 2 year follow-up of patients enrolled in the Multicenter Orthopedic Outcomes Network (MOON) ACLR study, the largest prospective ACLR outcomes study in the US, 19 out of 322 (5.9%) patients suffered graft failure. In order to study potential risk factors associated with the timing of graft failure, a greater number of graft failures must be captured. The Multicenter ACL Revision Study was designed to prospectively assess RACLR outcomes and has amassed nearly 1000 patients since 2006. The extraction of demographic and prior ACLR surgical data is feasible and would include the date of ACLR, allowing for the
calculation and use of time-to-failure as the dependent variable. To date no published study has investigated time-to-failure as a dependent outcome of interest.

Although sex has been established as a strong risk factor for initial ACL injuries, a small number of studies have explored the effect of sex on graft failure.\(^7, 19, 32, 46, 108\) Results range from small to no association between sex and graft failure\(^32, 46, 108\) to a strong association.\(^19, 108\) Many studies have prospectively investigated ACLR outcomes with a specific interest in autograft and allograft comparisons, with most lacking proper randomization, reporting on fewer than 100 patients, and follow-up less than 3 years.\(^29, 78, 116, 118, 136, 150\) Again, there does not appear to be a clear answer regarding the effect of graft type on failure. Nearly all ACLR studies are difficult to assess due to the lack of a clear definition of graft failure resulting in consistent reporting.

The purpose of the present study was to investigate the role sex plays in time-to-graft failure, or time-to-failure (TTF). The potential confounding and/or modifying effects of activity level and graft type were also assessed. Understanding the effect of sex on failure within a temporal construct can provide important information from which the surgeon, patient, and post-operative therapist can determine a more precise course of care.
6.2 Methods

6.2.1 Study Design

The current cross-sectional study involved secondary analysis of patients enrolled in MARS. All patients had confirmed ACLR graft failures and were scheduled for RACL at 3 MARS member sites (The Ohio State University, Washington University, and Vanderbilt University) at the time of data collection. The dependent variable is time-to-graft failure, or time-to-failure (TTF), following ACLR.

6.2.2 Study population

The current study includes participants of MARS enrolled from March 23, 2006 to July 31, 2010 at 3 member sites (The Ohio State University, Vanderbilt University, and Washington University). Inclusion and exclusion criteria for MARS have previously been reported and are listed in Table 6.1. Failure was defined by: MRI, knee laxity (KT > 5mm), a positive pivot shift, a positive Lachman’s, functional instability, and/or by arthroscopic confirmation. Patients scheduled for RACL with either partial (Grade I or II) and/or complete (Grade III) simultaneous ligamentous injuries to the collateral ligaments and/or the posterior cruciate ligament were also included. Patients with ACLR failure treated non-operatively were also eligible for inclusion in MARS. None of the patients in the current study were treated non-operatively.
Table 6.1 Inclusion/exclusion criteria for the multicenter ACL revision study (MARS)

<table>
<thead>
<tr>
<th>Inclusion Criteria</th>
<th>Exclusion Criteria</th>
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<tbody>
<tr>
<td>Aged 12-65</td>
<td>Prior intra-articular infection</td>
</tr>
<tr>
<td>Prior ACLR presenting to a participating MARS surgeon</td>
<td>Arthrofibrosis</td>
</tr>
<tr>
<td>Identified with a failed ACLR</td>
<td>Regional pain syndrome</td>
</tr>
<tr>
<td></td>
<td>Allograft source for RACLR not obtained from the Musculoskeletal Transplant Foundation (MTF)</td>
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<tr>
<td></td>
<td>Unwilling/unable to complete repeat questionnaire at 2-year follow-up</td>
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</table>

In order to obtain a more accurate date of graft failure, 3 MARS member sites were selected for patient chart review. In addition to demographic and ACLR surgical data collected as part of MARS, the date of injury noted by the surgeon during the initial clinic visit following injury was extracted allowing for accurate calculation of TTF. The date of injury noted in the chart was used as a proxy for date of graft failure. One hundred ninety three patients were included in this subset, of which 136 had valid TTF data (Figure 6.1).
Figure 6.1 Analytic population of the study. OSU: The Ohio State University, WU: Washington University, VU: Vanderbilt University, TTF: time-to-failure, ACLR: anterior cruciate ligament reconstruction.
6.2.3 Data collection

Data collection methods for MARS have been previously detailed.\textsuperscript{92} Briefly, data collection involved the completion of a patient and surgeon questionnaire. The patient questionnaire is a self-administered 13-page instrument containing the validated outcomes of the Short Form-36 (SF36, version 2), Western Ontario and McMaster Osteoarthritis Index (WOMAC), Knee injury Osteoarthritis Outcome Score (KOOS), International Knee Documentation Committee subjective form (IKDC), and Marx activity scale. The patient questionnaire was administered following informed consent and completion occurred between the clinic visit and RAclr.

The surgeon questionnaire was completed just prior to and shortly after surgery and included sections on the history of knee injury and/or surgery on both knees, the results of the general knee examination done under anesthesia, recording of all previous and new treatments to the meniscus and articular cartilage, and the surgical technique used for the revision ACL reconstruction. Findings of the general knee examination were classified according to the updated 1999 International Knee Documentation Committee guidelines.\textsuperscript{68,69} Meniscal injuries were classified by size, location, and partial versus complete tears with the following treatment categories: none, repair, or extent of resection. These classifications were based on a previous interrater agreement study.\textsuperscript{28} The date of both ACLR and RAclr were recorded. However, the date of injury leading to the clinic visit, assumed to be an accurate proxy of the date of failure, is not recorded.
in the MARS database. A chart review of all patients from 3 MARS sites was conducted in order to obtain the date of injury, allowing for a more accurate TTF calculation.

Each participating site submitted, via mail, completed data forms to the central data collection site (Vanderbilt University). To avoid potential errors common during manual data entry, patient and surgeon data were scanned with TeleForm software (Cardiff Software, Inc, Vista, California) using optical character recognition. Upon verification, the data were exported to a database. A matched, barcoded identification number was printed on each page of the patient and surgeon questionnaires allowing for de-identification and database merging.

6.2.4 Covariates and outcomes

Activity level and graft type have been associated with increased risk of graft failure, and were included in the current study due to their potential to confound or modify the effect of sex on TTF. The sex-TTF association was assessed at each level of activity (Marx <12 and 12+) and separately at each level of graft type (autograft and allograft).

The focus of many studies involving graft failure has been placed on factors associated with incident failure within a specified follow-up period. The main outcome of interest in this study is the time from ACLR to graft failure, or time-to-failure. To date there is no clearly defined timeframe in which graft failure is deemed early or late. Kamath et al. have suggested that early (<6 months) laxity of the graft following ACLR
is typically associated with sub-optimal surgical techniques as well as poor biologic incorporation; however a clearly defined timeframe for “early” graft failure is not discussed. Magnussen et al.\textsuperscript{86} suggest 14 months as a timeframe for “early” revision, although time of failure was not assessed in their study. Despite the lack of an accurate definition for “early” failure, the need for identification of factors associated with graft failure within a temporal construct would be a valuable addition to understanding post-operative risks and specifying optimal post-operative care.

6.2.5 Statistical analysis

Descriptive statistics were used to provide overall study population characteristics by sex. Differences between females and males were assessed using Fisher’s exact $\chi^2$ test for categorical variables and Mann-Whitney U test for medians. Survival functions of male and female patients were assessed using Kaplan-Meier (K-M) plots. It was assumed \textit{a priori} that the activity level to which the patient returned following ACLR and graft type could potentially modify the sex-TTF association; therefore, associations were stratified on Marx activity level and graft type separately. All survival function comparisons were assessed using the Tarone-Ware test for equality. Tarone-Ware was preferred over the log-rank test as it assigns more weight to early differences between observed and expected number of failures. All p-values were 2-sided.
6.3 Results

6.3.1 General

920 patients were enrolled in MARS from March 23, 2006 to July 31, 2010. Three member sites were selected for chart review, accounting for 193 patients, of which 136 had available TTF data, representing the study population. Demographics of the analytic population by sex are presented in table 6.2.

Table 6.2 Demographic characteristics

<table>
<thead>
<tr>
<th>Variables of interest</th>
<th>Female</th>
<th>Male</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>n=62 (45.6%)</td>
<td>n=74 (54.4%)</td>
</tr>
<tr>
<td>Demographic Characteristics</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TTF (months)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>median (25th, 75th percentile)</td>
<td>16 (7,52)</td>
<td>30 (11,76)</td>
</tr>
<tr>
<td>Age at ACLR</td>
<td></td>
<td></td>
</tr>
<tr>
<td>median (25th, 75th percentile)</td>
<td>17.5 (15,22.5)</td>
<td>19.0 (16,23)</td>
</tr>
<tr>
<td>&gt; 18 yrs</td>
<td>26 (41.9)</td>
<td>38 (51.4)</td>
</tr>
<tr>
<td>≤ 18 yrs</td>
<td>36 (58.1)</td>
<td>36 (48.6)</td>
</tr>
<tr>
<td>Marx activity score</td>
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<td></td>
</tr>
<tr>
<td>&lt;12</td>
<td>30 (48.4)</td>
<td>29 (39.2)</td>
</tr>
<tr>
<td>≥12</td>
<td>32 (51.6)</td>
<td>45 (60.8)</td>
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<tr>
<td>Surgical Characteristics (ACLR)</td>
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<td></td>
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<tr>
<td>Graft Type</td>
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<td></td>
</tr>
<tr>
<td>Autograft</td>
<td>39 (62.9)</td>
<td>58 (79.5)</td>
</tr>
<tr>
<td>Allograft</td>
<td>23 (37.1)</td>
<td>15 (20.5)</td>
</tr>
<tr>
<td>Graft Source</td>
<td></td>
<td></td>
</tr>
<tr>
<td>BTB</td>
<td>27 (60.0)</td>
<td>45 (70.3)</td>
</tr>
<tr>
<td>HS (ST+Gr)</td>
<td>18 (40.0)</td>
<td>19 (29.7)</td>
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<tr>
<td>Surgical Technique</td>
<td></td>
<td></td>
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<tr>
<td>Arthroscopic 2-incision</td>
<td>16 (26.2)</td>
<td>13 (17.8)</td>
</tr>
<tr>
<td>Arthroscopic 1-incision</td>
<td>45 (73.8)</td>
<td>60 (82.2)</td>
</tr>
<tr>
<td>Prior Medial Meniscus Surgery</td>
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<td></td>
</tr>
<tr>
<td>No</td>
<td>43 (69.4)</td>
<td>52 (70.3)</td>
</tr>
</tbody>
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Table 6.2 continued

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<thead>
<tr>
<th>Condition</th>
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<th>Yes</th>
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<td></td>
</tr>
<tr>
<td>No</td>
<td>51 (82.3)</td>
<td>53 (71.6)</td>
</tr>
<tr>
<td>Yes</td>
<td>11 (17.7)</td>
<td>21 (28.4)</td>
</tr>
<tr>
<td>Femoral Tunnel Position</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ideal</td>
<td>30 (48.4)</td>
<td>31 (42.5)</td>
</tr>
<tr>
<td>Compromised</td>
<td>32 (51.6)</td>
<td>42 (57.5)</td>
</tr>
<tr>
<td>Tibial Tunnel Position</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ideal</td>
<td>50 (80.6)</td>
<td>53 (72.6)</td>
</tr>
<tr>
<td>Compromised</td>
<td>12 (19.4)</td>
<td>20 (27.4)</td>
</tr>
</tbody>
</table>


Males accounted for 54.4% of the cohort. The median age at ACLR was similar for males and females (19 years and 17.5 years, respectively; p-value: 0.187). High activity level within the 12 months prior to failure, indicated by a patient-reported Marx Activity Score of 12 or greater, was most frequently reported (56.6% overall; males 60.8%, females 51.6%). The cohort predominately reported 12 or more years of education (82%), never having smoked (80%), and most commonly normal weight (46%) at the time of revision. The most common reported race was white (85%) followed by African-American (9%). A non-contact injury mechanism was reported by a majority of the cohort (57%; 61% of males, 53% of females). Prior ACLR was performed by the revising surgeon in 37% of the cases and most often occurred in the second decade of life (61%) (Figure 6.2). Revision ACLR most often occurred during the third decade (43% overall; ), again with similar median age at RACL between males (24 years, range 14-48 years) and females (22 years, range 10-58 years).
Intraoperative visualization of the graft at the time of revision found: 54% present, with the majority torn; 27% absent; 19% present, but elongated. Mode of failure, as deemed by the revising surgeon, was traumatic for 45%; technical, 19%; biologic, 13%; combination, 22% (surgeons marked all that applied); and unreported or missing, less than 2%. Biologic failure was previously defined in this cohort$^{92}$ as “lack of
incorporation of the graft as evidenced by early failure without a significant traumatic episode or obvious significant technical problems with the previous reconstruction.”

Technical failure was determined at the time of revision by the surgeon. Patient history, physical examination, radiographs, and arthroscopic evaluation were used to determine technical error. Surgeons were allowed to indicate more than one type of technical error. The most common technical error reported was femoral tunnel malposition (37%; as sole reason 26%, in combination with other factors 11%), followed by tibial tunnel malposition (9%; as sole reason 2%, in combination with other factors 7%). Prior femoral tunnel surgical technique was single tunnel 99% and double tunnel less than 1%. Prior femoral tunnel position was deemed ideal in 45% of the patients and compromised in 55%. The most common aspects of a compromised femoral tunnel were positions deemed too anterior (43%) and too vertical (39%). Prior tibial tunnel position was deemed ideal in 80%. The most common aspect of a compromised tibial tunnel was a position deemed too anterior or too posterior (63%).

Primary ACLR graft type was autograft 72% and allograft 28%. The most common autograft sources were BTB (62%) and HS (semitendinosis+gracilis) (37%). The most common allograft sources were tibialis anterior (42%) and BTB (29%). Prior surgical approach was arthroscopic single incision in 77%, rear entry 2-incision in 21%, and arthrotomy (mini- or traditional) less than 2%. Previous meniscal surgery was noted in 45% of patients; prior surgery involving solely the medial meniscus 21%, solely the lateral meniscus 15%, and both 9%. Excision accounted for 76% of previous medial meniscus surgeries and 84% of lateral meniscus surgeries.
6.3.2 Stratified analysis

Overall, the median time-to-failure from last reconstruction was 24 months. The TTF was less than 1 year in 35% of patients, between 1 and 2 years for 16%, and greater than 2 years in 49% of patients. Nearly 12% experienced a TTF of 10 years or more. The median TTF for females was less than males (16 and 30.5 months, respectively; p-value: 0.041). The distribution of failure times for females and males is presented in Figure 6.3. The goal of this study was to investigate the association between sex and TTF. It was assumed a priori that the activity level to which the patient returned following ACLR and graft type could potentially confound or modify the sex-TTF association; therefore associations were stratified on Marx activity level and graft type separately.

