Robert G. Marx
Editor

Revision ACL Reconstruction

Indications and Technique

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I would like to dedicate this book to my wife Rena for her support, guidance, and encouragement, without which this book would not have been possible. I am also grateful to my daughters Ella and Hannah who are sources of inspiration and love.

Foreword

This book edited by Dr. Robert Marx on anterior cruciate ligament revision reconstruction is an excellent resource for the surgeon. The complex issues of alignment, slope, meniscus loss, and associated injuries to the medial collateral ligament and postero-lateral corner are covered in detail. Multiple techniques for dealing with misplaced or expanded tunnels are very well covered. Other difficult clinical problems such as failed double-bundle reconstructions and patients who have failed multiple operations are covered in great depth. This is the first text to cover all aspects of ACL revision surgery. The book has the potential to help surgeons avoid failed revision reconstructions in the future.

Overall, this is a superb book that will greatly aid both the young as well as the experienced surgeon in managing these difficult problems.

New York, NY, USA — Russell F. Warren MD

Preface

To produce this textbook, I recruited some of the most experienced and knowledgeable ACL surgeons and therapists from around the world. Contributors from over a dozen countries covering every continent on the planet bring varying perspectives to the care of the failed ACL reconstruction. The book is intentionally divided up into chapters that necessitate overlap. Since revision ACL reconstruction comprises a heterogeneous group of patients with many different problems, the overlap allows for various viewpoints and different techniques for the same problem. In revision ACL reconstruction, there is often not a single right answer, but instead several reasonable options to choose from. In these cases, it is up to the surgeon to select the technique that they are most comfortable with and that will work best in their hands. It is my hope that this book will bring new thoughts and techniques for revision ACL reconstruction to surgeons to assist them in caring for their patients.

New York, NY, USA Robert G. Marx

Acknowledgments

I have been fortunate to have had outstanding mentors during the course of my career. During my residency training, Allan Gross and Jim Waddell succeeded each other as the chairman of orthopedic surgery at the University of Toronto. Their leadership was invaluable to me during that time. Jim Wright was my thesis supervisor for my research fellowship and he taught me the key principles for performing and evaluating clinical research. Tom Wickiewicz was the fellowship director for my sports medicine fellowship and his emphasis on education provided a valuable foundation. Russ Warren was a great mentor to me during my fellowship and he had a profound impact on how I care for patients. Lastly, my colleagues on the Sports Medicine and Shoulder Service at HSS contribute to a rich academic environment where we continue to learn from one another year after year. I am extremely grateful to all of these individuals for their time and effort teaching me and for motivating me to teach others.

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Patient-Related Risk Factors for ACL Graft Failure

1

Andrew R. Duffee, Timothy E. Hewett, and Christopher C. Kaeding

Introduction to Patient-Related Risk Factors for ACL Graft Failure

An anterior cruciate ligament (ACL) tear is a devastating injury to an athlete and unfortunately is one of the more common knee injuries in athletes involved in rapid deceleration moves. An ACL deficient knee has a very high risk of instability, subsequent injury, and long-term osteoarthritis. It is estimated that between 100,000 and 250,000 of these injuries occur each year in the United States [1, 2]. Many of these athletes are adolescents involved in cutting, pivoting, and jumping sports. Reconstruction of the ACL is commonly performed to restore stability to the knee and allow the patient to return to a healthy and active lifestyle.

There have been numerous published studies that investigated risk factors for tearing a native ACL. Some of the identified risk factors include sex [3–11], activity level and sports participation [12–17], anatomic variables such as notch width and tibial slope [18–20], and neuromuscular control and lower extremity biomechanics [21, 22]. However, there is a relative dearth of scientific data examining risk factors for graft failures or re-tears after an ACL reconstruction.

The past 2 decades have seen significant advancements in our ability to restore stability and function to an ACL deficient knee with a primary ACL reconstruction. Though the procedure and rehabilitation has become more predictable, it still requires many months of rehabilitation and time away from the athlete's sport. After committing the time, effort and expense of a primary ACL reconstruction, to have it then re-tear is not only a frustrating and discouraging event for all involved, but there is also growing evidence that the long-term health of the knee is then at even greater risk [23]. In a meta-analysis, the overall graft failure rate was estimated to be 5.8 % at 5-year follow-up [24]. Reports of ACL graft failure rates range from 2 to 25 % in the literature. Why re-tear rates have been reported with such varied results has become a subject of further investigation. Certain subgroups have begun to be identified as having increased risk of ACL graft failure. Understanding these risk factors is the first step toward minimizing the re-tear rates of ACL grafts.

ACL graft failure has been related to poor surgical technique, trauma, failure of biological incorporation, graft type, infection, and undiagnosed concurrent knee injury [8, 25–31]. Only recently, however, have researchers begun to examine some of the patient-related risk factors for re-tears such as neuromuscular control, age,

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sex, and activity level. The importance of identifying and quantifying patient-related risk factors is twofold. A more complete understanding of these risk factors would enable clinicians to better counsel patients on their expected outcomes. In addition, if the risk factors are modifiable, there would be the opportunity to prevent or reduce the incidence of re-tears. If the risk factors are significant and cannot be modified, the patients should be made aware of the risk. If the risk factor is modifiable, consideration should be made of the efforts required that would reduce the risk of re-tear. We will review activity level, sex, age, biomechanical factors, and neuromuscular control as risk factors for graft failure after primary ACL reconstruction.

Activity Level

Though not fully investigated, there is increasing evidence that the level of activity to which an athlete returns after ACL reconstruction is a significant risk factor for graft failure. Those that return to higher levels of jumping, cutting, and start/stop activities are more likely to have a re-tear of their graft.

Borchers et al. demonstrated in a case-control study that higher activity level after reconstruction puts the patient at increased risk for graft failure [25]. This 1:2 case to control matched design identified 21 patients with ACL graft failures from the Multicenter Orthopedic Outcomes Network (MOON) prospective cohort database. MOON is a multicenter research consortium dedicated to studying clinical outcomes following ACL reconstruction. In this study, only one surgeon's data was used to minimize potential confounders. The 21 case subjects were compared to 42 age- and sex-matched controls. All subjects underwent the same surgical technique, as well as identical postoperative rehabilitation and return-to-play guidelines. Activity level was measured using the Marx activity scale which is a validated instrument quantifying the amount of running, cutting, decelerating and pivoting an individual performs on a 0–16 scale with 16 being the highest level [32]. The mean Marx scores for both case and control subjects at the time of initial ACL injury was 16. The graft failure group had a mean Marx score of 16 at the time of re-tear which averaged 12 months after reconstruction. This was compared to a mean Marx score of only 12 for the control group, at the same mean postoperative time period of 12 months. Restated, both the re-tear group and control groups had Marx 16 activity levels when they tore their native ACL. The re-tear group returned to Marx 16 activity after their ACL reconstruction, whereas the age and sex matched controls only returned to Marx 12 activity levels. Logistic regression was used to evaluate this outcome variable. Those athletes who returned to an activity score greater than 12 had a 5.53 greater odds of ACL graft failure than did those who returned to activity scores of 12 or less (95 % CI 1.18–28.61; $p=0.009$).