Sex by activity level

The TTF function for males and females differed significantly (Tarone-Ware p-value: 0.048) (Figure 6.4). Females had a shorter median TTF than did males (16 months, 95% CI:8.3-23.7 months and 30 months, 95% CI:15.2-44.8 respectively; Mann-Whitney p-value:0.041). When stratified on activity level (Figures 6.5 and 6.6), the difference was greater among those that reported a Marx score of 12 or higher (Tarone-Ware p-value: 0.015). Within this more active group females had a shorter median TTF
Figure 6.3 Time from ACL reconstruction to failure. TTF: time-to-failure.

than males (11 months, 95%CI: 6.85-15.15 months and 24 months, 95%CI: 17.43-60.57 months respectively, Mann-Whitney p-value: 0.004). A difference of TTF functions between the sexes was not observed among those reporting a Marx score less than 12 (Tarone-Ware p-value, 0.481). There was also no difference in median TTFs between males and females within this group (45 months, 95% CI: 32.7-57.3 months and 42 months, 95% CI: 17.9-66.2 months respectively; Mann-Whitney p-value: 0.549). A
greater proportion of females received allografts than did males (37.1% and 20.5%, respectively; p-value: 0.037). In order to investigate whether graft type was driving the difference in TTF rather than sex, survival functions of autograft and allograft patients were compared within each activity level strata. No difference of TTF functions between graft types was observed in either activity stratum (Marx <12, Tarone-ware p-value: 0.140; Marx ≥ 12, Tarone-Ware p-value: 0.584), suggesting the difference in TTF functions between females and males was effected by the disproportionate allograft use in female patients.
Figure 6.4 Survival functions by sex. TTF: time-to-failure. Median time-to-failure for females: 16 months, males: 30 months (Mann-Whitney test, p-value: 0.041). Tarone-Ware test for equality of survival functions, p-value: 0.048.
Figure 6.5 Survival functions by sex among those reporting a lower activity level (Marx < 12). TTF: time-to-failure. Median time-to-failure for females: 42 months, males: 45 months (Mann-Whitney test, p-value: 0.554). Tarone-Ware test for equality of survival functions, p-value: 0.481.
Figure 6.6 Survival functions by sex among those reported a high activity level (Marx 12+). TTF: time-to-failure. Median time-to-failure for females: 11 months, males: 24 months (Mann-Whitney p-value: 0.004). Tarone-Ware test for equality of survival functions, p-value: 0.003.
When stratified on graft type used in the previous ACLR (autograft and allograft), no difference of TFF functions between sexes was observed within the autograft group (Tarone-Ware p-value: 0.623, Figure 6.7). The median TTF was 26 months for males (95%CI: 16.4-35.6 months) and 19 months (95%CI: 3.7-34.3 months) for females (Mann-Whitney median test p-value: 0.541). However, among those that received an allograft, a significant difference of TTF functions between sexes was observed (Tarone-Ware p-value: 0.004, Figure 6.8). Females had a significantly shorter median TTF than males (12 months, 95% CI: 4.2-19.8 months and 51 months, 95% CI: 24.5-77.5 months respectively; Mann-Whitney p-value: 0.008).
Figure 6.7 Survival functions by sex among the autograft patients. TTF: time-to-failure. Median time-to-failure for females: 19 months, males: 26 months (Mann-Whitney median test p-value: 0.541). Tarone-Ware test for equality of survival functions, p-value: 0.623.
Figure 6.8 Survival functions by sex among the allograft patients. TTF: time-to-failure. Median time-to-failure for females: 12 months, males: 51 months (Mann-Whitney p-value: 0.008). Tarone-Ware test for equality of survival functions, p-value: 0.004.

6.4 Discussion

The current study investigated the effects of sex on time-to-graft failure accounting for activity level and graft type. While previous studies have suggested allograft use and high activity level are predictors of increased incidence of graft failure,
sex has not consistently been shown to be a factor.\textsuperscript{19, 32, 46, 86} No study has considered the modifying effect of graft type and activity level on the association of sex and time-to-graft failure. Results from the current study suggest that while the difference in survival functions between sexes was marginally significant, when stratified on activity level females that return to a high activity level following ACLR have a shorter TTF than their highly active male counterparts. This difference was not observed in those that returned to a less active level. In this study a disproportionate number of females received allografts compared to males. Despite this, no difference between autograft and allograft survival functions was found when similarly stratified on activity level, suggesting a difference between sexes and not graft type. Additionally, among those that received an allograft in their previous ACLR, females consistently had a shorter TTF than males. The results should be interpreted with caution as there were only 23 females and 15 males within the allograft group. The earlier time-to-failure among females may in fact be a result of the combination of allograft use and high activity level. Delayed incorporation of the allograft coupled with the patients feeling of being able to return to activity earlier, due to less pain and greater strength and mobility, may result in earlier failure. This association may be exacerbated by a return to a high level activity.

Although a prospective study may provide more reliable results, high enrollment and lengthy follow-up is needed to ensure an adequate number of graft failures, resulting in higher cost per case identified. The current study provides a method that can be applied to circumstances where a large number of failures have been previously identified. Also, this is the first study to investigate time-to-graft failure with a particular focus on male
and female differences at varying levels of activity and graft type. This study also involves the date of injury resulting in a clinic visit where graft failure was confirmed, allowing for a precise calculation of time-to-failure. A larger sample would allow for the creation of more complex survival models incorporating several covariates in order to assess multiple interactions simultaneously. Results suggest that graft type and activity level should be taken into account when investigating the timing of graft failure between males and females. Subsequent research should consider the interaction of sex, graft type, and activity level when attempting to identify predictors of early graft failure.

The current study does have limitations. Due to the time and labor intensive nature of chart review, only 3 sites were selected for inclusion, resulting in a small sample size. This subset accounts for 15% of the entire MARS population enrolled during the same period and may not be representative of the larger population of patients with graft failure. Information regarding activity level prior to ACLR was unavailable for this study, restricting the ability to investigate the effect a change in pre-ACLR activity level has on time-to-failure. However, Marx activity score collected at the time of the clinic visit provided information on the level to which the patient returned before graft failure. The decreased time to failure among those that returned to high activity found in this study can provide additional information to the patient when discussing post-ACLR risks. This information can be useful in a post-PACLR, physiotherapy setting as knowledge of the potential risk of early graft failure, associated with the desired level of activity may help guide rehabilitation. Also, data on postoperative rehabilitation protocol following primary ACLR were not available and could affect the timing of graft failure, however
standardized post-ACLR rehabilitation protocols are in place and assume to be followed at the 3 MARS member sites involved in this study.
Chapter 7: Conclusions, Implications, Closing Remarks

Anterior cruciate ligament injury is one of the most common injuries among athletes, frequently leading to reconstructive surgery. While most ACL reconstructions are successful, subsequent graft failure occurs and much like native ACL rupture, most likely results from multiple factors. Several studies have investigated factors associated with incidence of graft failure; however, no study has analyzed time-to-revision or time-to-failure, as the dependent outcome. This study describes patient and surgical characteristics of the largest collection of ACL graft failures in the US and identifies factors associated with early revision ACL reconstruction. It also investigates the modifying effect of graft type and activity level on the relationship between sex and graft failure.

The single most common mode of failure found in the study cohort was determined to be traumatic injury followed by technical error. Several previous studies have indicated that technical aspects were the most common cause of graft failure proposing that more than half of failures were due to technical factors.\textsuperscript{21, 27, 72, 137} These studies included technical failure as a broad category, not allowing for specific details on the type of technical failure. In this study the reporting surgeon was provided the option of indicating multiple modes of failure, resulting in combinations of factors which may explain the differences. In the current study a combination of factors was found to be the
most common overall cause in this cohort, representing nearly 35% of failures. This is larger than the traumatic (33%) and technical failure group (23%) and suggests the complex nature of graft failure. Femoral and tibial tunnel malposition were found to be the most common technical errors in this cohort and are general agreement with previous studies with delineated aspects of technical error. The present study provides a detailed description of femoral and tibial tunnel position and size, setting it apart from other studies investigating tunnel placement. Findings from this research indicate the most commonly cited femoral malposition among graft failure patients is one that is placed too anterior and the most common tibial malposition is one that is too anterior or posterior.

The time from last reconstruction was less than 1 year in 21% of patients, between 1 and 2 years for 22%, greater than 2 years for 57%. Nearly 14% of the total cohort had a time from last reconstruction of 10 years or more. Among patients without prior revision, the time from last reconstruction was less than 1 year in 22%, between 1 and 2 years for 21%, greater than 2 years for 57%. Fourteen percent of 1st revisions occurred 10 years or more after primary ACLR. Among patients with 1 or more prior revisions, time from last reconstruction was less than 1 year in 15%, between 1 and 2 years in 30%, and greater than 2 years in 55%. Eleven percent of this sub-group had revision surgery 10 years or more after previous reconstruction. The high percentage of revisions that occurred 10 years or more after the last reconstruction suggests longer follow-up times may be needed in primary ACLR outcome studies. A common belief is that if graft failure occurs it will occur within a short time period (24-36 months) following ACLR, in which time the
individual presumably regains full stability and returns to pre-injury activity levels. However, an increase in ACL re-injury rate has been reported with longer follow-up. At 5-year follow-up, Salmon et al.\textsuperscript{128} reported that 1 in 8.3 (12\%) individuals sustained a second ACL injury and at 10 year follow-up\textsuperscript{117} of the same cohort 1 in 3.7 (27\%) had sustained a second ACL injury. The high percentage of failures occurring 10 or more years after reconstruction warrants further study with the goal of answering the question: are there differentiating factors among those that have a revision 10 or more years after ACLR and those that have an earlier revision?

The effect of graft type on a wide range of outcomes has been investigated. In a meta-analysis involving 256 autograft and 278 allograft patients with at least 2 years of follow-up, the odds of graft failure were significantly higher for allografts compared to autografts (OR, 5.03; \( p=0.01 \)).\textsuperscript{79} In a 5-year prospective cohort study comparing outcomes for allograft and autograft reconstructions, Poehling et al.\textsuperscript{118,114} found that within the first 3 months following ACLR, the autograft group experienced increased pain and decreased knee function when compared to the allograft group. Over the entire 5-year period, the allograft group had significantly more knee laxity. These findings suggest that allograft patients may be more likely to return to high level activity early in the postoperative period because they have less pain and more knee function, placing them at higher risk for graft failure than autograft patients. These findings are consistent with the results of our study where allograft patients had higher odds of revision within the 30 months of PACLR.
Activity level has also been studied as a risk factor for ACL graft failure. Athletes that return to a high activity level have been shown to have a greater risk of ACL graft failure.\textsuperscript{20, 114, 128} Borchers et al.\textsuperscript{19} found high activity level and allograft use to be strong predictors of graft failure. While their finding of increased risk of failure due to a return to high activity is consistent with our study, it differs with respect to allograft use. Although their study was not designed to analyze when failures occurred, the reported median time from primary ACLR to failure was greater among allograft patients compared to autograft patients (12 and 9 months, respectively). This is counter to findings in the current study where median time to revision among allograft and autograft was 28 and 33 months, respectively, and that allograft patients had nearly two and half times the odds of revision within 30 months of PACLR. This discrepancy may be due to the different outcomes, failure and revision, and additional studies investigating the effect of graft choice on the time from failure to revision may be needed.

Previous studies have also shown an association between a younger age at PACLR and subsequent re-injury. Shelbourne et al.\textsuperscript{135} found patients less than 18 years of age at the time of ACLR had the highest risk of graft failure when compared to those aged 18-25 and older than 25. They also found that among this younger age group, 72% returned to full activity before 6 months post-ACLR (mean, 4.6±1.9 months), a standard time frame for ACLR postoperative rehabilitation. This additional finding may partially explain the greater incidence of failure. Younger age at the time of ACLR has also been proposed as a predictor for revision ACLR within 24 months.\textsuperscript{86} Results from the current study indicate that among a population of graft failures, a younger age at PACLR is also
associated with revision within 30 months post-ACLR. Results of our study indicate increased odds of revision within 30 months of PACLR for hamstring with semitendinosis plus gracilis and prior lateral meniscus surgery. A decreased odds of early revision was found among femoral tunnel positions deemed too anterior or too vertical. These additional factors should be considered in future studies investigating time-to-revision or time-to-graft failure.

In addition, findings of the current study suggest that while the difference in survival functions between sexes was marginally significant, when stratified on activity level females that return to a high activity level following ACLR have a shorter TTF than their highly active male counterpart. This difference was not observed in those that returned to a less active level. In this study a disproportionate number of females received allografts compared to males. Despite this, no difference between autograft and allograft survival functions was found when similarly stratified on activity level, suggesting a difference between sexes and not graft type. Additionally, among those that received an allograft in their previous ACLR, females consistently had a shorter TTF than males. The results should be interpreted with caution as there were only 23 females and 15 males within the allograft group.

While a prospective study may provide more reliable results, high enrollment and lengthy follow-up is needed to ensure an adequate number of graft failures, resulting in higher cost per case obtained. The current study provides a method that can be applied to situations where a large number of failures have been previously obtained and recorded. Also, this is the first study to investigate time-to-graft failure with a particular focus on
male and female differences at varying levels of activity and graft type. This study also involves very precise and accurate data on time-to-failure. A larger sample would allow for the creation of more complex survival models incorporating several covariates in order to assess multiple interactions simultaneously. Results suggest that graft type and activity level should be taken into account when investigating the timing of graft failure between males and females. Subsequent research should consider the interaction of sex, graft type, and activity level when attempting to identify predictors of early graft failure.
References


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142. Spindler KP: The Multicenter ACL Revision Study (MARS): a prospective longitudinal cohort to define outcomes and independent predictors of outcomes.


Appendix A: Participating MARS locations

United States
California (3)
   Scripps Memorial Hospital (OrthoCal Healthcare)
   University of California - Los Angeles (UCLA)
   University of California - San Francisco
Colorado (2)
   Orthopaedic Associates of Aspen and Glenwood
   University of Colorado
Connecticut (2)
   Connecticut Children's Medical Center
   University of Connecticut Health Center
Florida (1)
   UHZ Sports Medicine Institute
Idaho (1)
   Intermountain Orthopaedics
Illinois (2)
   Rush University Medical Center
   American Orthopaedic Society for Sports Medicine (AOSSM)
Indiana (1)
   Methodist Sports Medicine Center
Iowa (1)
   University of Iowa
Maryland (1)
   Cheaspeake Orthopaedics and Sports Medicine Center
Massachusetts (1)
   Beth Israel Deaconess Medical Center
Michigan (1)
   University of Michigan
Minnesota (2)
   Mayo Clinic
   Regions Hospital (Health Partners Research Foundation)
Missouri (3)
   Washington University at St. Louis
   Montana
   Bridger Orthopaedic and Sports Medicine
New Hampshire (1)
   New Hampshire Knee Center
New Jersey (2)
   Robert Wood Johnson Medical School
   Princeton Orthopaedic Associates
New York (5)
   University of Buffalo
   Hospital for Special Surgery
   Manhattan Orthopaedics, P.C.
   NYU School of Medicine
<table>
<thead>
<tr>
<th>State</th>
<th>Institutions</th>
</tr>
</thead>
<tbody>
<tr>
<td>North Carolina</td>
<td>Keller Army Community Hospital - USMA</td>
</tr>
<tr>
<td></td>
<td>University of North Carolina Medical Center</td>
</tr>
<tr>
<td></td>
<td>Perry Orthopaedics and Sports Med (Carolinas Healthcare System)</td>
</tr>
<tr>
<td>Ohio</td>
<td>Cleveland Clinic</td>
</tr>
<tr>
<td></td>
<td>University Hospitals of Cleveland (Case Western)</td>
</tr>
<tr>
<td></td>
<td>The Ohio State University</td>
</tr>
<tr>
<td>Oregon</td>
<td>Slocum Research and Education Foundation</td>
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<tr>
<td></td>
<td>Orthopaedic and Fracture Clinic</td>
</tr>
<tr>
<td>Pennsylvania</td>
<td>Booth, Bartolozzi, Balderston Orthopaedics</td>
</tr>
<tr>
<td></td>
<td>The Rothman Institute / Thomas Jefferson University</td>
</tr>
<tr>
<td></td>
<td>University of Pittsburgh</td>
</tr>
<tr>
<td>South Dakota</td>
<td>Orthopaedic Institute</td>
</tr>
<tr>
<td>Tennessee</td>
<td>Southeastern Orthopaedics / Knoxville Orthopaedic Clinic</td>
</tr>
<tr>
<td></td>
<td>Vanderbilt University</td>
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<tr>
<td></td>
<td>Tennessee Orthopaedic Alliance</td>
</tr>
<tr>
<td>Texas</td>
<td>W.B. Carroll Memorial Clinic</td>
</tr>
<tr>
<td>Vermont</td>
<td>University of Vermont College of Medicine</td>
</tr>
<tr>
<td>Virginia</td>
<td>National Sports Medicine Institute</td>
</tr>
<tr>
<td></td>
<td>Town Center Orthopaedic Associates</td>
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<tr>
<td></td>
<td>Commonwealth Orthopaedics and Rehabilitation</td>
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<tr>
<td>Washington</td>
<td>Inland Orthopaedics/Washington State University</td>
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<tr>
<td>Canada</td>
<td>British Columbia (1)</td>
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<td></td>
<td>Royal Columbian Hospital (FraserHealth)</td>
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<tr>
<td>Ontario</td>
<td>Fowler Kennedy Sports Medicine Clinic/Univ. of Western Ontario</td>
</tr>
</tbody>
</table>
Appendix B: MOON-MARS patient questionnaire
**MOON / MARS STUDY**

**Patient Information**

<table>
<thead>
<tr>
<th>First Name</th>
<th>Middle Name</th>
<th>Last Name</th>
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<table>
<thead>
<tr>
<th>Number &amp; Street Address</th>
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<table>
<thead>
<tr>
<th>Number &amp; Street Address (continued)</th>
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<table>
<thead>
<tr>
<th>City</th>
<th>State</th>
<th>Zip Code</th>
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<table>
<thead>
<tr>
<th>Phone Number</th>
<th>Cell Phone</th>
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<td>( )-<strong><strong>-</strong></strong></td>
<td>( )-<strong><strong>-</strong></strong></td>
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<tr>
<th>Primary Email Address</th>
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<tr>
<th>Secondary Email Address</th>
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</table>

**Which knee is being operated on?**
- [ ] Right
- [ ] Left
- [ ] Both

**Gender:**
- [ ] Male
- [ ] Female

**Are you a twin?**
- [ ] No
- [ ] Yes

**Has anyone in your family had an ACL tear and/or ACL surgery?**
- [ ] Yes
  - [ ] Parent
  - [ ] Child
  - [ ] Brother / Sister
  - [ ] Aunt / Uncle
  - [ ] Cousin
- [ ] No

**Date of Birth**

<table>
<thead>
<tr>
<th>M</th>
<th>M</th>
<th>M</th>
<th>Y</th>
<th>Y</th>
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</table>

**Date of Surgery**

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<th>D</th>
<th>D</th>
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<th>Y</th>
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**Today's Date**

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</table>

**Age**

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</tr>
</tbody>
</table>

**Marital status:**
- [ ] Single
- [ ] Widowed
- [ ] Married
- [ ] Separated
- [ ] Divorced

**Ethnicity / Race:**
- [ ] American Indian
- [ ] Asian
- [ ] Black / African American
- [ ] Hispanic
- [ ] Native Hawaiian / Pacific Islander
- [ ] White
- [ ] Other

---

_Sometimes people move to new places. It would be helpful if you would provide us with the name and address of someone who doesn't live with you and could give us your new contact information should you decide to move. When it is time to send you the follow-up surveys, we would only contact this person if we are unable to get in touch with you._

Name __________________________

Address __________________________

City, State, Zip ___________/_________/____ Phone (____)____-____ Cell (____)____-____

Email __________________________

Relationship to you __________________________

---

**THANK YOU VERY MUCH!**

**Each Site should complete the following:**

**Registration Number**

<p>| | | | | | |</p>
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<thead>
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</tbody>
</table>

**Type of ACL Surgery:**
- [ ] Primary (MIRROR Study)
- [ ] Revision (MARS Study)
- [ ] Other

**Timepoint:**
- [ ] Initial
- [ ] 6 yrs
- [ ] 2 yrs
- [ ] 10 yrs

---

Page 1
Please answer the following questions about both your left and right knees:

<table>
<thead>
<tr>
<th>LEFT KNEE</th>
<th>RIGHT KNEE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Have you had surgery on this knee(s)? □ No □ Yes □ No □ Yes</td>
<td>□ No □ Yes</td>
</tr>
<tr>
<td>If so, what was the most recent surgery date? M M / D D / Y Y Y Y</td>
<td>M M / D D / Y Y Y Y</td>
</tr>
<tr>
<td>2. Have you ever had a severe injury to this knee? □ No □ Yes □ No □ Yes</td>
<td>□ No □ Yes</td>
</tr>
<tr>
<td>If so, what was the date? M M / D D / Y Y Y Y</td>
<td>M M / D D / Y Y Y Y</td>
</tr>
<tr>
<td>3. When did your knee pain start? (Indicate only month or year if you can't remember the exact date) M M / D D / Y Y Y Y</td>
<td>M M / D D / Y Y Y Y</td>
</tr>
</tbody>
</table>

If you answered "No" to both Questions #1 and #2, please continue to Question S1 on page 3. If you answered "Yes" to either Question #1 or #2, please continue to Question #4 below.

<table>
<thead>
<tr>
<th>LEFT KNEE</th>
<th>RIGHT KNEE</th>
</tr>
</thead>
<tbody>
<tr>
<td>4. Were you playing a sport at the time of injury? □ No □ Yes □ No □ Yes</td>
<td>□ No □ Yes</td>
</tr>
<tr>
<td>If NO, was it during: □ Activities of daily living (going down the stairs, for example) □ Work □ Traffic accident □ Other</td>
<td>□ Activities of daily living (going down the stairs, for example) □ Work □ Traffic accident □ Other</td>
</tr>
<tr>
<td>If YES, was it during: □ Football □ Basketball □ Gymnastics □ Skating □ Baseball / Softball □ Soccer □ Other</td>
<td>□ Football □ Basketball □ Gymnastics □ Skating □ Baseball / Softball □ Soccer □ Other</td>
</tr>
</tbody>
</table>

At the time of injury...

5. Did it involve contact with another player? □ Yes □ No □ Yes □ No
6. Were you able to continue playing? □ Yes □ No □ Yes □ No
7. Were you jumping? □ Yes □ No □ Yes □ No
8. Did you hear or feel a "pop"? □ Yes □ No □ Yes □ No
9. How long until your knee began to swell? □ None □ < 1 Hr □ 1-8 Hrs □ > 8 Hrs □ None □ < 1 Hr □ 1-8 Hrs □ > 8 Hrs
10. How many "giving way" episodes have you had in total? (0 = no episodes) □ (number) □ (number)
11. How many times has your knee(s) been swollen? (0 = none) □ (number) □ (number)
12. What is the total number of injuries you have had to your knee(s)? (0 = none) □ (number) □ (number)
This survey asks for your view about your knee. This information will help us keep track of how you feel about your knee and how well you are able to do your usual activities.

Answer every question by filling in the appropriate box, only one box for each question. If you are unsure about how to answer a question, please give the best answer you can.

**Symptoms**

These questions should be answered thinking of your knee symptoms during the last week.

<table>
<thead>
<tr>
<th>Question</th>
<th>Never</th>
<th>Rarely</th>
<th>Sometimes</th>
<th>Often</th>
<th>Always</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1. Do you have swelling in your knee?</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
</tr>
<tr>
<td>S2. Do you feel grinding, hear clicking or any other type of noise when your knee moves?</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
</tr>
<tr>
<td>S3. Does your knee catch or hang up when moving?</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
</tr>
<tr>
<td>S4. Can you straighten your knee fully?</td>
<td>Always</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
</tr>
<tr>
<td>S5. Can you bend your knee fully?</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
</tr>
</tbody>
</table>

**Stiffness**

The following questions concern the amount of joint stiffness you have experienced during the last week in your knee. Stiffness is a sensation of restriction or slowness in the ease with which you move your knee joint.

<table>
<thead>
<tr>
<th>Question</th>
<th>None</th>
<th>Mild</th>
<th>Moderate</th>
<th>Severe</th>
<th>Extreme</th>
</tr>
</thead>
<tbody>
<tr>
<td>S6. How severe is your knee joint stiffness after first waking in the morning?</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
</tr>
<tr>
<td>S7. How severe is your knee stiffness after sitting, lying, or resting later in the day?</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
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</tbody>
</table>

**Pain**

How often do you experience knee pain?

<table>
<thead>
<tr>
<th></th>
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<tbody>
<tr>
<td></td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
</tr>
</tbody>
</table>

What amount of knee pain have you experienced the last week during the following activities?

<table>
<thead>
<tr>
<th>P2. Twisting/pivoting on your knee</th>
<th>None</th>
<th>Mild</th>
<th>Moderate</th>
<th>Severe</th>
<th>Extreme</th>
</tr>
</thead>
<tbody>
<tr>
<td>P3. Straightening knee fully</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
</tr>
<tr>
<td>P4. Bending knee fully</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
</tr>
<tr>
<td>P5. Walking on flat surface</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
</tr>
<tr>
<td>P6. Going up or down stairs</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
</tr>
<tr>
<td>P7. At night while in bed</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
</tr>
<tr>
<td>P8. Sitting or lying</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
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<tr>
<td>P9. Standing upright</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
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</tbody>
</table>
The following questions concern your physical function. By this we mean your ability to move around and to look after yourself. For each of the following activities, please indicate the degree of difficulty you have experienced in the last week due to your knee.

<table>
<thead>
<tr>
<th>Activity</th>
<th>None</th>
<th>Mild</th>
<th>Moderate</th>
<th>Severe</th>
<th>Extreme</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1. Descending stairs</td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>A2. Ascending stairs</td>
<td></td>
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<tr>
<td>For each of the following activities please indicate the degree of difficulty you have experienced in the last week due to your knee.</td>
<td></td>
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<tr>
<td>A3. Rising from sitting</td>
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<tr>
<td>A4. Standing</td>
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<tr>
<td>A5. Bending to floor/pick up an object</td>
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<tr>
<td>A6. Walking on flat surface</td>
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<td>A7. Getting in/out of car</td>
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<td>A8. Going shopping</td>
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<tr>
<td>A9. Putting on sock/stockings</td>
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<tr>
<td>A10. Rising from bed</td>
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<td>A11. Taking off sock/stockings</td>
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<tr>
<td>A12. Lying in bed (turning over, maintaining knee position)</td>
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<tr>
<td>A13. Getting in/out of bath</td>
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<tr>
<td>A14. Sitting</td>
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<tr>
<td>A15. Getting on/off toilet</td>
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<tr>
<td>For each of the following activities please indicate the degree of difficulty you have experienced in the last week due to your knee.</td>
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<tr>
<td>A16. Heavy domestic duties (moving heavy boxes, scrubbing floors, etc.)</td>
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<tr>
<td>A17. Light domestic duties (cooking, dusting, etc.)</td>
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</tbody>
</table>

The following questions concern your physical function when being active on a higher level. The questions should be answered thinking of what degree of difficulty you have experienced during the last week due to your knee.

<table>
<thead>
<tr>
<th>Activity</th>
<th>None</th>
<th>Mild</th>
<th>Moderate</th>
<th>Severe</th>
<th>Extreme</th>
</tr>
</thead>
<tbody>
<tr>
<td>SP1. Squatting</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SP2. Running</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SP3. Jumping</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SP4. Twisting/pivoting of your injured knee</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SP5. Kneeling</td>
<td></td>
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<td></td>
<td></td>
</tr>
</tbody>
</table>
Quality of Life

Q1: How often are you aware of your knee problem?  

- Never  
- Monthly  
- Weekly  
- Daily  
- Constantly

Q2: Have you modified your lifestyle to avoid potentially damaging activities to your knee?  

- Not at All  
- Mildly  
- Moderately  
- Severely  
- Totally

Q3: How much are you troubled with lack of confidence in your knee?  

- Not at All  
- Mildly  
- Moderately  
- Severely  
- Extremely

Q4: In general, how much difficulty do you have with your knee?  

- None  
- Mild  
- Moderate  
- Severe  
- Extreme

Please indicate how often you performed each activity in your healthiest and most active state, in the past year.