Salmon et al. examined the rates of contralateral ACL rupture and ACL graft failure after reconstruction using either hamstring or patellar tendons [8]. This case series also identified patient characteristics that would increase the risk of injury or re-injury including activity level. Six hundred seventy-five patients with single limb ACL reconstructions were interviewed by telephone 5 years after surgery. Activity level in the form of an International Knee Documentation Committee scale score was collected. Six hundred twelve patients were followed-up and 39 patients had sustained a graft failure (6 %), whereas 35 patients sustained contralateral ACL tears (6 %). Athletes that returned to level 1 or 2 sports involving jumping, pivoting, and side-stepping increased the odds of contralateral knee ACL tear by a factor of 10. With respect to the ACL reconstructed knee, 8 % of those that returned to level 1 or 2 sports had a re-tear compared to only 4 % of those that only returned to level 3 or 4 sports (adjusted OR = 2.1; 95 % CI 1.0–4.6; $p=0.05$).

In a retrospective comparative study, Barrett et al. analyzed outcomes of bone-patellar tendon-bone (BT) fresh-frozen allograft ACL reconstructions in patients under the age of 40 with regard to Tegner activity scores [26]. Patients were required to have a minimum of 2 years of follow-up, no concomitant ligament injuries or prior surgeries. Seventy-eight of 111 patients met inclusion criteria and were available for follow-up. The control group consisted of 411 BTB autograft ACL reconstructions. Allograft reconstruction patients who returned to higher activity had a 2.6-fold increase of failure rate compared to low-activity allograft patients ($p=0.048$).

Shelbourne et al. followed 1,820 patients prospectively for 5 years following primary ACL reconstruction using BTB autograft, and complete follow-up data was obtained on 78 % of patients ($n=1{,}415$) [27]. Activity level data was collected including the time at which they returned to full activity, the type of activity, as well as the level to which they returned. This information was collected during office visits in the first year and yearly by mail subsequently. Jumping, twisting, pivoting sports at the collegiate or professional level were rated as 10, school-age or club level as 9, and recreational level as 8. They concluded that return to higher activity correlated with higher re-tear rates.

Laboute et al. in their analysis of 298 ACL reconstructions found the following re-tear rates by level of competition: regional 8.1 %, national 10.4 %, international 12.5 % [33]. Though this trend did not reach statistical significance, it is in keeping with the other studies demonstrating increasing level of activity as a risk factor for graft failure.

If returning to a higher level of activity after an ACL reconstruction increases one's risk of graft re-tear, the next question that arises is whether the timing of return to full activity influences risk of re-tear. This issue has not been prospectively studied. The timing of return to full activity could be associated with the graft's biologic incorporation as well as the patient's recovery of neuromuscular control; both of which may be time dependant. Shelbourne et al. in their analysis of re-injury within 5 years after ACL reconstruction with patella tendon grafts found that return to full activity before or after 6 months did not significantly affect graft failure rates [27]. Tanaka et al. in their conclusions recommended that early return to activity should be avoided as all of their failures occurred early and none after 2 years [30]. Laboute et al. reported that athletes that returned to full activity prior to 7 months had a higher re-tear rate than those that returned at greater than 7 months: 15.3 % vs. 5.2 % ($p=0.0014$) [33].

In summary, activity appears to be a significant risk factor for graft re-tears after ACL reconstruction. There are several quality studies that all indicate that returning to higher activity levels after reconstruction places the graft at a greater risk for re-tear. This intuitively is consistent with the observation that participation in aggressive deceleration and cutting sports places the native ACL at risk for failure. The timing of when patients return to full activity and its influence on ACL reconstruction outcomes warrants further study.

Sex-Based Differences

While native ACL injuries occur more often in women than men, there is conflicting evidence in the literature regarding whether gender is a significant risk factor for ACL graft failure. Wright et al. using the MOON prospective cohort, found a revision rate of 3 % ($n=7$) of 235 subjects at a follow-up of 2 years [29]. Male patients constituted six of the seven failures. This did not however translate to a statistically significant difference given the sample size. Tanaka et al. found a rate of 9.4 % re-tears in a case series of 64 female basketball players [30]. Stevenson and Noojin have shown greater re-tear rates in females, but were not able to show statistical significance [9].

Shelbourne et al. showed no difference for re-tear between men and women ($p=0.5543$) in their overall cohort [27]. However, boys did show a statistically higher graft failure rate in the group of patients <18 years of age.

Salmon et al. also showed a higher percentage of males experiencing re-tears than women at overall incidence rates of 8 % (30/383) and 4 % (9/229), respectively; however, this did not reach statistical significance (95 % CI 0.4–1.9; $p=0.67$) [8]. Barrett et al. did not find sex as a significant risk factor for re-tear in their analysis of 263 males and 226 females [26]. The studies by Kaeding et al. [31] and Laboute et al. [33] also did not find a difference in graft re-tear rates between males and females.

The above studies did not do an adequate job at controlling for return to activity after ACL reconstruction. If there is a difference in the post-reconstruction activity level between the male and female groups then no meaningful comparison can be made.

Paterno et al. performed a systematic review comparing sex differences in ACLR outcomes by graft type [34]. One factor that may contribute to AP knee laxity after ACLR is the strength and integrity of the graft type used to reconstruct the native ACL. The debate on optimal graft type choice for ACLR remains controversial. The two most commonly used autogenous grafts include the BTB and hamstrings tendon (HS) [1, 35, 36]. Advantages of BTB grafts include tissue accessibility for graft harvest, strong structural properties, bony fixation (potential for bone-to-bone healing) and predictable success rate in restoration of knee stability [37]. On the contrary, advantages of HS grafts include fewer donor-site complications [37]. Reconstructions with HS grafts tend to demonstrate increased anterior laxity with time post surgery [38–40]. Many authors continue to recommend HS grafts as a viable, stable alternative to BTB grafts, and there has been a large increase in the relative percentage of HS grafts used by sports medicine surgeons in the United States and abroad [41, 42].

Sex differences in AP knee laxity between HS and BTB grafts have been reported by multiple studies. In general, females with a HS graft have demonstrated significantly greater AP knee laxity than males with a HS graft [3–5, 41]. Muneta et al. reported that patients who received a HS graft had a greater percentage of subjects with greater than 5 mm of asymmetry in AP knee laxity [6]. In addition, there were more females with greater than 5 mm of asymmetry in AP knee laxity than males. Pinczewski et al. reported that females with a HS graft ACLR had significantly greater AP translation and significantly fewer patients with less than 3 mm of asymmetry than males with an identical procedure at 2 years post-reconstruction [7]. The change in their outcome at 10 years when compared to 2 years post-operative may be related to subject drop out due to re-injury and contralateral injury. In addition to the studies that examined subjects with both HS and BTB grafts, studies that investigated only subjects with HS grafts presented similar results. Salmon et al. [43] and Noojin et al. [9] noted greater AP translation in females when compared to males with HS grafts.