<table>
<thead>
<tr>
<th>Activity</th>
<th>Less than one time in a month</th>
<th>One time in a month</th>
<th>One time in a week</th>
<th>2 or 3 times in a week</th>
<th>4 or more times in a week</th>
</tr>
</thead>
<tbody>
<tr>
<td>Running</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cutting</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Decelerating</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pivoting</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
1. In general, would you say your health is: □ Excellent □ Very Good □ Good □ Fair □ Poor

2. Compared to 1 year ago, how would you rate your health in general now? □ Much better now than 1 year ago □ Somewhat better now than 1 year ago □ About the same as 1 year ago □ Somewhat worse now than 1 year ago □ Much worse now than 1 year ago

3. The following questions are about activities you might do during a typical day. Does your health now limit you in these activities? If so, how much?

<table>
<thead>
<tr>
<th>Activity</th>
<th>Yes, limited a lot</th>
<th>Yes, limited a little</th>
<th>No, not limited at all</th>
</tr>
</thead>
<tbody>
<tr>
<td>a. Vigorous activities, such as running, lifting heavy objects, participating in strenuous sports</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>b. Moderate activities, such as moving a table, pushing a vacuum cleaner, bowling or playing golf</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>c. Lifting or carrying groceries</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>d. Climbing several flights of stairs</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>e. Climbing one flight of stairs</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>f. Bending, kneeling or stooping</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>g. Walking more than a mile</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>h. Walking several hundred yards</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>i. Walking one hundred yards</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>j. Bathing or dressing yourself</td>
<td></td>
<td></td>
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</tbody>
</table>

4. During the past 4 weeks, how much of the time have you had any of the following problems with your work or other regular daily activities as a result of your physical health?

<table>
<thead>
<tr>
<th>Problem</th>
<th>All of the time</th>
<th>Most of the time</th>
<th>Some of the time</th>
<th>A little of the time</th>
<th>None of the time</th>
</tr>
</thead>
<tbody>
<tr>
<td>a. Cut down on the amount of time you spent on work or other activities</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>b. Accomplished less than you would like</td>
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<tr>
<td>c. Were limited in the kind of work or other activities</td>
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<tr>
<td>d. Had difficulty performing the work or other activities</td>
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</tr>
</tbody>
</table>

5. During the past 4 weeks, how much of the time have you had any of the following problems with your work or other regular daily activities as a result of any emotional problems (such as feeling depressed or anxious)?

<table>
<thead>
<tr>
<th>Problem</th>
<th>All of the time</th>
<th>Most of the time</th>
<th>Some of the time</th>
<th>A little of the time</th>
<th>None of the time</th>
</tr>
</thead>
<tbody>
<tr>
<td>a. Cut down on the amount of time you spent on work or other activities</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>b. Accomplished less than you would like</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>c. Did work or other activities less carefully than usual</td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>
6. During the past 4 weeks, to what extent has your physical health or emotional problems interfered with your normal social activities with family, friends, neighbors, or groups?
   - Not at all
   - Slightly
   - Moderately
   - Quite a bit
   - Extremely

7. How much bodily pain have you had during the past 4 weeks?
   - None
   - Very Mild
   - Mild
   - Moderate
   - Severe
   - Very severe

8. During the past 4 weeks, how much did pain interfere with your normal work (including both work outside the home and housework)?
   - Not at all
   - A little bit
   - Moderately
   - Quite a bit
   - Extremely

9. These questions are about how you feel and how things have been with you during the past 4 weeks. For each question, please give the one answer that comes closest to the way you have been feeling. How much of the time during the past 4 weeks...

   a. did you feel full of life?
   b. have you been very nervous?
   c. have you felt a lot down in the dumps that nothing could cheer you up?
   d. have you felt calm and peaceful?
   e. did you have a lot of energy?
   f. have you felt downhearted and depressed?
   g. did you feel worn out?
   h. have you been happy?
   i. did you feel tired?

10. During the past 4 weeks, how much of the time has your physical health or emotional problems interfered with your social activities (like visiting friends, relatives, etc.)?
   - All of the time
   - Most of the time
   - Some of the time
   - A little of the time
   - None of the time

11. How TRUE or FALSE is each of the following statements for you?

   a. I seem to get sick a little easier than other people
   b. I am as healthy as anybody I know
   c. I expect my health to get worse
   d. My health is excellent
Symptoms*:
* Grade symptoms at the highest activity level at which you think you could function without significant symptoms, even if you are not actually performing activities at this level.

1. What is the highest level of activity that you can perform without significant knee pain?
   - [ ] Very strenuous activities like jumping or pivoting as in basketball or soccer
   - [ ] Strenuous activities like heavy physical work, skiing or tennis
   - [ ] Moderate activities like moderate physical work, running or jogging
   - [ ] Light activities like walking, housework, or yard work
   - [ ] Unable to perform any of the above activities due to knee pain

2. During the past 4 weeks, or since your injury, how often have you had pain?
   0  1  2  3  4  5  6  7  8  9  10  Constant
   Never

3. If you have pain, how severe is it?
   0  1  2  3  4  5  6  7  8  9  10  Worst pain imaginable
   No pain

4. During the past 4 weeks, or since your injury, how stiff or swollen was your knee?
   - [ ] Not at all
   - [ ] Mildly
   - [ ] Moderately
   - [ ] Very
   - [ ] Extremely

5. What is the highest level of activity you can perform without significant swelling in your knee?
   - [ ] Very strenuous activities like jumping or pivoting as in basketball or soccer
   - [ ] Strenuous activities like heavy physical work, skiing or tennis
   - [ ] Moderate activities like moderate physical work, running or jogging
   - [ ] Light activities like walking, housework, or yard work
   - [ ] Unable to perform any of the above activities due to knee swelling

6. During the past 4 weeks, or since your injury, did your knee lock or catch?
   - [ ] Yes
   - [ ] No

7. What is the highest level of activity you can perform without significant giving way in your knee?
   - [ ] Very strenuous activities like jumping or pivoting as in basketball or soccer
   - [ ] Strenuous activities like heavy physical work, skiing or tennis
   - [ ] Moderate activities like moderate physical work, running or jogging
   - [ ] Light activities like walking, housework, or yard work
   - [ ] Unable to perform any of the above activities due to giving way of the knee
Sports Activities:

8. What is the highest level of activity you can participate in on a regular basis?
   - □ Very strenuous activities like jumping or pivoting as in basketball or soccer
   - □ Strenuous activities like heavy physical work, skiing or tennis
   - □ Moderate activities like moderate physical work, running or jogging
   - □ Light activities like walking, housework, or yard work
   - □ Unable to perform any of the above activities due to knee

9. How does your knee affect your ability to:
   a. Go up stairs
   b. Go down stairs
   c. Kneel on the front of your knee
   d. Squat
   e. Sit with your knee bent
   f. Rise from a chair
   g. Run straight ahead
   h. Jump and land on your involved leg
   i. Stop and start quickly

<table>
<thead>
<tr>
<th>Function</th>
<th>Not difficult at all</th>
<th>Minimally difficult</th>
<th>Moderately difficult</th>
<th>Extremely difficult</th>
<th>Unable to do</th>
</tr>
</thead>
</table>

FUNCTION
10. How would you rate the function of your knee on a scale of 0 to 10 with 10 being normal, excellent function and 0 being the inability to perform any of your usual daily activities which may include sports?

FUNCTION PRIOR TO YOUR KNEE INJURY:

<table>
<thead>
<tr>
<th>Cannot perform daily activities</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>□</td>
<td>□</td>
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<td>□</td>
<td>□</td>
</tr>
</tbody>
</table>

CURRENT FUNCTION OF YOUR KNEE

<table>
<thead>
<tr>
<th>Cannot perform daily activities</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>□</td>
<td>□</td>
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<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
</tr>
</tbody>
</table>
Sports Activities:

11. What sport have you participated in the most time over the last 2 years? *(Please select only one)*

- [ ] None
- [ ] Baseball / Softball
- [ ] Basketball
- [ ] Skiing
- [ ] Football
- [ ] Soccer
- [ ] Gymnastics
- [ ] Other ______________
- [ ] Volleyball

12. What is the highest or most advanced level you achieved in that sport in the last 2 years? *(Please select only one)*

- [ ] None
- [ ] College - NCAA Div. I
- [ ] Recreational
- [ ] Semi-Pro (Minor league, Arena)
- [ ] Amateur (team or club)
- [ ] Pro (NFL)
- [ ] High School
- [ ] College - not NCAA Div. I

13. What second sport have you participated in most over the last 2 years? *(Please select only one)*

- [ ] None
- [ ] Baseball / Softball
- [ ] Basketball
- [ ] Skiing
- [ ] Football
- [ ] Soccer
- [ ] Gymnastics
- [ ] Other ______________
- [ ] Volleyball

14. What is the highest or most advanced level you achieved in that sport in the last 2 years? *(Please select only one)*

- [ ] None
- [ ] College - NCAA Div. I
- [ ] Recreational
- [ ] Semi-Pro (Minor league, Arena)
- [ ] Amateur (team or club)
- [ ] Pro (NFL)
- [ ] High School
- [ ] College - not NCAA Div. I

15. What is the highest or most advanced level at any time since your injury you have achieved in sports?

- [ ] None
- [ ] College - NCAA Div. I
- [ ] Recreational
- [ ] Semi-Pro (Minor league, Arena)
- [ ] Amateur (team or club)
- [ ] Pro (NFL)
- [ ] High School
- [ ] College - not NCAA Div. I

Name level/league = __________________________
**COMMON HEALTH PROBLEMS:**

The following is a list of common health problems. Please indicate yes in the first column if you **do** have the problem. If you **do not** have the problem, go to the next health problem. If you do have the problem, please indicate in the second column if you receive medications or some other type of treatment for the problem. In the third column, indicate if the problem limits any of your activities. In the last column indicate the year or your age when the problem began.

<table>
<thead>
<tr>
<th>Problem</th>
<th>Do you have the problem?</th>
<th>Do you receive treatment for it?</th>
<th>Does it limit your activities?</th>
<th>When did this problem begin?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heart disease</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>Year or Age</td>
</tr>
<tr>
<td>High blood pressure</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td></td>
</tr>
<tr>
<td>Asthma or pulmonary disease</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td></td>
</tr>
<tr>
<td>Diabetes</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td></td>
</tr>
<tr>
<td>Ulcer or stomach disease</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td></td>
</tr>
<tr>
<td>Bowel disease</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td></td>
</tr>
<tr>
<td>Kidney disease</td>
<td>☐</td>
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<td>☐</td>
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<tr>
<td>Liver disease</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td></td>
</tr>
<tr>
<td>Anemia or other blood disease</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td></td>
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<tr>
<td>Overweight</td>
<td>☐</td>
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<td>☐</td>
<td></td>
</tr>
<tr>
<td>Cancer</td>
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<td>☐</td>
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<tr>
<td>Depression</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
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<tr>
<td>Osteoarthritis, degenerative arthritis</td>
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<td>☐</td>
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<tr>
<td>Rheumatoid arthritis</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td></td>
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<tr>
<td>Back pain</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td></td>
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<tr>
<td>Lyme disease</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td></td>
</tr>
<tr>
<td>Other medical problem</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td></td>
</tr>
<tr>
<td>Alcoholism</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td></td>
</tr>
</tbody>
</table>

1. Do you smoke cigarettes?
   - ☐ Yes
   - ☐ No, I quit in the last six months
   - ☐ No, I quit more than six months ago
   - ☐ No, I have never smoked

2. Your height: ☐' ☐' ☐'

1. Have you experienced swelling in any of the following joints over the last week? □ No □ Yes
   If "No", go to question 2.
   If "Yes", please check below the joints in which you have had swelling over the last week:
   - Hand(s) and Wrist(s) □ □
   - Elbow(s) □ □
   - Shoulder(s) □ □
   - Hip(s) □ □
   - Foot(s) and Ankle(s) □ □
   - Back □ □
   - Neck □ □

2. Have you had any knee joint injections since your surgery? □ No □ Yes
   If "No", go to question 3.
   If "Yes", please indicate which knee it involved and the year(s) that it occurred:

<table>
<thead>
<tr>
<th>Injection?</th>
<th>Year</th>
<th>Injection?</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yes</td>
<td></td>
<td>Yes</td>
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<td>□</td>
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<td>□</td>
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<td>□</td>
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</tbody>
</table>

3. Have you used any type of topical cream or balm to your surgical knee in the past 4 weeks? □ No □ Yes
   If yes, please list the type and frequency below.
   Name of cream: ____________________________ Times per week: __________

4. Have you used any type of brace or sleeve on your involved knee in the past 4 weeks? □ No □ Yes
   If yes, please list the type and frequency of use below.

<table>
<thead>
<tr>
<th>Type of Brace/Sleeve</th>
<th>Times Per Week</th>
<th>Activities Performed</th>
</tr>
</thead>
<tbody>
<tr>
<td>□ Functional knee brace</td>
<td></td>
<td></td>
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<tr>
<td>□ Unloader brace for arthritis</td>
<td></td>
<td></td>
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<tr>
<td>□ Sleeve</td>
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<tr>
<td>□ Collateral brace</td>
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</tbody>
</table>
5. Please write below all the drugs or medicines you have taken over the last **four weeks** (include aspirin, birth control pills, and any drug or medicine with or without prescription):

<table>
<thead>
<tr>
<th>NAME OF DRUG OR MEDICINE</th>
<th>DOSE (If known)</th>
<th>How many per day</th>
<th>How many per week</th>
</tr>
</thead>
<tbody>
<tr>
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</tbody>
</table>

(Please list any others on a separate page)

6. Do any of these drugs cause you side effects?  □ No  □ Yes

If "Yes", please write the drug(s) and the side effect(s) below:

<table>
<thead>
<tr>
<th>DRUG</th>
<th>SIDE EFFECT(S)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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</tbody>
</table>

7. What is your current occupation?  (If you are not working now, what was your past occupation?)

<p>| | |</p>
<table>
<thead>
<tr>
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<tbody>
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</tr>
</tbody>
</table>

8. At this time, are you?

□ Working full time
□ Working part time
□ Homemaker
□ Retired
□ Student
□ Disabled
□ Other (describe): __________________________

9. Estimate the average number of hours you work per week:

□□□□

10. How many other people live at home with you? □□□□

(check all that apply)

□ I live alone
□ Parents
□ Spouse / partner
□ Sons or daughters
□ Brothers or sisters
□ Others (describe): __________________________

11. How many years of school have you completed?  (e.g. 1=1st grade, 12=high school senior, 13=freshman in college, etc.)