No studies that investigated the influence of sex and graft source on outcomes after ACLR reported significant sex differences in asymmetry in AP knee laxity with a BTB graft [34]. Ferrari et al. reported the mean side-to-side differences in AP knee laxity of male patients who had ACLR with a BTB graft was significantly less than in females [44]. However, there was no difference in the percentage of patients who had greater than 5 mm of asymmetry in AP laxity. The studies of stronger methodological design reported no significant difference in AP knee laxity between sexes following ACLR with a BTB graft. These results are consistent with other studies in the literature that reported no sex differences in AP knee laxity [45, 46] or graft failure [47, 48] with a BTB graft.

Females with a HS graft may demonstrate significantly greater side-to-side differences in AP translation than a cohort of females patients with a BTB graft [3, 5, 41]. Other studies also reported greater values in mean AP knee laxity asymmetries in females with a HS graft when compared to a BTB graft ACLR [3, 4]. Pinczewski et al. reported in a study with 10-year follow-up that there was no difference in mean AP laxity between the HS and BTB groups [7]. Taken together, these findings indicate that females experience greater asymmetry in AP knee laxity after an ACLR with a HS graft than with a BTB graft.

In summary, the evidence for sex as a risk factor for graft re-tear after ACL reconstruction is conflicting. This may be due largely to confounding factors such as activity level after ACL reconstruction. It is clear that for equal exposure to high risk sports, females have a 2–6 times increased risk of tearing their native ACL than males. If there is no difference between male and female re-tear rates after ACL reconstruction, then something has changed from the baseline conditions. Several scenarios can potentially explain this. One can speculate that the ACL graft is stronger than the native female ACL and that they are not at an increased risk after reconstruction compared to males receiving similar strength grafts. This would be supported by Shelbourne's observation that females do not have an increased risk of tearing their ACL grafts, but do have an increased risk of tearing their contralateral native ACL compared to males [27]. This would assume that both lower extremities return to equal neuromuscular function, use and risk exposure. Another scenario would be that females continue to have their baseline increased risk of ACL injury after reconstruction but this is not observed because they do not return to as high a level of activity after reconstruction compared to males. This decreased exposure would hide their increased intrinsic risk. A third scenario would be that a neuromuscular adaptation is made during the surgery/rehabilitation process that reduces their risk.

Age

Kaeding et al. demonstrated that age was a significant risk factor for graft failure using the MOON prospective longitudinal cohort. [31] Failure was defined as revision ACL reconstruction within 2 years of the index operation. In order to control for confounders they examined a single surgeon's 281 ACL reconstructions. Multivariable regression analysis was performed for ACL graft failure. The model was confirmed against the remainder of the MOON cohort for generalizability of the results. For every 10 year decrease in age, it was shown that the risk of re-tear increased 2.3 times. Essentially, the risk of re-tear fell nearly in half for every 10 years of increased age. Further, patients in the second decade of life had the highest failure rate at 8.2 %. The authors discuss that age is likely a proxy for activity level and that if activity level is well controlled, age independently may not be a true risk factor for failure of reconstruction.

Shelbourne et al. found that patients <18 years of age had a re-tear rate of 8.7 % while those aged 18–25 had a 2.6 % re-tear rate, and those over 25 re-tore at only 1.1 % [27]. While showing that younger patients had higher re-tear rates, he also documented that younger patients participated in higher levels of activity both before and after ACL reconstruction ($p < 0.0001$). These patients were statistically more likely to undergo subsequent ACL tear, in either knee, than older patient groups. The incidence of subsequent ACL injury was 8.7 % for both the reconstructed and contralateral knee.

Tanaka et al. found the mean age of graft failures to be younger but this was not found to be statistically significant [30]. All graft re-tears occurred in high school girls and the authors suggest that this may be due to the lack of supervision during follow-up as most high schools do not employ athletic trainers. Barrett et al. also found age to be a significant predictor of graft failure ($p = 0.012$) [49]. In their cohort, patients 25 years or younger experienced a failure rate of 16.5 % while 8.3 % of those older than 25 years failed.

In summary, younger patients are consistently reported to have a higher incidence of graft failure after ACL reconstruction. As there is strong evidence that post-reconstruction activity is an independent risk factor, care must be taken to evaluate whether age is only a proxy for activity. As Shelbourne et al. demonstrated, activity and age are strongly correlated in ACL reconstruction patients [27], many activity scales may not be sensitive enough to separate the interaction between age and activity. For example if "playing basketball" is a measure of activity, are the loads seen at the knee equal between high school varsity and over-40 league basketball players? They would grade equal on the activity scale, but the high school player may experience higher loads at the knee and thus actually have a higher exposure of activity risk that was not detected by the activity scale and may be attributed to young "age" in a multivariate analysis. This difficulty in separating age and activity must be kept in mind when one is interpreting or designing a study evaluating these factors.

Neuromuscular Factors for ACL Graft Failure

Tanaka et al. demonstrated in their case series of ACL reconstructions that preoperative quadriceps and hamstring strength was lower in the re-tear group [30]. Measurements compared to the contralateral extremity were 65 % and 71 % respectively. However, only the quadriceps difference was statistically significant from those that did not re-tear. Postoperative strength did not differ between groups. The authors suggest that early reconstruction may affect the ability of the athlete to regain strength, balance, and agility prior to reconstruction and that this may ultimately affect their outcome and risk of failure.

Paterno et al. performed a prospective study designed to identify predictors of a second ACL injury (ipsilateral or contralateral) after primary ACL reconstruction and return to sport [28]. Thirty-five female and 21 male participants had undergone ACL reconstruction and had returned to a pivoting or cutting sport. Three-dimensional biomechanical analysis of movement during a drop vertical jump (DVJ), assessment of postural stability, and assessment of anterior-posterior (A-P) knee laxity were obtained. Following their initial testing session, subjects were then contacted monthly for the following 12 months. The number of athlete-exposures and knee injuries was recorded at the time of each contact. An athlete-exposure was defined as an activity that puts the athlete at risk for ACL injury. Statistical analysis identified four variables from the DVJ test that combined to predict a second ACL injury following ACL reconstruction. These included greater uninvolved limb hip internal rotation during initial landing, greater coronal plane valgus of the involved limb upon landing, greater side-to-side differences in knee extension moments at initial contact in the sagittal plane, and less single-leg postural stability in the involved limb.

Paterno et al. demonstrated that postural stability deficits and altered neuromuscular control of the hip and knee during landing are risk factors for second injury following ACL reconstruction [28]. These authors examined both ipsilateral and contralateral limbs in combination. Specifically, net hip external rotation torque at initial contact of landing, increased valgus knee motion, side-to-side differences in relative quadriceps to hamstrings activation and deficits in postural stability predicted second ACL injury with high sensitivity and specificity.