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>9</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>11</td>
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</table>

**END OF QUESTIONNAIRE**

**THANK YOU!**
Appendix C: MOON-MARS surgeon questionnaire
MOON / MARS STUDY
SURGEON FORM

Reconstruction Type:  Operated Side:
☐ Primary ACL (MOON Study)  ☐ Right
☐ Revision ACL (MARS Study)  ☐ Left
☐ Other: ________________________

Surgeon Initials: F M L

Patient Initials: ________________________

Date of Surgery: M M / D D / Y E A R

Patient's Date of Birth: M M / D D / Y E A R

Medical Record #: ________________________

1a. CONTRALATERAL KNEE (Surgeon asks the patient):
   - Normal
   - Nearly normal
   - Abnormal
   - Severely abnormal

1b. MECHANISM OF INJURY (from the patient’s perception):
   - Non-traumatic; GRADUAL onset
   - Non-traumatic; SUDDEN onset
   - Traumatic; NON-CONTACT onset
   - Traumatic; CONTACT onset

2. INFLAMMATORY ARTHRITIS (i.e. Rheumatoid):
   - No
   - Yes

3a. MRI taken?  3b. Does a bone bruise exist?  3c. If yes, in which compartment?
   - No  No  Lateral femoral condyle
   - Yes  Yes  Lateral tibial plateau
          No  Other

4. PREVIOUS SURGERY (either knee):
   - No If no, please proceed to QUESTION #12 (page 4)
   - Yes If yes, which side?  ☐ Right  ☐ Left  ☐ Both

Page 1

156
### TYPE OF PREVIOUS SURGERY (Check ALL that apply)

5. **MENISCUS SURGERY:**

<table>
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<tr>
<th></th>
<th>Right</th>
<th>Left</th>
<th>Medial</th>
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<td>MM Repair</td>
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<td>MM Transplant</td>
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<td>LM Debridement</td>
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<td>LM Repair</td>
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<td>LM Transplant</td>
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6. **LIGAMENT SURGERY:**

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<th>ACL</th>
<th></th>
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<td></td>
<td>Single Hamstring</td>
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<td>2 Bundle Hamstring</td>
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<td>4 Bundle Hamstring</td>
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<td>Quad Tendon</td>
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<td>MCL Repair/Reconst</td>
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<td>LCL Repair/Reconst</td>
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7. **EXTENSOR MECHANISM SURGERY:**

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<td>Medial Imbrication Soft Tissue Realignment</td>
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<td>Lateral Release</td>
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<td>Tibial Tuberosity Movement</td>
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<td>Trochieoplasty</td>
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<td>Patellecocy</td>
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</table>

If Yes, check ALL that apply:

- proximal
- distal
- anterior
- medial
- lateral
8. OSTEOARTHRITIS SURGERY:

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<tr>
<th>Right</th>
<th>Left</th>
<th>Osteotomy</th>
<th>Knee Replacement</th>
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</thead>
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9a. NUMBER OF PREVIOUS ARTICULAR CARTILAGE SURGERIES:

9b. ARTICULAR SURFACE SURGERY:

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<thead>
<tr>
<th>Right</th>
<th>Left</th>
<th>Type</th>
<th>Location</th>
<th>MFC</th>
<th>MTP</th>
<th>LFC</th>
<th>LTP</th>
<th>PAT</th>
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<td>☐</td>
<td>Other (i.e. infection)</td>
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10. ARTHROSCOPIC AND/OR OPEN DEBRIDEMENTS FOR INFECTION:

<table>
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<tr>
<th>Right</th>
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<th>If yes, # of debridements:</th>
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</table>

11. Plica/Synovium Surgery:

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<tr>
<th>Right</th>
<th>Left</th>
<th>Excision - Medial Plica</th>
<th>Excision - Lateral Plica</th>
<th>Excision - Other:</th>
<th>Partial Synovectomy - Inflam Arthritis</th>
<th>Complete Synovectomy - Inflam Arthritis</th>
<th>Partial Synovectomy - Other:</th>
<th>Complete Synovectomy - Other:</th>
<th>Biopsy Synovium</th>
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</table>
Physical Exam Under Anesthesia

12. Are the following PE findings recorded below from the OR as EUA?  
   □ No  □ Yes

13. SIDE OF INVOLVED KNEE: 
   □ Right  □ Left

14a. GENERALIZED LAXITY:  
   □ Tight  □ Normal  □ Lax 
   □ Obvious varus  □ Normal  □ Obvious valgus
   □ Baja  □ Normal  □ Alta
   □ Centered  □ Subluxable  □ Subluxed  □ Dislocated

15a. ROM -- MEASURED WITH AN INSTRUMENTED GONIOMETER?  
   □ No  □ Yes

15b. ROM: 
   e.g. 10 degrees hyperextension, 150 degrees of flexion = 1 0 0 0 1 5 0
   (positive value)
   a. INVOLVED: Passive  □ □ □ □ □ Active  □ □ □ □
   b. Uninvolved: Passive  □ Hyper  □ Ext  □ Flexion  □ Active  □ Hyper  □ Ext  □ Flexion

16. EFFUSION: 
   □ None  □ fluid wave (< 25cc)  □ easily ballotable (25-60cc)  □ tense knee (> 60cc)
   □ None  □ fluid wave (< 25cc)  □ easily ballotable (25-60cc)  □ tense knee (> 60cc)

Page 4
Physical Exam Under Anesthesia (cont’d)

17. LACHMAN (@ 25 deg. flexion):
SIDE-TO-SIDE difference (involved minus uninvolved)

<table>
<thead>
<tr>
<th>Normal</th>
<th>degree laxity</th>
<th>tight</th>
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</thead>
<tbody>
<tr>
<td>-1 to 2 mm</td>
<td>(3 to 5 mm)</td>
<td>(-1 to -3 mm)</td>
</tr>
<tr>
<td>(6 to 10 mm)</td>
<td>(&gt;10 mm)</td>
<td>(&lt;-3 mm)</td>
</tr>
</tbody>
</table>

18. INSTRUMENTED?  
- Yes
- No

A. IF SO, BY WHAT TECHNIQUE?
- KT
- Other

B. SIDE-TO-SIDE EXCURSION: □□□□ mm

C. FORCE USED:
- 15 lbs
- 20 lbs
- 30 lbs (recommended)
- max. manual
- Other: __________ lbs

19. ENDPOINT LACHMAN:

a. INVOLVED:  
- Firm
- Soft

b. Uninvolved:  
- Firm
- Soft

20. TOTAL AP TRANSLATION (@ 70 deg. flexion):
SIDE-TO-SIDE difference (involved minus uninvolved)

- (0 to 2 mm)
- (3 to 5 mm)
- (6 to 10 mm)
- (> 10 mm)
21. **POSTERIOR SAG** (@ 70 deg. flexion):
   a. INVOLVED
   - tibial plateau anterior to MFC
   - tibial plateau flush with MFC
   - tibial plateau behind the MFC
   - tibial plateau significantly sagged behind MFC
   b. UNINVOLVED
   - tibial plateau anterior to MFC
   - tibial plateau flush with MFC
   - tibial plateau behind the MFC
   - tibial plateau significantly sagged behind MFC

22. **POSTERIOR DRAWER TEST** (@ 70 deg. flexion):
   *Side-to-side difference with a posterior force applied from resting position (involved minus uninvolved):*
   - (0 to 2 mm)
   - (3 to 5 mm)
   - (6 to 10 mm)
   - (> 10 mm)

23. **POSTERIOR DRAWER ENDPOINT:**
   a. INVOLVED: □ Firm □ Soft
   b. UNINVOLVED: □ Firm □ Soft

24. **MEDIAL JOINT OPENING** (0 DEGREES):
   *Side-to-side difference (involved minus uninvolved)*
   - (0 to 2 mm)
   - (3 to 5 mm)
   - (6 to 10 mm)
   - (> 10 mm)

25. **MEDIAL JOINT OPENING** (20 DEGREES):
   *Side-to-side difference (involved minus uninvolved)*
   - (0 to 2 mm)
   - (3 to 5 mm)
   - (6 to 10 mm)
   - (> 10 mm)

26. **LATERAL JOINT OPENING** (0 DEGREES):
   *Side-to-side difference (involved minus uninvolved)*
   - (0 to 2 mm)
   - (3 to 5 mm)
   - (6 to 10 mm)
   - (> 10 mm)

27. **LATERAL JOINT OPENING** (20 DEGREES):
   *Side-to-side difference (involved minus uninvolved)*
   - (0 to 2 mm)
   - (3 to 5 mm)
   - (6 to 10 mm)
   - (> 10 mm)
28a. PIVOT SHIFT:
   a. INVOLVED: Negative  GR 1 glide  GR 2 clunk  GR 3 gross
   b. Uninvolved: Negative  GR 1 glide  GR 2 clunk  GR 3 gross

28b. REVERSE PIVOT SHIFT:
   a. INVOLVED: Negative  GR 1 glide  GR 2 clunk  GR 3 gross
   b. Uninvolved: Negative  GR 1 glide  GR 2 clunk  GR 3 gross

29. POSTEROLATERAL STRUCTURE
   (side-to-side comparison)
   Perform in: Prone  Supine
   a. External Rotation Test (30 deg. flexion)
      GR 0 (< 5 deg.)
      GR 1 (6 to 10 deg.)
      GR 2 (11 to 19 deg.)
      GR 3 (> 20 deg.)
   b. External Rotation Test (90 deg. flexion)
      GR 0 (< 5 deg.)
      GR 1 (6 to 10 deg.)
      GR 2 (11 to 19 deg.)
      GR 3 (> 20 deg.)

30. POSTEROMEDIAL STRUCTURE
   (side-to-side comparison)
   Perform in: Prone  Supine
   a. Internal Rotation Test (30 deg. flexion)
      GR 0 (< 5 deg.)
      GR 1 (6 to 10 deg.)
      GR 2 (11 to 19 deg.)
      GR 3 (> 20 deg.)
   b. Internal Rotation Test (90 deg. flexion)
      GR 0 (< 5 deg.)
      GR 1 (6 to 10 deg.)
      GR 2 (11 to 19 deg.)
      GR 3 (> 20 deg.)

31. PATELLOFEMORAL CREPITUS (with full extension from 90 deg. of flexion)
   a. INVOLVED: None  Moderate  Severe (palpable and audible)
   b. Uninvolved: None  Moderate  Severe (palpable and audible)

32. MEDIAL COMPARTMENT CREPITUS (with passive motion and VARUS force)
   a. INVOLVED: None  Moderate  Severe (palpable and audible)
   b. Uninvolved: None  Moderate  Severe (palpable and audible)

33. LATERAL COMPARTMENT CREPITUS (with passive motion and VALGUS force)
   a. INVOLVED: None  Moderate  Severe (palpable and audible)
   b. Uninvolved: None  Moderate  Severe (palpable and audible)
VENDOR IMPLANT / ALLOGRAFT LABELS

Please affix all labels from implant/allograft devices used in the O.R. below:
Please use this figure to draw in patient's pathology and treatment:

**LEFT KNEE ARTHROSCOPY DIAGRAM**

**Comments:**
Please use this figure to draw in patient's pathology and treatment.

RIGHT KNEE ARTHROSCOPY DIAGRAM

LFC  COLLATERALS  MFC

LTP  MCL  MTP

FH  L  M

LFC  MFC

TIBIAL PLATEAU

LM  PCL

MM  ACL

P  A

COMMENTS:
1. **TOURNIQUET TIME** (in minutes): □ □ □ □ □

2. **TYPE OF OBJECTIVE DOCUMENTATION:**
   - None
   - Video
   - Pictures
   - Video AND pictures

3. **LOOSE BODIES:**
   - No
   - Yes, articular cartilage
   - Yes, bone
   - Yes, articular cartilage AND bone
   - Other

4. **INFLAMMATORY SYNOVITIS:**
   - None
   - Rheumatoid Arthritis
   - Traumatic
   - Other ______

5. **SYNOVITIS TREATMENT:**
   - None
   - Partial synovectomy
   - Complete synovectomy
   - Biopsy
A. Ligaments

6. ACL Tear (Moon Study Only):
   - [ ] No
   - [ ] Partial → if partial, the % of intact fibers: [ ]
   - [ ] Complete

7. ACL Graft Tear (Mars Study Only):
   - [ ] No
   - [ ] Partial → if partial, the % of intact fibers: [ ]
   - [ ] Complete

8. PCL Tear:
   - [ ] No
   - [ ] Partial → if partial, the % of intact fibers: [ ]
   - [ ] Complete

9. PCL Graft Tear:
   - [ ] No
   - [ ] Partial → if partial, the % of intact fibers: [ ]
   - [ ] Complete
A. Ligaments (cont'd)

10. MCL:
   - Normal
   - Grade I
   - Grade II (laxity at 20 degrees only)
   - Grade III (laxity at 0 degrees)

MCL TEAR identified via arthroscopy or arthroscopy
   - N/A
   - Not localized
   - Men-tib lig
   - Men-fem
   - Tibial
   - Femoral
   - Arthroscopy
   - Combination = __________________________

11. LCL:
   - Normal
   - Grade I
   - Grade II (laxity at 20 degrees only)
   - Grade III (laxity at 0 degrees)

LATERAL COMPLEX TEAR identified via arthroscopy or arthroscopy
   - N/A
   - Not localized
   - Partial LCL
   - Complete LCL
   - Popliteus
   - Posterior corner
   - Complete LCL + posterolateral corner
   - LCL + posterolateral + popliteus
   - Other __________________________
B. ACL Surgery

12. ACL RECONSTRUCTION:
   - No
   - Yes - If NO, proceed to Section E (page 26)

13. ACL REPAIR:
   - No
   - Repair - midsubstance
   - Repair - avulsion of the femur
   - Repair - avulsion of the tibia
   - Repair and augment

14. TYPE OF ACL RECONSTRUCTION:
   - Primary → (Proceed to SECTION C -- MOON Study only)
   - Revision
     → High Tibial Osteotomy
       - Prior to today’s surgery
       - At today’s surgery
     → Meniscus Transplant
       - Medial meniscus
         - Prior to today’s surgery
         - At today’s surgery
       - Lateral meniscus
         - Prior to today’s surgery
         - At today’s surgery

Proceed to Section D (MARS Study only)
C. Primary ACLR (MOON Study only)

**PLEASE DISREGARD SECTION C IF YOU ARE DOING A REVISION**

15. **GRAFT TYPE:**
- Autograft
- Allograft
- Both allograft and autograft
- Prosthetic

16. **GRAFT SOURCE:**
- B-PT-B
- Quadriceps - bone
- Hamstring - semitendinosis
- Hamstring - semitendinosis + gracilis
- ITB
- Achilles tendon
- Tibialis anterior
- Tibialis posterior
- Other: ____________________________

17. **# STRANDS** (example, hamstring):