Valgus kinematics of the lower extremity and the neuromuscular contributions that control these movements during the deceleration phase of landing have been identified as strong predictors of future ACL injury in both healthy athletes and in athletes following ACLR [28]. This position of dynamic valgus alignment of the lower extremity has been described by several authors as a body position where the knee joint collapses medially and represents the combination of hip adduction, hip internal rotation, knee flexion, and internal tibial rotation [21, 50, 51]. This position has been shown in cadaveric models to increase strain on the ACL [52–54] and, in one prospective cohort study, to predict future ACL injury in a cohort of high school female athletes [21].

There appears to be an exceedingly high incidence of second ACL injury after ACLR and return to play, with prevalence in the range of one in eight to one in four [21]. The Paterno et al. study prospectively evaluated biomechanical and neuromuscular variables during the landing phase of a DVJ, in addition to assessing dynamic postural stability at the time the athlete was released to return to sport, to determine if deficits in these variables were predictive of a second ACL injury [28]. The study findings indicate that generation of a net hip internal rotation torque, frontal plane knee range of motion, asymmetries in sagittal plane knee moments at initial contact of landing and postural stability are collectively a strong predictor of a second ACL injury after ACLR with high sensitivity and specificity. The net hip internal rotation moment by itself appears to be a strong predictor of second ACL injury risk.

The reported findings of hip muscle external rotation torque deficits are highly clinically significant. Targeting interventions to address impaired hip strength has the potential to dramatically reduce second ACL injury following ACLR. Therefore, implementation of these interventions at the end stages of rehabilitation after ACLR may have the potential to also reduce second ACL injury rates as well. This doesn't necessarily translate to graft failure, but a larger population looking at only ipsilateral limbs may show the same effect with respect to graft rupture rates.

Tibial Slope

Simon et al. showed that the lateral plateau in patients with native ACL injuries had greater posterior slopes then knees in individuals that had never torn an ACL [18]. We are not aware of any studies evaluating slope as a risk factor for graft re-tear following ACL reconstruction. In theory, knees with greater posterior tibial slope may have increased risk of re-injury after reconstruction as the graft may be subject to greater loads due to osseous anatomy. With axial loading, knees with greater posterior angled tibial plateau slopes would likely produce greater anteriorly directed forces on the tibia, thus placing larger loads on the ACL graft.

BMI/Smoking

Kowalchuk et al. demonstrated that a BMI > 30 and smoking both correlated with decreased patient reported outcomes after ACL reconstruction [55]. They did not look at re-tear rates. Whether smoking affects the biologic incorporation of the graft, neuromuscular control/recovery, or activity level (and hence graft re-tear) has not been well investigated. The influence of BMI on graft re-tear has not been fully investigated as well. BMI may have an influence on loads seen by the ACL graft or the level to which patients return after ACL reconstruction.

Future Direction

The Multicenter ACL Revision Study (MARS) cohort has been developed to obtain sufficient numbers of subjects to allow multivariable analysis to determine predictors of clinical outcomes after revision ACL reconstruction. This multi-surgeon, multicenter prospective cohort is the first and largest cohort of its kind and will enable further study of patient variables that affect ACL graft failure. The authors provided descriptive analysis of this cohort in a recent publication [56]. The most common mode of failure of the initial 460 enrolled patients was traumatic (32 %). Seventy-six percent reported they were playing a sport at the time of re-injury, most commonly soccer or basketball. The age at the time of revision differed by gender with females undergoing revision earlier (second decade) than men (third decade).

To obtain further information on patient factors that affect ACL graft failure, high quality, prospective multicenter studies will be required. The data collected from MARS and similar large multicenter cohorts will not only help answer further questions about risk factors for graft failure from primary and revision ACL reconstructions, but will also facilitate quality research regarding clinical outcomes of ACL reconstructions.

Summary

Establishing and quantifying risk factors for graft failure in primary ACL reconstruction greatly enhances the ability of the surgeon to counsel and treat patients accordingly. While activity level and age have been shown to be significant risk factors for graft failure after primary ACL reconstruction, age may merely be a proxy for activity. The athlete that intends to return to a very high level of cutting/jumping activity is clearly at greater risk for failure and should be made aware of this at the time of pre- and postoperative counseling. Further, gender has not been definitively shown to be a significant risk factor for graft failure, although the risk has been shown to be higher in females for native ACL tears. Certainly neuromuscular risk factors have been identified and may be the most modifiable [28]. With respect to patient-related risk factors for ACL graft re-tear, high activity level after ACL reconstruction is supported by the most evidence in the literature.

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2

Avoiding the Failed ACL: How to Prevent ACL Tears Before They Occur

Jessica Hettler and Grethe Myklebust

Injuries to the anterior cruciate ligament (ACL) are common throughout the athletic population starting as young as 6 years old. These injuries occur from either traumatic, contact injuries or non-contact mechanisms (jumping or pivoting) during sport participation. Females are plagued by a 4–6 times higher incidence in non-contact injuries [1, 2]. There has been a large amount of research completed over the years regarding surgical techniques and rehabilitation after surgery, but prevention has been studied less. This chapter will review common causes for ACL injuries, discuss gender differences, introduce assessment for injury risk, and highlight the importance of different training components (strengthening, flexibility, plyometrics, proprioception/neuromuscular, and sport-specific training) to assist in ACL injury prevention.

Rationale for Prevention

The concept of ACL injury prevention was initially controversial. However, over the past 10 years, a significant body of research has emerged to demonstrate that prevention programs clearly decrease the number of ACL tears. An analysis of seven studies of ACL injury prevention programs that were conducted between 1999 and 2008 evaluating over 12,000 athletes found that, on average, participation in a prevention program reduced the risk of non-contact ACL injury by 71 % [3].

In addition to reducing ACL injuries, prevention programs can also reduce other knee injuries as well as ankle and overuse injuries [4]. However, the programs must be done by the athletes throughout the season in order to have the effect. This requires a coordinated effort on behalf of the athletes, the coaches, and the team managers.

Extrinsic Versus Intrinsic Risk Factors

Risk factors for ACL injury may fall into two categories: extrinsic factors or intrinsic factors. Intrinsic factors are specific to the individual and may include: anatomical differences, hormonal changes, neuromuscular risk factors, and gender. Extrinsic factors vary from person to person and include: level and type of competition, footwear and field surface, and weather conditions [5].

The ACL has been found to have receptor sites for sex hormones (estrogen, testosterone, and relaxin). Also, the use of oral contraceptives and hormone fluctuations during follicular and ovulatory phases of the menstrual cycle may affect ACL susceptibility to injury. Overall, further research is needed to help better understand the

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female hormonal changes throughout the menstrual cycle and how they can affect the neuromuscular system with relation to athletic participation [5, 6].

Gender difference will be discussed throughout the research presented in this chapter. Overall sex differences play a role in knee kinematics and movement patterns. Women have been shown to demonstrate a greater knee abduction moment at initial contact and decreased peak stance internal rotation of the knee when compared to men. In addition, looking at recreational athletes may disguise sex-based tendencies due to variations in neuromuscular control and muscular strength [7].