18. **PREVIOUS GRAFT HARVEST:**
- Autologous patellar tendon
- Hamstring tendon
- Quadriceps tendon

19. **SURGICAL EXPOSURE:**
- Arthroscopic assist, two-incision
- Arthroscopic assist, one-incision or endoscopic
- Traditional arthroscopy (patella retinaculum violated)
- Mini-arthroscopy (patella retinaculum intact)

20. **NOTCHPLASTY:**
- No
- Small (< 5 mm)
- Moderate (> 5 mm but < 10 mm)
- Large (> 10 mm)

21. **FEMORAL POSITION:**
- Bone tunnel
- Over-the-top (OTT)
- Modified OTT
C. Primary ACLR (MOON Study only)

PLEASE DISREGARD SECTION C IF YOU ARE DOING A REVISION

22. METHOD TO ACHIEVE FEMORAL POSITION:
- "Freehand" / Placement with or without drill guide
- Reference probe = ____________________
- Isometry type = ____________________
- X-Ray
- Reference probe + X-Ray

23. FEMORAL FIXATION:
- Interference screw (metal)
- Interference screw (bioabsorbable)
- Suture + button / Endobutton
- Suture + post
- Suture + staple
- Staple tissue
- Screw tissue
- Interference screw + suture to ____________________
- Cross pin (bioabsorbable)
- Cross pin (nonabsorbable)
- Other: ____________________

24. TIBIAL POSITION:
- Bone tunnel
- OTT
- Modified OTT

25. METHOD TO ACHIEVE TIBIAL POSITION:
- "Freehand" / Placement with or without drill guide
- Reference probe = ____________________
- Isometry type = ____________________
- X-Ray
- Reference probe + X-Ray

26. TIBIAL FIXATION:
- Interference screw (metal)
- Interference screw (bioabsorbable)
- Suture + button
- Suture + post
- Suture + staple
- Staple tissue
- Screw tissue
- Interference screw + suture to ____________________
- Other: ____________________
C. Primary ACLR (MOON Study only)

PLEASE DISREGARD SECTION C IF YOU ARE DOING A REVISION

27. ESTIMATED GRAFT EXCURSION, FROM 0-90 DEGREES:

\[
\begin{array}{c}
\text{mm} \\
\hline
\end{array}
\]

28. WAS AN EXTRAARTICULAR PROCEDURE PERFORMED?

\[
\begin{array}{c}
\text{No} \\
\text{Yes} \\
\hline
\end{array}
\]

29. POST-OP FULL ACTIVE OR PASSIVE ROM IS ALLOWED WHEN?

\[
\begin{array}{c}
\text{days} \\
\hline
\end{array}
\]

30. FWB WITHOUT SUPPORT IS ALLOWED WHEN?

\[
\begin{array}{c}
\text{days post-op} \\
\hline
\end{array}
\]

31. HOW LONG DO YOU USE A FUNCTIONAL ACL STABILIZING BRACE FOR ACL POST-OP?

\[
\begin{array}{c}
\text{days} \\
\hline
\end{array}
\]

If a Collateral (MCL/LCL) or Corner (PM/PL) Surgery was performed, proceed to Questions 67 and 68 (page 24).

--- Otherwise, please proceed to Section E (page 26) ---
D. Revision ACLR (MARS STUDY)

32. WHAT REVISION NUMBER: [ ] One (first failure of ACL graft)
[ ] Two
[ ] Three
[ ] Four
[ ] Five

32a. DATE OF THE LAST ACL RECONSTRUCTION: ___/___/___

33. SURGEON’S OPINION ON CAUSE OF FAILURE:
[ ] Traumatic
[ ] Technical error from prior surgery
[ ] Biologic failure to heal (i.e., tissue stretching)
[ ] Combination of above
[ ] Infection (if YES, you are finished)
[ ] Other

34. IS SURGEON REVISION HIS/HER OWN FAILURE?
[ ] No
[ ] Yes

35. CAUSE OF TECHNICAL FAILURE (in Surgeon’s opinion):
(check all that apply)
[ ] None
[ ] Femoral tunnel malposition
[ ] Tibial tunnel malposition
[ ] Malalignment (in any plane)
[ ] Femoral fixation
[ ] Tibial fixation
[ ] Autograft source
[ ] Allograft source
[ ] Posteromedial laxity
[ ] Posterolateral laxity
[ ] Other _______________________

36. PATIENT’S PRIOR INCISIONS:
(check all that apply)
[ ] Hamstring
[ ] BTB ipsilateral vertical
[ ] BTB ipsilateral horizontal
[ ] BTB contralateral vertical
[ ] BTB contralateral horizontal
[ ] Allograft tibial incision

37. PRIOR SURGICAL TECHNIQUE:
[ ] Arthroscopic two-incision
[ ] Arthroscopic one-incision
[ ] Traditional arthrotomy
[ ] Mini-arthrotomy (patellar retinaculum intact)

38. TECHNIQUE OF PRIOR ACL FEMORAL TUNNEL:
[ ] Single tunnel
[ ] Double tunnel
39. VISUALIZATION OF FAILED ACLR GRAFT:
   - ACL graft absent
   - ACL graft present, but elongated
   - ACL graft present, but majority torn

40. PRIOR ACL GRAFT TYPE:
   - Autograft
   - Allograft
   - Both autograft and allograft
   - Prosthetic
   - Combined (autograft or allograft with prosthetic)

41. PRIOR GRAFT SOURCE:
   - BTB
   - Quad BT
   - Hamstring - semitendinosis
   - Hamstring - semitendinosis + gracilis
   - ITB
   - Achilles tendon
   - Tibialis anterior
   - Tibialis posterior
   - Unknown
   - Other: __________________________

42. NUMBER OF PRIOR HAMSTRING OR SOFT TISSUE STRANDS:
   - Unknown ☐

43. PREVIOUS GRAFT HARVEST:
   - Autologous patellar tendon ........ Involved ☐ Uninvolved knee
   - Hamstring tendon ................ Involved ☐ Uninvolved knee
   - Quadriceps tendon ............... Involved ☐ Uninvolved knee
   - None ☐

44. CUTANEOUS NUMBNESS:
   - Anterior ☐
   - Lateral ☐
   - Medial ☐
   - None ☐

45. CURRENT SURGICAL EXPOSURE AND TECHNIQUE:
   - Arthroscopically assisted, one-incision; TRANS-TIBIAL drilling
   - Arthroscopically assisted, one-incision; anterior medial portal drilling
   - Arthroscopically assisted, two-incision
   - Traditional arthroscopy (patella retinaculum violated)
   - Mini-arthroscopy (patella retinaculum intact)
46. CURRENT NOTCHPLASTY:  
- No
- Small (< 5 mm)
- Moderate (> 5 mm but < 10 mm)
- Large (> 10 mm)

**FEMORAL TUNNEL AND FIXATION DESCRIPTION**

47. PRIOR FEMORAL FIXATION:  
(check all that apply)  
- Interference screw (metal)
- Interference screw (bioabsorbable)
- Stacked screws
- Suture + button / Endobutton
- Suture + post
- Suture + staple
- Staple tissue
- Screw tissue
- Interference screw + suture to ____________________________
- Cross pin (bioabsorbable)
- Cross pin (nonabsorbable)
- Other: ____________________________

48. PRIOR FEMORAL TUNNEL APERTURE POSITION AT THE TIME OF REVISION:  
- Ideal (both position and size of tunnel aperture)
- Ideal (both position and size), but enlarged tunnels
- Compromised aperture position to VERTICAL
- Compromised aperture position to ANTERIOR
- Compromised aperture size (i.e. enlarged)
- Compromised - due to BOTH position and size of tunnel aperture

49a. CURRENT FEMORAL TUNNEL METHOD:  
- Drilling
- Dilation

49b. CURRENT FEMORAL TUNNEL APERTURE POSITION (after drilling), IS BEST DESCRIBED AS:  
- same tunnel aperture, optimum position
- same tunnel aperture, but compromised position (by how many mm ______)
- entirely new tunnel aperture
- blended new tunnel aperture
- double tunnel (add a 2nd tunnel)
- Over-the-top (OTT)
- modified OTT
D. Revision ACLR (MARS STUDY)

50. **CURRENT FEMORAL TUNNEL BONE GRAFT:**
- Yes, at current procedure
- Staged (prior to current procedure)
- None

51. **BONE QUALITY OF FEMUR:**
- Normal
- Abnormal (ie. soft)

52. **CURRENT FEMORAL FIXATION:**
(check all that apply)
- Interference screw (metal)
- Interference screw (bioabsorbable or composite)
- Stacked screws
- Suture + button / Endobutton
- Suture + post
- Suture + staple
- Staple tissue
- Screw tissue
- Interference screw + suture to _______________________
- Cross pin (bioabsorbable)
- Cross pin (nonabsorbable)
- Other: _______________________

---

**TIBIAL TUNNEL AND FIXATION DESCRIPTION**

53. **PRIOR TIBIAL FIXATION:**
(check all that apply)
- Interference screw (metal)
- Interference screw (bioabsorbable)
- Stacked screws
- Suture + button / Endobutton
- Suture + post
- Suture + staple
- Staple tissue
- Screw tissue
- Interference screw + suture to _______________________
- Cross pin (bioabsorbable)
- Cross pin (nonabsorbable)
- Intrafix (bioabsorbable)
- Intrafix (metal)
- Other: _______________________

---

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### D. Revision ACLR (MARS STUDY)

54. **Prior Tibial Tunnel Aperture Position at the Time of Revision:**
- [ ] Ideal (both position and size of tunnel aperture)
- [ ] Ideal (both position and size), but enlarged tunnel exists extraarticular within the plateau
- [ ] Compromised aperture position either to MEDIAL or LATERAL
- [ ] Compromised aperture position either to ANTERIOR or POSTERIOR
- [ ] Compromised aperture size (i.e. enlarged)
- [ ] Compromised - due to BOTH position and size of tunnel aperture

55. **Current Tibial Tunnel Method:**
- [ ] Drilling
- [ ] Dilatation

56. **Current Tibial Tunnel Aperture (after drilling), Is Best Described As:**
- [ ] Same tunnel aperture, optimum position
- [ ] Same tunnel aperture, but compromised position (by how many mm ________)
- [ ] Entirely new tunnel aperture
- [ ] Blended new tunnel aperture
- [ ] Double tunnel (add a 2nd tunnel)
- [ ] Over-the-top (OTT)
- [ ] Modified OTT

57. **Current Tibial Tunnel Bone Graft:**
- [ ] Yes, at current procedure
- [ ] Staged (prior to current procedure)
- [ ] None

58. **Bone Quality of Tibia:**
- [ ] Normal
- [ ] Abnormal (i.e. soft)

59. **Current Tibial Fixation:**
   (check all that apply)
- [ ] Interference screw (metal)
- [ ] Interference screw (bioabsorbable)
- [ ] Stacked screws
- [ ] Suture + button / Endobutton
- [ ] Suture + post
- [ ] Suture + staple
- [ ] Staple tissue
- [ ] Screw tissue
- [ ] Interference screw + suture to ____________________________
- [ ] Cross pin (bioabsorbable)
- [ ] Cross pin (nonabsorbable)
- [ ] Intrafix (bioabsorbable)
- [ ] Intrafix (metal)
- [ ] Other: ____________________________
D. Revision ACLR (MARS STUDY)

60. CURRENT ACL GRAFT TYPE:
   [ ] Autograft
   [ ] Allograft
   [ ] Both autograft and allograft
   [x] Prosthetic

61. CURRENT GRAFT SOURCE:
   [ ] BTB
   [ ] Quadriceps - Bone
   [ ] Hamstring - semitendinosis
   [ ] Hamstring - semitendinosis + gracilis
   [ ] ITB
   [ ] Achilles tendon
   [ ] Tibialis anterior
   [ ] Tibialis posterior
   [ ] Other

61a. NUMBER OF HAMSTRING OR SOFT TISSUE STRANDS:

62. DID YOU PRE-TENSION THE GRAFT?  
   [x] No
   [ ] Yes

63. BIOLOGIC ENHANCEMENT:
   [ ] No
   [x] Yes (describe): ________________________

63a. LOCATION OF BIOLOGIC ENHANCEMENT:
   (check all that apply)
   [ ] None
   [ ] Femoral tunnel
   [ ] Intra-articular graft
   [ ] Tibial tunnel

64. ESTIMATED GRAFT EXCURSION (at full ROM; 0-135 degrees):

65. KNEE POSITION AT TIME OF GRAFT FIXATION (in degrees):
   [ ] (Extension)
   [ ] Positive #
      (Hyper-extension)

66. TENSION ON GRAFT AT TIME OF FIXATION:
   [ ] Manual
   [ ] Measured, by: ________________________
D. Revision ACLR (MARS STUDY)

Collateral (MCL/LCL) and Corner (PM, PL) Structures

67. MCL OR POSTEROMEDIAL REPAIR OR RECONSTRUCTION PERFORMED?

☐ No - If NO, proceed to question #68
☐ Yes

67a. Type of MCL or PM Surgery:

☐ Repair suture
☐ Repair staple/screw
☐ Repair suture + repair staple/screw
☐ Autograft reconstruction = ___________________________
☐ Allograft reconstruction = ___________________________
☐ Other: ___________________________

68. LCL OR POSTEROLATERAL REPAIR OR RECONSTRUCTION PERFORMED?

☐ No - If NO, proceed to question #69
☐ Yes

68a. Type of LCL or PL Surgery:

☐ Repair suture
☐ Repair staple/screw
☐ Repair suture + repair staple/screw
☐ Autograft reconstruction = ___________________________
☐ Allograft reconstruction = ___________________________
☐ Other: ___________________________
D. Revision ACLR *(MARS STUDY)*

### REHABILITATION

69. **DO YOU RESTRICT PASSIVE ROM POST-OP?**  
   - No  
   - Yes  
   69a. **If yes, when do you allow full passive ROM?**  
        [ ] [ ] [ ] days post-op

70. **DO YOU RESTRICT ACTIVE ROM POST-OP?**  
   - No  
   - Yes  
   70a. **If yes, when do you allow full active ROM?**  
        [ ] [ ] [ ] days post-op

71. **DO YOU RESTRICT FULL WEIGHT-BEARING W/O SUPPORT (ie. crutches) POST-OP?**  
   - No  
   - Yes  
   71a. **If yes, when do you allow full weightbearing w/o support?**  
        [ ] [ ] [ ] days post-op

72. **DO YOU PRESCRIBE A MOTION CONTROL BRACE (double upright or knee immobilizer) POST-OP?**  
   - No  
   - Yes  
   72a. **If yes, how long do you prescribe a motion control brace to be used for?**  
        [ ] [ ] [ ] days