Anatomical variations include notch size and posterior tibial slope. Bilateral ACL injuries may result from having a smaller notch width. ACL size tends to be smaller in females which may predispose them to less linear stiffness, a lower load to failure, and lack of energy absorption [5]. Potential injury may also occur due to association of general joint laxity, femur length, and posterior tibial slope and anterior tibial translation that can result in increased stress on the ACL [5, 6].

Neuromuscular control is the only intrinsic condition that the athlete and therapist may be able to change. The ACL is affected by anterior shear forces which can be coupled with coronal and axial plane forces. Anterior shear forces vary depending on the amount of quadriceps activation and degree of knee flexion the athlete displays with landing and movement changes. As knee flexion angles move less than 30°, there is an increased anterior shear force provided by the quadriceps and less co-activation of hamstrings, allowing for increased injury risk [5].

Neuromuscular differences occur between female and male athletes throughout stages of development. Evidence shows that the numbers of ligament strains are relatively equal in boys and girls before adolescence, but girls' rates will increase following a growth spurt spanning into maturity [6]. Girls between ages 12–16 demonstrate landing postures with increased knee extension and valgus (knock-knees) stress throughout stance. Females generally have an increase in knee joint laxity, genu-recurvatum, and less resistance to tibial rotation which can allow for injury in the sagittal, frontal, or transverse planes of motion. Males, on the other hand, demonstrate neuromuscular changes after growth spurts. This separates the males from the females as they will demonstrate development in power, strength, and coordination. This can be seen in improved scores of vertical jump height in male vs. female adolescent population [6]. Males and females will be affected equally by fatigue during athletic participation. As fatigue increases, the dynamic stability and timing of motion response to stimulus decrease, leaving the ACL susceptible to increased anterior shear forces and injury [5].

Extrinsic risk factors will also influence the risk of ACL injury, but athletes may have more control over them. Level of competition has demonstrated an increase in ACL injuries during game time situations compared to practice setting. Footwear and surface friction is necessary for stability, but too much friction may cause catching or stopping of the foot unintentionally. Torsional resistance can be altered when a football athlete wears shoes with more cleats or a handball player changes surfaces from artificial to wood flooring. Weather conditions will increase susceptibility of ACL injury with causing variations in footwear-surface interface. Protective (prophylactic) bracing has been used in skiers, military cadets, and football athletes, but no significant difference has been demonstrated [5].

Neuromuscular Imbalances

Females demonstrate sex-related neuromuscular imbalances: ligament dominance, quadriceps dominance, leg dominance, and trunk dominance. Neuromuscular imbalances may demonstrate differences in muscular strength, power, or activation patterns which may lead to increased joint and ligament loads on the knee [6].

Ligament Dominance

Ligament dominance can be defined as an imbalance between neuromuscular and ligamentous control of dynamic knee stability. This results in the ligament instead of lower extremity musculature absorbing ground reaction forces during sport. Lack of control is demonstrated in the frontal plane with landing and cutting movements, such as single-leg landing, pivoting, and deceleration. Valgus stress is produced when the athlete demonstrates poor trunk control. The ground reaction forces follow trunk motion and will shift the athlete's center of mass laterally to the center of the knee resulting in dynamic valgus positioning. Addressing the posterior chain (gluteals, hamstrings, and gastroc-soleus complex) will provide proper recruitment to obey Newton's third law (obeying equal and opposite reaction forces) [2, 6].

Quadriceps Dominance

Quadriceps dominance is an imbalance between recruitment of quadriceps and hamstrings [2]. Increased injury risk is shown with landing and cutting at low knee flexion angles (<30°). Knee flexion less than 30° has demonstrated increased quadriceps anterior pull on the tibia and less co-contraction of the hamstring and gastrocnemius, resulting in additional strain on the ACL [2]. The hamstrings will provide a synergistic motion and pull the tibia posteriorly to decrease stress on the ACL. During landing, the hamstring and gastrocnemius activate to generate an equal and opposite torque to prevent excessive forward movement of the athlete's center of mass. When the center of mass is too far forward, the knee will extend and will be enhanced by the GRF. Previous research has demonstrated that males, unlike females, activate their hamstrings first when landing. Women activate quadriceps first and display lower knee flexion angles with landing, resulting in an increased risk of ACL injury [8].

Leg Dominance

Leg dominance can be defined as an imbalance from side to side. There are deficits in regard to muscular strength, flexibility, and coordination [2, 6]. This deficiency presents a risk for both lower extremities. The athlete can become over reliant on the dominant leg, therefore adding increased stress and torque on that knee. The non-dominant or weaker limb is at risk due to the inability of load absorption to meet the demands of the sport by the surrounding musculature [2].

Trunk Dominance

Trunk dominance occurs more often in women than in men. This deficit is seen when an athlete is unable to control his or her center of mass which may be related to growth and maturation. A female's center of mass is located higher from the ground and the distribution of body mass and percentage of body fat is greater in women [8]. With decreased ability to control trunk motions and control perturbations, the athlete will respond with excessive frontal plane trunk motion. This increase in GRF and valgus force subjects the knee to increased injury risk [6]. Research has shown women respond better when treatment focuses on dynamic trunk training. Men demonstrate improvement in trunk control with single-leg balance and wobble board balance programs [8].

Building a Foundation for Prevention

In 1999, Hewett et al. proposed a three phase jump training program:

Phase I: Techniques Phase: focus on correction of posture, maintain vertical motion of jump, soft-landing, and instant recoil for next jump [2]

Phase II: Fundamental Phase: building strength, power, and agility

Phase III: Performance Phase: achievement of maximal vertical jump height

Hewett found that neuromuscular training can elicit biomechanical effects including reduction of landing forces, reduction of abduction-adduction moments, and increased hamstring-quadricep ratios. Improving posterior chain strength will contribute to improved control in the coronal plane, therefore demonstrating a reduction in valgus stress. Improving hamstring activation is crucial to diminish increased anterior shear on the knee as women tend to be quadriceps dominant. The hamstring provides important stabilization to the knee and should not be neglected. As a result of this program, women demonstrated hamstring to quadricep ratios at comparable levels to men [9].

Caraffa et al. [10], in 1996, looked at prevention of ACL injuries in soccer players. She utilized a preseason (30 day) training program for 20 min daily consisting of five phases:

1. Single-leg stance 2.5 min (4 trials per day)
2. Single-leg stance on rectangular balance board
3. Single-leg stance on round board
4. Single-leg stance on a combined round and rectangular board
5. Single-leg stance on BAPS board (multiplanar)

This program was reduced in frequency to 3× per week minimum during the soccer season. As a result the proprioceptively trained group saw a reduction sevenfold over the control group (70 arthroscopically confirmed ACL tears in the control group compared to only 10 in the trained group) [10].

In 2003, Myklebust et al. looked at a span of three seasons on prevention programs for ACL injury in female team handball. The program was completed 3× per week for a duration of 5–7 weeks during preseason, and 1× per week during season. The program focused on understanding and demonstrating quality movements, core stabilization, and proper hip and knee position with running, cutting, and jumping motions. Each week the athlete was progressed with more challenging exercises in each domain. In the end, neuromuscular training programs work best when athletes are motivated and younger. Younger athletes demonstrate a lack of preestablished movements and can easily be educated and trained with proper technique in which to build on that foundation [11].

Myer et al. [2] in 2004, reported on three essential components of broad training program:

1. Dynamic: educate on correct biomechanical movements utilizing a controlled environment for high-risk, sport-specific maneuvers
2. Neuromuscular: improvement in development of joint stabilization and muscle pre-activation to reduce high impact loads on the knee
3. Analysis: educate the athlete with feedback (visual and verbal) during and after task completion

It is important to remember that quality of movement must be maintained as quantity of repetitions is increased for successful training outcomes [2].

Ligament Dominance: Identification

Utilization of a 31-in box-drop test with maximal vertical leap can help identify an athlete as "ligament dominant." The athlete will show knee adduction during landing and low knee flexion angles which sets up the athlete for injury. The athlete must be made aware of the dangerous positions that they display as well as education in proper technique. Having the athlete visually see her technique flaws with the use of a mirror will make the athlete aware of errors in task completion. It is also important to have the coach utilize proper terminology and consistent cues when giving feedback during specific timing (during jump or landing) of the exercise. Sample feedback phrases may be "on your toes" during the jump phase and "knees bent" during landing [2] (Fig. 2.1).

Ligament Dominance: Treatment

First the athlete should be educated in proper athletic ready position: knees bent, shoulders back, eyes looking straight ahead, body weight on the balls of the feet (knees never over toes), and feet shoulder-width apart (Fig. 2.2). Simple wall-

Fig. 2.1 Vertical jumps. (**a**) Landing phase. (**b**) Jump phase. Reproduced with permission from "The ACL Solution: Prevention and Recovery for Sports' Most Devastating Knee Injury". Marx, Myklebust & Boyle, Demos Publishing 2012

Fig. 2.2 Athletic ready position. Reproduced with permission from "The ACL Solution: Prevention and Recovery for Sports' Most Devastating Knee Injury". Marx, Myklebust & Boyle, Demos Publishing 2012

jump exercises can be taught with increasing intensity of jumps. It is important for the athlete to keep knees apart with landing which reduces loading of the ACL and increases knee flexion. Progression from wall jumps to the tuck jump will allow for analysis of coronal plane movements. Utilization of the broad jump with 3–5 s holds advances the athlete in gaining and maintaining dynamic stability. To assess transverse plane motion, 180° jump can be used which teaches dynamic trunk and lower extremity control as forces are absorbed and immediately redirected in opposite motion [2].

After mastering double-leg jumps and lands, it is time to progress to single-limb hop-and-hold exercises. This motion is comparable to mechanisms that cause non-contact ACL injuries. As the athlete improves, she will be advised to land with deeper knee flexion. Finally drills involving unanticipated cutting (Fig. 2.3) are important since valgus loads are doubled with these motions. Teaching and practicing these skills may carry over to real-time game situations as they become a learned movement response [2].

Fig. 2.3 Running and cutting. Reproduced with permission from "The ACL Solution: Prevention and Recovery for Sports' Most Devastating Knee Injury". Marx, Myklebust & Boyle, Demos Publishing 2012

Quadriceps Dominance: Identification

Quadriceps dominance can be defined as an imbalance between strength, recruitment, and coordination of quadriceps and hamstrings [6]. Hamstring to quadriceps isokinetic strength ratio <55–60 % indicates quadriceps dominance. Another test that may indicate quadriceps dominance is single-leg hop-and-hold in deep squat (>90°). If the athlete is unable to maintain deep flexion or maintain upright posture, there may be less than optimal hamstring firing [2].

Quadriceps Dominance: Treatment

It is important to address strengthening of the posterior chain (gluteals, hamstring, and gastrocnemius) to prevent improper, low flexion angle form instance, landing and cutting [8]. Drills using squat jumps and broad jump and hold assist in hamstring co-contraction training for stabilization in static positions [2]. Also exercises such as plyometric 90/90 squat jumps (Fig. 2.4a, b), Russian hamstring curls (resistance band around trunk for concentric and eccentric loading), ball bridge curls (double- to single-leg progression) and plank are appropriate for activation of hamstring and abdominal stability [8] (Fig. 2.5a, b).

Carcia et al. [12] noted a gait deviation called "gluteus maximus lurch" in which there is significant gluteus maximus weakness. This deviation demonstrates increased trunk extension at heel-strike and center of mass moves posterior to the hip. This will cause inhibition of gluteus maximus, minimizing hip extension activation [12].

Activation of gluteus medius and maximus is important to diminish hip internal rotation and adduction during landing, and overall knee valgus loading forces. Suggested exercises to improve gluteal function were side-lying clam, side-lying hip abduction, single-limb squat, single-limb dead-lift, lateral band walks, multiplanar lunges (Fig. 2.6), and multiplanar hops. The gluteus medius functions concentrically to abduct the hip, eccentrically to control hip adduction and internal rotation, and acts to stabilize the pelvis. Ideal gluteus medius exercises included sidelying hip abduction, single-limb squats (Fig. 2.7), lateral band walk, single-limb deadlift, and single-limb side hop (Fig. 2.8). Gluteus maximus was shown to have the highest activation with the transverse plane lunge, single-limb squat, and single-limb deadlift [13].

Leg Dominance: Identification

Leg dominance is a neuromuscular imbalance indicated by asymmetrical strength or power (difference of 20 % or more) between limbs. This may be assessed by performance of single-limb stance on an unstable platform allowing postural sway to be calculated. Another way to assess leg dominance is by utilization of single-limb hops, where an athlete hops into different quadrants [2].