73. **WILL AN ACL DEROTATION BRACE BE USED IN POST-OP REHAB?**  
   - No  
   - Yes  
   73a. **If so, for how long?**  
        [ ] [ ] [ ] days

74. **WILL AN ACL DEROTATION BRACE BE USED IN RETURN TO SPORT?**  
   - No  
   - Yes  
   74a. **If so, for how long?**  
        [ ] [ ] [ ] days
E. Medial Meniscus Tear #1

75a. DOES THIS PATIENT HAVE A MEDIAL MENISCUS TEAR?  □ Yes  (proceed to question #75b)

OR

DID THIS PATIENT HAVE PRIOR MENISCUS SURGERY?  □ Yes  (proceed to question #85)

*If NO tear, proceed to Section F (page 29)*

75b. MEDIAL MENISCUS TEAR #1:

□ Yes, partial
□ Yes, complete

76. LOCATION:

a. Anterior vs. Posterior  □ Anterior
□ Posterior
□ Anterior + posterior

b. Central vs. Peripheral  □ Central 1/3
□ Middle 1/3
□ Peripheral 1/3
□ Central + middle 1/3
□ Central + middle + peripheral 1/3
□ Middle + peripheral 1/3

77. TYPE:

□ Radial
□ Oblique
□ Longitudinal - vertical
□ Bucket handle - displaced
□ Horizontal
□ Complex

78. LENGTH (in mm):

□□□ .□□

79. DEGENERATIVE COMPONENT (cavitation, multiple cleavage planes, etc.):

□ No
□ Yes
E. Medial Meniscus Tear #1 (cont'd)

80. TREATMENT:

- No treatment for tear
- Excision
- Repair
- Abrade + trephine
- Meniscus transplant

81. Quantify extent of CURRENT EXCISION:

*Please document on knee diagram on pages 9/10 of this survey
(If greater than or equal to 50% of a region is excised, then compartment is considered excised)*

a. Posterior

- None
- 33% (central 1/3)
- 67% (central + middle 1/3)
- 100% (entire meniscus)

b. Anterior

- None
- 33%
- 67%
- 100%

c. Remaining meniscus tissue

- Normal
- Degenerative changes
- Stable tear
- Unstable tear
- Tear left in-situ

d. Circumferential hoop fibers

- Intact
- Disrupted
E. Medial Meniscus Tear #1 (cont'd)

82. **CURRENT MENISCUS REPAIR TECHNIQUE:**
- Inside-out
- Outside-in
- All-in
- Both inside-out and all-in
- Other

83. **TYPE OF "SUTURE":**
- Absorbable suture
- Nonabsorbable suture
- Absorbable stint or implant - name

84. **NUMBER OF "SUTURES":**

85. **WAS PREVIOUS MENISCUS SURGERY PERFORMED?**
- No
- Yes, excision
- Yes, repair healed/stable
- Yes, repair not healed, unstable

86. **Quantify extent of PREVIOUS Meniscus Surgery** (based on surgeon's evaluation at ACLR)

*Please document on knee diagram on pages 9/10 of this survey
(If greater than or equal to 50% of a region is excised, then compartment is considered excised)*

a. **Posterior**
- None
- 33% (central 1/3)
- 67% (central + middle 1/3)
- 100% (entire meniscus)

b. **Anterior**
- None
- 33%
- 67%
- 100%

*For Additional Medial Meniscal Pathology, also complete Section L (page 39)*
F. Lateral Meniscus Tear #1

87a. DOES THIS PATIENT HAVE A LATERAL MENISCUS TEAR? □ Yes (proceed to question #87b)

OR

DID THIS PATIENT HAVE PRIOR MENISCUS SURGERY? □ Yes (proceed to question #98)

If NO tear, proceed to Section G (page 32)

87b. LATERAL MENISCUS TEAR #1:

□ Yes, partial
□ Yes, complete

88. LOCATION:

a. Anterior vs. Posterior
□ Anterior
□ Posterior
□ Anterior + posterior

b. Central vs. Peripheral
□ Central 1/3
□ Middle 1/3
□ Peripheral 1/3
□ Central + middle 1/3
□ Central + middle + peripheral 1/3
□ Middle + peripheral 1/3

89. IS THE TEAR CENTRAL OR ADJACENT TO THE POPLITEAL HIATUS?

□ No
□ Yes

90. TYPE:

□ Radial
□ Oblique
□ Longitudinal (vertical)
□ Bucket handle (displaced)
□ Horizontal
□ Complex

91. LENGTH (in mm):

□ □ □

92. DEGENERATIVE COMPONENT (cavitation, multiple cleavage planes, etc.):

□ No
□ Yes
F. Lateral Meniscus Tear #1 (cont'd)

93. TREATMENT:
- [ ] No treatment for tear
- [ ] Excision
- [ ] Repair
- [ ] Abrade + trephine
- [ ] Meniscus transplant

94. Quantify extent of CURRENT EXCISION:
Please document on knee diagram on pages 9/10 of this survey
(if greater than or equal to 50% of a region is excised, then compartment is considered excised)

a. Posterior
- [ ] None
- [ ] 33% (central 1/3)
- [ ] 67% (central + middle 1/3)
- [ ] 100% (entire meniscus)

b. Anterior
- [ ] None
- [ ] 33%
- [ ] 67%
- [ ] 100%

c. Remaining meniscus tissue
- [ ] Normal
- [ ] Degenerative changes
- [ ] Stable tear
- [ ] Unstable tear
- [ ] Tear left in-situ

d. Circumferential hoop fibers
- [ ] Intact
- [ ] Disrupted
F. Lateral Meniscus Tear #1 (cont’d)

95. CURRENT MENISCUS REPAIR TECHNIQUE:
   ![Checkboxes for repair techniques:]
   - Inside-out
   - Outside-in
   - All-in
   - Both inside-out and all-in
   - Other

96. TYPE OF "SUTURE":
   - Absorbable suture
   - Nonabsorbable suture
   - Absorbable suture or implant - name ______________
   [If any implant, please check next box.]

97. NUMBER OF "SUTURES":
   ![Number boxes for sutures:]

98. WAS PREVIOUS MENISCUS SURGERY PERFORMED?
   - No
   - Yes, excision
   - Yes, repair healed/stable
   - Yes, repair not healed, unstable

99. Quantify extent of PREVIOUS Meniscus Surgery (based on surgeon's evaluation at ACLR)

   Please document on knee diagram on pages 9/10 of this survey
   (If greater than or equal to 50% of a region is excised, then compartment is considered excised)

   a. Posterior
   ![Percentage boxes for posterior:]
   - None
   - 33% (central 1/3)
   - 67% (central + middle 1/3)
   - 100% (entire meniscus)

   b. Anterior
   ![Percentage boxes for anterior:]
   - None
   - 33%
   - 67%
   - 100%

For Additional Lateral Meniscal Pathology, also complete Section M (page 41)
G. Femoral Condyle Articular Lesions

100. Grade lesion of each section (by **WORST GRADE**) involved via I-IV Outerbridge scale using "1,2,3,4"

where, 
1 = Grade I (normal)
2 = Grade II (fissures, superficial changes)
3 = Grade III (fragmentation, deep changes)
4 = Grade IV (bone)

![Diagram of femoral condyles]

**Where is the lesion weight-bearing?**

*(please refer to knee diagram above and on pages 9/10 of this survey)*

101a. MEDIAL FEMORAL CONDYLE:
- 0 degrees
- 45 degrees
- 90 degrees

101b. LATERAL FEMORAL CONDYLE:
- 0 degrees
- 45 degrees
- 90 degrees
### G. LFC -- Articular Lesions

102. **IS AN ARTICULAR LESION PRESENT ON THE LATERAL FEMORAL CONDYLE?** □ Yes

*If NO, proceed to Next Page (MFC - Articular Lesions)*

103. **CHONDROMALACIA:**
- **a. Acute (Traumatic)**
  - No □
  - Yes ■
- **b. Degenerative**
  - No □
  - Yes ■
- **c. Grade**
  - Grade I
  - Grade II fissures (superficial changes)
  - Grade III fragmentation (deep changes)
  - Grade IV (bone)

104. **% OF MEDIAL-TO-LATERAL WIDTH:**
- 0% □
- 25% □
- 50% □
- 75% □
- 100% ■

105. **DEGREES ON CONDYLE SURFACE:**
  (from anterior to posterior)
  □ □ □ degrees

106. **DIMENSIONS OF LARGEST LESION:**
- **Length:** □ □ mm
- **Width:** □ □ mm

107. **TREATMENT FOR CHONDROMALACIA:**
- None □
- Chondroplasty (debride loose art. cartilage only) □
- Abrasion arthroplasty (debride into bone) □
- Microfracture □
- Mosaicplasty □
- Cell Rx □
- Allograft □
- Thermal □
- Other: ____________________________ □

108. **ARTICULAR CARTILAGE FRACTURES? (linear cracks)**
- No □
- Yes ■

108b. **NUMBER OF FRACTURES:**
- □ #0 - 9 (maximum)

109. **LENGTH OF THE LONGEST/DEEPEST FRACTURE:**
- □ mm

110. **ORIENTATION OF LONGEST/DEEPEST FRACTURE:**
- Sagittal (A to P) □
- Coronal (M to L) □

111. **TREATMENT FOR THESE ARTICULAR CARTILAGE FRACTURES:**
- None □
- Chondroplasty □
- Abrasion arthroplasty □
- Microfracture □
- Mosaicplasty □
- Cell Rx □
- Allograft □
- Thermal □
- Other: ____________________________ □
G. MFC -- Articular Lesions

112. IS AN ARTICULAR LESION PRESENT ON THE MEDIAL FEMORAL CONDYLE? □ Yes

If NO, proceed to Next Page (LTP - Articular Lesions)

113. CHONDROMALACIA:
   a. Acute (Traumatic)
   b. Degenerative
   □ No □ Yes □ No □ Yes
   c. Grade
   □ Grade I
   □ Grade II fissures (superficial changes)
   □ Grade III fragmentation (deep changes)
   □ Grade IV (bone)

114. % OF MEDIAL-TO-LATERAL WIDTH:
   □ 0% □ 25% □ 50% □ 75% □ 100%

115. DEGREES ON CONDYLE SURFACE:
   (from anterior to posterior)
   □ degrees

116. DIMENSIONS OF LARGEST LESION:
   Length: □ mm
   Width: □ mm

117. TREATMENT FOR CHONDROMALACIA:
   □ None
   □ Chondroplasty (debride loose art. cartilage only)
   □ Abrasion arthroplasty (debride into bone)
   □ Microfracture
   □ Mosaicplasty
   □ Cell Rx
   □ Allograft
   □ Thermal
   □ Other: ____________________________

118. ARTICULAR CARTILAGE FRACTURES? (linear cracks)
   □ No □ Yes

118b. NUMBER OF FRACTURES:
   □ #0 - 9 (maximum)

119. LENGTH OF THE LONGEST/DEEPEST FRACTURE:
   □ mm

120. ORIENTATION OF LONGEST/DEEPEST FRACTURE:
   □ Sagittal (A to P)
   □ Coronal (M to L)

121. TREATMENT FOR THESE ARTICULAR CARTILAGE FRACTURES:
   □ None
   □ Chondroplasty
   □ Abrasion arthroplasty
   □ Microfracture
   □ Mosaicplasty
   □ Cell Rx
   □ Allograft
   □ Thermal
   □ Other: ____________________________

Page 34
H. LTP - Articular Lesions

122. IS AN ARTICULAR LESION PRESENT ON THE LATERAL TIBIAL PLATEAU? □ Yes

If NO, proceed to Next Page (MTP - Articular Lesions)

123. CHONDROMALACIA:
   a. Acute (Traumatic)
      □ No □ Yes
   b. Degenerative
      □ No □ Yes
   c. Grade
      □ Grade I
      □ Grade II fissures (superficial changes)
      □ Grade III fragmentation (deep changes)
      □ Grade IV (bone)

124. % OF MEDIAL-TO-LATERAL WIDTH:
      □ 0% □ 25% □ 50% □ 75% □ 100%

125. % OF ANTERIOR-TO-POSTERIOR:
      □ 0% □ 25% □ 50% □ 75% □ 100%

126. TREATMENT FOR CHONDROMALACIA:
      □ None
      □ Chondroplasty (debride loose art. cart. only)
      □ Abrasion arthroplasty (debride into bone)
      □ Microfracture
      □ Mosaicplasty
      □ Cell Rx
      □ Allograft
      □ Thermal
      □ Other: ____________________________

127. ARTICULAR CARTILAGE FRACTURES?
      (linear cracks)
      □ No □ Yes

127b. NUMBER OF FRACTURES:
      □ #0 - 9 (maximum)

128. LENGTH OF THE LONGEST/DEEPEST
      FRACTURE:
      □ mm

129. ORIENTATION OF LONGEST/DEEPEST
      FRACTURE:
      □ Sagittal (A to P)
      □ Coronal (M to L)
      □ Outline of inner meniscus contour
      □ Other: ____________________________

130. TREATMENT FOR THE ARTICULAR
      CARTILAGE FRACTURES:
      □ None
      □ Chondroplasty
      □ Abrasion arthroplasty
      □ Microfracture
      □ Mosaicplasty
      □ Cell Rx
      □ Allograft
      □ Thermal
      □ Other: ____________________________
I. MTP -- Articular Lesions

131. IS AN ARTICULAR LESION PRESENT ON THE MEDIAL TIBIAL PLATEAU?  □ Yes

If NO, proceed to Next Page (Patellar - Articular Lesions)

132. CHONDROMALACIA:
   a. Acute (Traumatic)
   □ No        □ Yes
   b. Degenerative
   □ No        □ Yes
   c. Grade
   □ Grade I
   □ Grade II fissures (superficial changes)
   □ Grade III fragmentation (deep changes)
   □ Grade IV (bone)

133. % OF MEDIAL-TO-LATERAL WIDTH:
   □ 0%
   □ 25%
   □ 50%
   □ 75%
   □ 100%

134. % OF ANTERIOR-TO-POSTERIOR:
   □ 0%
   □ 25%
   □ 50%
   □ 75%
   □ 100%

135. TREATMENT FOR CHONDROMALACIA:
   □ None
   □ Chondroplasty (debride loose art cart only)
   □ Abrasion arthroplasty (debride into bone)
   □ Microfracture
   □ Mosaicplasty
   □ Cell Rx
   □ Allograft
   □ Thermal
   □ Other: ____________________________