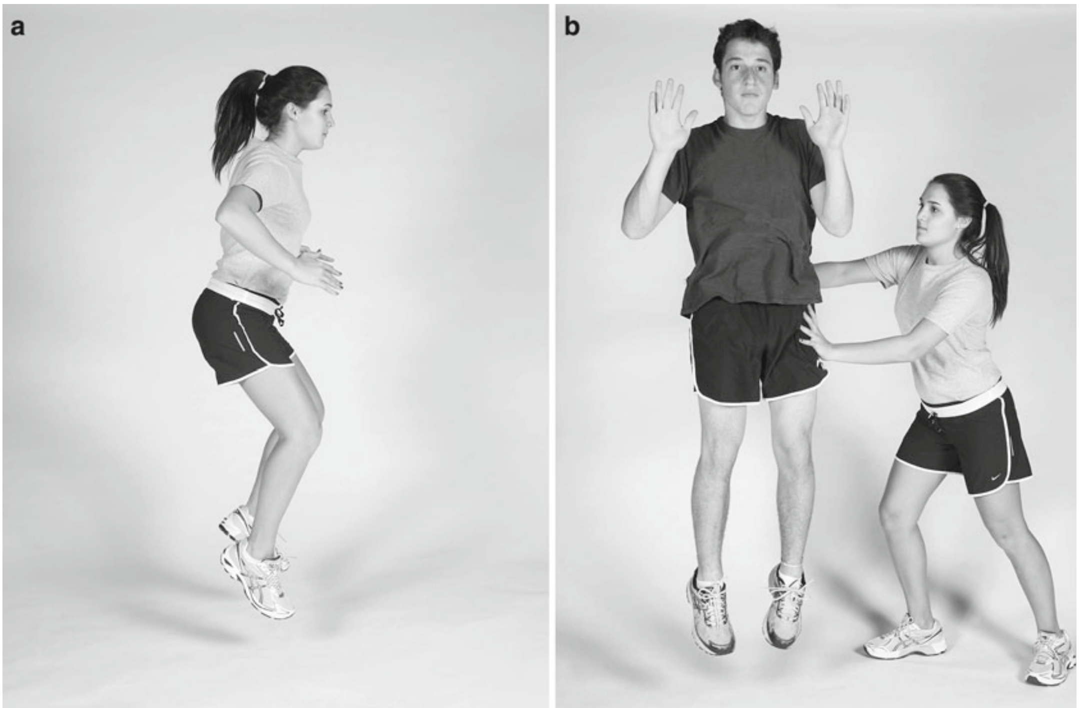

Fig. 2.4 (**a**) Box jumps (side-to-side, front-to-back, and along both diagonals). (**b**) Box jumps with Partner's push. Reproduced with permission from "The ACL Solution: Prevention and Recovery for Sports' Most Devastating Knee Injury". Marx, Myklebust & Boyle, Demos Publishing 2012

Fig. 2.5 (**a**) Thirty second plank. (**b**) Thirty second plank with one leg lift. Reproduced with permission from "The ACL Solution: Prevention and Recovery for Sports' Most Devastating Knee Injury". Marx, Myklebust & Boyle, Demos Publishing 2012

Fig. 2.6 Walking lunges. Reproduced with permission from "The ACL Solution: Prevention and Recovery for Sports' Most Devastating Knee Injury". Marx, Myklebust & Boyle, Demos Publishing 2012

Leg Dominance: Treatment

When addressing leg dominance deficits, it is important to start activities with double-leg

Fig. 2.7 One-leg squats on wobble-board. Reproduced with permission from "The ACL Solution: Prevention and Recovery for Sports' Most Devastating Knee Injury". Marx, Myklebust & Boyle, Demos Publishing 2012

Fig. 2.8 Lateral jumps. Reproduced with permission from "The ACL Solution: Prevention and Recovery for Sports' Most Devastating Knee Injury". Marx, Myklebust & Boyle, Demos Publishing 2012

before single-leg activity. It is important to maintain equal strength, balance, and foot placement between legs. For example, allowing one leg to land posterior will foster poor and unsafe habits when landing from a double-leg hop. Single-leg exercises, such as hop-and-hold or single-limb balance on unstable surfaces can help address improper landing or overuse of dominant leg. Bounding will assist in learning movement in multiplanar directions and achieve maximal vertical height and horizontal distance with each repetition [2]. When both lower extremities are alternately used in single-limb activities, there is a cross-over effect. Single-limb hopping may also influence recruitment of the posterior chain musculature, therefore assisting in reduction of quadriceps dominance as well.

Trunk Dominance: Identification

The most difficult imbalance to detect is trunk dominance during dynamic function. Performing a ball bridge with hamstring curl may assist in identifying pelvic instability by demonstrating rotation or anterior/posterior (AP) pelvic tilt during task completion in the transverse and frontal planes. Assessment of hip external rotation strength may also be a good predictor of future injury since that acts as a main stabilizer of the core and lower extremities [8].

Trunk Dominance: Treatment

It is important that the focus is not directed to the rectus abdominus, but rather to the deep

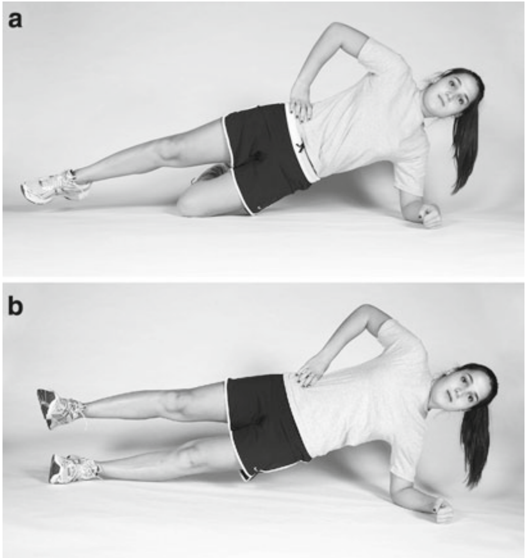

Fig. 2.9 (**a**) Side plank static. (**b**) Side plank with leg lift. Reproduced with permission from "The ACL Solution: Prevention and Recovery for Sports' Most Devastating Knee Injury". Marx, Myklebust & Boyle, Demos Publishing 2012

musculature of the core: transverse abdominus and multifidus. One way to address rotational hip strength in a closed kinetic chain is by using a resistance band to work concentric and eccentric rotational motion while on one leg. This rotational motion is an example of pelvic rotation on the femur. It is important to cue the patient and provide appropriate feedback to prevent pelvic drop in the frontal plane or pelvic tilting in the sagittal plane [12].

Leetun et al. [14] in 2004 hypothesized that lack of core stability contributes to lower extremity injuries in females. They looked at the quadratus lumborum as a lumbar stabilizer and hip abduction and external rotation strength to assist in maintaining a level pelvis and prevention of hip adduction and internal rotation while in single-limb stance. When testing for endurance in side plank (Fig. 2.9a, b), women showed a lack of endurance along with reduced hip abduction and external rotation isometric strength. When the hip and trunk are weak, females may be susceptible to large external forces during athletic participation. It is important to build endurance and train stabilizing pelvic musculature to assist in appropriate weight transfers and maintaining proper center of mass with motion involving cutting, jumping, and single-limb loading [14].

How Can We Assess for Potential Injury?

Development of a screening tool for injury risk is important to utilize before season. This tool should be simple to carry out and require dynamic movement rather than static testing. If coaches can see the deficits during preseason, they will be more inclined to complete a prevention program to specifically address the individual deficits. This screening tool should also be utilized for reassessment to monitor an athlete's progress [8].

The tuck jump is a "clinician-friendly" field-based tool that incorporates limb symmetry, core stability, posterior chain muscle firing, and control of both lower extremities in the sagittal plane [8]. Quality of motion during a 10-s trial of consecutive jumps is used to assess technique. During flight and at landing, the clinician should observe for the following movement flaws to determine which dominance the athlete displays (see Table 2.1) [8, 15].

Neuromuscular Training

An important part of athlete education for proper movement patterns is neuromuscular training. Athletes can learn how to utilize safer joint stabilization patterns and muscular pre-activation pat-

Table 2.1 Movement flaws in jump training

Dominance	During flight/jump	At landing
Ligament dominance	N/A	Valgus at landing Foot placement > shoulder width apart
Quadriceps dominance	N/A	Excessive landing noise
Leg dominance	Thigh not side to side (during motion and peak height)	Pause between jumps Does not land in same footprint
Trunk dominance	Thighs do not reach parallel (at peak height)	Pause between jumps Does not land in same footprint

terns to decrease the potential danger to the ACL during isolated sport-specific motions [8]. Research has shown that females are at greater risk while participating in sports such as soccer and basketball. Both sports require typical movement patterns of jumping/landing and cutting which are classic non-contact mechanisms of ACL injury.