136. ARTICULAR CARTILAGE FRACTURES?
   (linear cracks)
   □ No
   □ Yes

136b. NUMBER OF FRACTURES:
   □ #0 - 9 (maximum)

137. LENGTH OF THE LONGEST/DEEPEST FRACTURE:
   □ mm

138. ORIENTATION OF LONGEST/DEEPEST FRACTURE:
   □ Sagittal (A to P)
   □ Coronal (M to L)
   □ Outline of inner meniscus contour
   □ Other: ____________________________

139. TREATMENT FOR THESE ARTICULAR CARTILAGE FRACTURES:
   □ None
   □ Chondroplasty
   □ Abrasion arthroplasty
   □ Microfracture
   □ Mosaicplasty
   □ Cell Rx
   □ Allograft
   □ Thermal
   □ Other: ____________________________
J. PATELLAR -- Articular Lesions

140. IS AN ARTICULAR LESION PRESENT ON THE PATELLA?  □ Yes

If NO, proceed to Next Page (Trochlear - Articular Lesions)

141. CHONDROMALACIA:
   a. Acute (Traumatic)  □ No □ Yes
   b. Degenerative  □ No □ Yes
   c. Grade
      □ Grade I
      □ Grade II fissures (superficial changes)
      □ Grade III fragmentation (deep changes)
      □ Grade IV (bone)

142. TREATMENT FOR CHONDROMALACIA:
      □ None
      □ Chondroplasty (debride loose articular cartilage only)
      □ Abrasion arthroplasty (debride into bone)
      □ Microfracture
      □ Mosaicplasty
      □ Cell Rx
      □ Allograft
      □ Thermal
      □ Other: __________________________

143. ARTICULAR CARTILAGE FRACTURES?  (linear cracks)  □ No □ Yes

144. WORST Grade Chondromalacia of each section involved via I-IV scale using “1,2,3,4”

RIGHT
   proximal middle distal
   lateral central medial

LEFT
   medall central lateral
K. TROCHLEAR — Articular Lesions

145. IS AN ARTICULAR LESION PRESENT ON THE TROCHLEAR REGION? □ Yes

If NO, proceed to Next Page (Section I)

146. CHONDROMALACIA:
   a. Acute (Traumatic)  b. Degenerative  c. Grade
   □ No  □ No  □ Grade I
   □ Yes  □ Yes  □ Grade II fissures (superficial changes)
          □ Grade III fragmentation (deep changes)
          □ Grade IV (bone)

147. TREATMENT FOR CHONDROMALACIA:
   None
   □ Chondroplasty (debride loose articular cartilage only)
   □ Abrasion arthroplasty (debride into bone)
   □ Microfracture
   □ Mosaicplasty
   □ Cell Rx
   □ Allograft
   □ Thermal
   □ Other: ______________________________________

148. ARTICULAR CARTILAGE FRACTURES? (linear cracks)
   □ No  □ Yes

149. WORST Grade Chondromalacia of each section involved via Outerbridge scale using "1,2,3,4"

RIGHT
lateral  central  medial

Trochlear Region
proximal
middle
distal

lat. cent. med.  lat. cent. med.

LEFT
medial  central  lateral

med. cent. lat.  med. cent. lat.
L. Medial Meniscus Tear #2

150a. DOES THIS PATIENT HAVE A 2ND MEDIAL MENISCUS TEAR?  □ Yes

*If NO tear, proceed to Section M (page 41)*

150b. MEDIAL MENISCUS TEAR #2:

- Yes, partial
- Yes, complete

151. LOCATION:

a. Anterior vs. Posterior
- Anterior
- Posterior
- Anterior + posterior

b. Central vs. Peripheral
- Central 1/3
- Middle 1/3
- Peripheral 1/3
- Central + middle 1/3
- Central + middle + peripheral 1/3
- Middle + peripheral 1/3

152. TYPE:

- Radial
- Oblique
- Longitudinal (vertical)
- Bucket handle (displaced)
- Horizontal
- Complex

153. LENGTH (in mm):

□ □ □ . □

154. DEGENERATIVE COMPONENT (cavitation, multiple cleavage planes, etc.):  □ No  □ Yes

155. TREATMENT:

- No treatment for tear
- Excision
- Repair
- Abrade + trephine
- Meniscus transplant
156. **Quantify extent of CURRENT EXCISION:**
(If greater than or equal to 50% of a region is excised, then compartment is considered excised)

a. Posterior
   - None
   - 33% (central 1/3)
   - 67% (central + middle 1/3)
   - 100% (entire meniscus)

b. Anterior
   - None
   - 33%
   - 67%
   - 100%

c. Remaining meniscus tissue
   - Normal
   - Degenerative changes
   - Stable tear
   - Unstable tear
   - Tear left in-situ

d. Circumferential hoop fibers
   - Intact
   - Disrupted

157. **CURRENT MENISCUS REPAIR TECHNIQUE:**
- None
- Inside-out
- Outside-in
- All-in
- Both inside-out and all-in
- Other

158. **TYPE OF "SUTURE":**
- None
- Absorbable suture
- Nonabsorbable suture
- Absorbable suture or implant - name

159. **NUMBER OF "SUTURES":**

160. **WAS PREVIOUS MENISCUS SURGERY PERFORMED?**
- No
- Yes, excision
- Yes, repair healed/stable
- Yes, repair not healed, unstable
M. Lateral Meniscus Tear #2

161a. DOES THIS PATIENT HAVE A 2ND LATERAL MENISCUS TEAR? ☐ Yes

If NO tear, proceed to Section N (page 49)

161b. LATERAL MENISCUS TEAR #2:
   ☐ Yes, partial
   ☐ Yes, complete

162. LOCATION:
   a. Anterior vs. Posterior
      ☐ Anterior
      ☐ Posterior
      ☐ Anterior + posterior
   b. Central vs. Peripheral
      ☐ Central 1/3
      ☐ Middle 1/3
      ☐ Peripheral 1/3
      ☐ Central + middle 1/3
      ☐ Central + middle + peripheral 1/3
      ☐ Middle + peripheral 1/3

163. IS THE TEAR CENTRAL OR ADJACENT TO THE POPLITEAL HIATUS?
   ☐ No
   ☐ Yes

164. TYPE:
   ☐ Radial
   ☐ Oblique
   ☐ Longitudinal (vertical)
   ☐ Bucket handle (displaced)
   ☐ Horizontal
   ☐ Complex

165. LENGTH (in mm):
   ☐ ☐ mm

166. DEGENERATIVE COMPONENT (cavitation, multiple cleavage planes, etc.):
   ☐ No
   ☐ Yes

167. TREATMENT:
   ☐ No treatment for tear
   ☐ Excision
   ☐ Repair
   ☐ Abrade + trephine
   ☐ Meniscus transplant
M. Lateral Meniscus Tear #2 (cont'd)

Quantify extent of CURRENT EXCISION:
(if greater than or equal to 50% of a region is excised, then compartment is considered excised)

a. Posterior
   - None
   - 33% (central 1/3)
   - 67% (central + middle 1/3)
   - 100% (entire meniscus)

b. Anterior
   - None
   - 33%
   - 67%
   - 100%

c. Remaining meniscus tissue
   - Normal
   - Degenerative changes
   - Stable tear
   - Unstable tear
   - Tear left in-situ

d. Circumferential hoop fibers
   - Intact
   - Disrupted

168. CURRENT MENISCUS REPAIR TECHNIQUE:
   - Inside-out
   - Outside-in
   - All-in
   - Both inside-out and all-in
   - Other

169. TYPE OF "SUTURE":
   - None
   - Absorbable suture
   - Nonabsorbable suture
   - Absorbable stint or implant - name ____________________________

170. NUMBER OF "SUTURES":

171. WAS PREVIOUS MENISCUS SURGERY PERFORMED?
   - No
   - Yes, excision
   - Yes, repair healed/stable
   - Yes, repair not healed, unstable
N. PCL Repair or Reconstruction Performed?

172. PCL REPAIR OF RECONSTRUCTION PERFORMED?  
☐ No - **If NO, proceed to Section O**  
☐ Yes

173. PRIMARY (1st) OR REVISION:

- Primary  
- Revision

- Reconstruction
- Repair mid-substance
- Repair avulsion femur
- Repair avulsion tibia
- Augment/Primary repair

174. GRAFT TYPE:

- Autograft
- Allograft
- Both allograft and autograft
- Prosthetic

175. GRAFT SOURCE:

**Single Bundle**
- BPTB
- Quad TB
- Hamstring
- Achilles TB
- Other: ________________

**Double Bundle**
- BPTB/Hamstring
- Quad TB/Hamstring
- Achilles Split TB
- BPTB/BPTB
- Other: ________________

176. SURGICAL EXPOSURE (Femoral):

- Arthroscopic - assisted (outside-in)
- Arthroscopic (endoscopic, all inside)
- Traditional arthrotomy (patella everted)
- Miniarthrotomy (patella not everted)

177. FEMORAL POSITION:

- Single bone tunnel (anterolateral)
- Double bone tunnel (anterolateral and posteromedial)

178. METHOD USED TO ACHIEVE FEMORAL POSITION:

- "Freehand" / Placement with or without drill guide
- Reference probe _____________
- Xray
- Ref probe + xray
- Other ______________
N. PCL Repair or Reconstruction
Perforated (cont’d)

179. FEMORAL FIXATION:
- Interference screw (metal)
- Interference screw (bioabsorbable)
- Suture + button
- Suture + post
- Suture + staple
- Staple tissue

180. TIBIAL POSITION:
- Bone tunnel
- Posterior tibial lattal
- Other __________

181. METHOD USED TO ACHIEVE TIBIAL POSITION:
- "Freehand" Placement with or without drill guide
- Reference probe __________
- X-ray
- Freehand with or without drill guide + x-ray
- Ref probe + x-ray
- Other __________

182. TIBIAL FIXATION:
- Screw and washer 6.5 mm cancellous screw
- Screw and washer 4.0 mm malleolar screw
- Screw and washer small fragment screws
- Interference screw (metal)
- Interference screw (bioabsorbable)
- Suture + button
- Suture + post

183. Graft tensioned at ______ degrees flexion

184. Residual posterior laxity following graft fixation at 70 degrees flexion: ______ mm

185. Postop full active or passive ROM is allowed when? ______ days

186. FWB without support is allowed when? ______ days post-op

187. How long do you use a functional PCL stabilizing brace for ADL post-op? ______ days

188. When do you allow closed chain activities? ______ days

189. When do you allow open chain activities? ______ days
O. OCD LESION

**OCD LESION:**  
☐ Yes  ☐ No *(if so, you are finished with this form)*

190. **PROCEDURE FOR OSTEOCHONDRITIS DISSECANS?**  
☐ No  ☐ Yes

191. **SURGICAL EXPOSURE** (check all that apply):  
☐ Arthroscopic  
☐ Mini-arthrotomy  
☐ Complete Arthrotomy (evert patella)  
☐ Extra-articular MEDIAL  
☐ Extra-articular LATERAL  
☐ Percutaneous MEDIAL  
☐ Percutaneous LATERAL

**MEDIAL ARTICULAR CARTILAGE FINDINGS**

192. **MEDIAL FEMORAL CONDYLE OCD?**

☐ Yes  
☐ No - if NO, go to #193

- intact  
- cracked attached  
- cracked detached lying in-situ  
- cracked detached loose body

- medial to lateral width (%)  
- medial to lateral (in mm)  
- anterior to posterior (in degrees)  
- anterior to posterior (in mm)  
- if attached, % of lesion still intact

**LATERAL ARTICULAR CARTILAGE FINDINGS**

193. **LATERAL FEMORAL CONDYLE OCD?**

☐ Yes  
☐ No - if NO, go to #194

- intact  
- cracked attached  
- cracked detached lying in-situ  
- cracked detached loose body

- medial to lateral width (%)  
- medial to lateral (in mm)  
- anterior to posterior (in degrees)  
- anterior to posterior (in mm)  
- if attached, % of lesion still intact

**TROCHLEAR ARTICULAR CARTILAGE FINDINGS**

194. **TROCHLEA OCD?**

☐ Yes  
☐ No - if NO, go to #195

- intact  
- cracked attached  
- cracked detached lying in-situ  
- cracked detached loose body

- medial to lateral width (%)  
- medial to lateral (in mm)  
- anterior to posterior (in degrees)  
- anterior to posterior (in mm)  
- if attached, % of lesion still intact
O. OCD LESION

TREATMENT

195. DEBRIDEMENT:
   
   - Yes
   - No
   
   If yes, select:
   - articular cartilage only
   - partial excision cartilage and bone
   - complete excision
   - other

196. EXCISION OF LOOSE BODY:
   
   - Yes
   - No
   
   If excision, check any additional procedures that apply:
   - debridement
   - drilling
   - microfracture
   - abrasion arthroplasty
   - bone grafting
   - osteochondral autograft transplant
   - osteochondral allograft transplant
   - autologous chondrocyte implantation

TREATMENT OF FRAGMENTS NOT EXCISED

197. DRILLING:
   
   - Yes
   - No
   
   Select:
   - antegrade (proximal to distal)
   - retrograde (through articular cartilage)
   
   a. # of cartilage punctures: 
   
   b. total # of drill passes (multi-directional same cartilage puncture): 
   
   c. mm K-wire size: 

O. OCD LESION

199. FIXATION:

☐ Yes
☐ No

☐ AO type screw

1. Size (mm):
2. # of screws:
3. Cannulated:

☐ Bioabsorbable screw

1. Size (mm):
2. # of screws:

☐ Herbert - Whipple

1. Size (mm):
2. # of screws:

☐ Accufix

1. Size (mm):
2. # of screws:

☐ Pins metal threaded

1. Size (mm):
2. # of screws:
3. Antegrade:
4. Retrograde:

☐ Pins metal smooth

1. Size (mm):
2. # of screws:
3. Antegrade:
4. Retrograde:

☐ Pins bioabsorbable

1. Size (mm):
2. # of screws:
3. Antegrade:
4. Retrograde:

☐ Biologic fixation - matchstick bone plugs

1. Size (mm):
2. # of screws:

☐ Biologic fixation - osteochondral autograft

1. Size (mm):
2. # of screws:
O. OCD LESION

199. BONE GRAFTING:  
☐ Yes  
☐ No  - If NO, you are finished with this form

200. BONE GRAFTING TECHNIQUE:  
☐ Antegrade  
☐ Retrograde packed behind fragment

201. BONE GRAFT SOURCE:  
☐ Autograft  
☐ Allograft  
☐ Other supplementation  
source — Medial femoral condyle  
☐ Lateral femoral condyle  
☐ Proximal tibia  
☐ Iliac crest