Paterno [1], in 2004, observed restoring dynamic functional control through postural stability. Assessment of stability measures in the anterior/posterior (AP), medial/lateral (ML), and total overall postural stability were assessed. He chose a 6-week dynamic neuromuscular training program including:

1. Balance training and hip/trunk/pelvis strengthening (to improve strength, stability, and coordination to assist in redirecting forces)
2. Plyometrics and dynamic movement patterns (progression of jumping, pivoting, and cutting along with advancements from double-limb to single-limb)
3. Resistance training (improve strength throughout full range of motion to compliment balance and plyometric advancements)

These subjects received constructive feedback from coaches during and after technique. Overall, improvements were seen in AP and total postural stability, but no significant improvement in ML (coronal plane). This supports findings that valgus stress is a risk factor for female athletes compared to males [1].

In 2005, Hewett et al. [16] studied biomechanical measures of neuromuscular control and valgus loading at the knee as a predictor of ACL injury in female athletes. ACL injuries occur frequently due to high external joint loading during deceleration, lateral pivoting, and landing during sports. Increased valgus stress will correlate to lack of neuromuscular control in the coronal plane. This may result from insufficient adaptations of adductors and hip flexors (ligament dominance) and poor hamstring strength (quadriceps dominance). His results demonstrated that neuromuscular training programs not only can help reduce GRF and valgus stress, but also resulted in an increase in muscular power within 6 weeks [16].

Myer et al. [17] in 2006 compared the effect of plyometric and dynamic stabilization/balance training on lower extremity biomechanics. Prior research has shown that plyometric training alone may not produce beneficial results for female athletes. Female athletes demonstrate primary coronal plane movement strategies to control knee movement, which has been proven to be unproductive for proper force dissipation. It is believed that a combination of plyometric and dynamic balance training will decrease valgus loading, contralateral limb asymmetries, and impact forces. Results showed female athletes had improved sagittal plane control eliminating reliance on insufficient coronal plane movements and therefore reducing injury risk [17].

Cowley et al. [18] in 2006 examined the differences in neuromuscular strategies between landing and cutting tasks in female basketball and soccer athletes. Movement strategies including drop vertical jump in basketball and cutting in soccer demonstrated an increase in GRF and a decrease in stance time. Cutting activities compared to sagittal plane running may double the valgus load on the knee. Demonstration of valgus stress during a sport-specific motion indicates that the athlete lacks control of GRF, therefore placing the ligament at risk for injury. The authors also noted limb asymmetry between tasks completed in both basketball and soccer. Basketball placed increased GRF on the non-dominant limb with drop vertical jump, and cutting motions in both soccer and basketball placed increased GRF on the dominant leg. These factors indicate the need to train these athletes differently to meet the demands of the sport. For example, training basketball athletes with depth jumping to focus on landing forces and valgus knee collapse, where soccer athletes may focus on minimizing valgus loading with unanticipated cutting drills [18].

Myer et al. [19] in 2005 studied how a neuromuscular training program improved performance and lower extremity biomechanics in female athletes. Participants underwent a 6-week progressive program consisting of plyometrics, resistance training, core and balance training, and speed training. After completion of the program, the trained individuals demonstrated significant increases in vertical jump, single-hop distance, speed, squat, and varus-valgus stress compared to untrained subjects. The authors determined that preseason and in-season program combining all training components was indicated [19].

When and How Do We Start Prevention Programs?

The ideal age to initiate prevention training programs to improve neuromuscular and biomechanical risk factors is unknown. Benjaminse and Otten [20] reports that age 6–12 may develop correct playing techniques and allows time for these learned movements to become automatic. Between ages 12 and 14, athletes may begin prevention programs to enhance body awareness during skilled movements. Myer et al. [6] found 12 years of age would correlate to 88 % of adult stature. They determined that prevention training programs should be implemented for females before the growth spurt during adolescence.

Motor learning for athletes has been studied. Implicit learning has been shown to be effective in allowing the brain and body to establish conditions where performance ability is greatest. Explicit learning was shown to be less efficient due to the complexity of sport requiring attention not only to the movement of the LE but also to the movement of the ball and opponent [20].

Visual and verbal cues are also important learning factors. Visualization of a task through the use of mirror or reviewing videotape of the athlete's performance is a tool used for implicit learning. This allows the athlete to view themselves completing a motion correctly or improperly with self-correction. The athlete will learn how to problem-solve and develop a solution that best fits the individual's body motion [20]. Verbal cues have also been shown as positive factors during task completion to allow the athlete to correct incorrect joint angles [21].

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3 Diagnosis of Failed ACL Reconstruction

Moises Cohen, Gustavo Gonçalves Arliani, Diego Costa Astur, and Camila Cohen Kaleka

Introduction

The anterior cruciate ligament (ACL) is the principal restraint to anterior tibial translation in the knee, and also controls rotation [1, 2] (see Fig. 3.1). It is the most commonly injured knee ligament [3]. The incidence is approximately 36.9–60.9 per thousand individuals [4–6]. ACL injuries primarily affect young, active individuals and can lead to joint instability [7]. The standard treatment for ACL tears in patients who participate in cutting or pivoting sports is surgical reconstruction [7, 8]. Approximately 100,000–200,000 reconstructions are performed annually in the United States, with direct costs estimated at $3 billion [7–9]. ACL reconstruction is currently the seventh most common surgical procedure performed in the United States [10]. With the increasing number of ACL reconstructions performed annually, there has been an associated increase in the number of revisions [11–13].

Studies have demonstrated that most ACL reconstructions are performed by surgeons who perform fewer than 10–20 reconstructions per year [10]. Multiple studies report failure rates of reconstruction to be between 10 and 20 % [14–16]. In the United States, approximately 3,000–10,000 revision ACL reconstructions are performed annually [10, 17]. Approximately 15 % of all ACL reconstructions at specialized institutions are revisions.

Various factors influence the success or failure of primary ACL reconstructions including proper surgical technique, postoperative rehabilitation, injuries to meniscus, cartilage, and secondary restraints, and patient expectations. It is crucial to identify the cause of failure prior to revision ACL reconstruction to allow for detailed planning of the revision.

Definition of Failure in ACL Reconstruction

Despite the enormous advances in prevention, treatment, and rehabilitation after ACL injuries in recent years, there is no consensus for the exact definition of failure of ACL reconstruction [6].

The term "failure" is very broad and not specific, which renders the task of defining it rather difficult [18]. ACL failure can be defined by the inability to regain pre-injury function, recurrent instability, chronic pain, loss of range of motion, or osteoarthritis. Some even define failure as side-to-side difference of 4 mm or greater on the KT-1000 examination.

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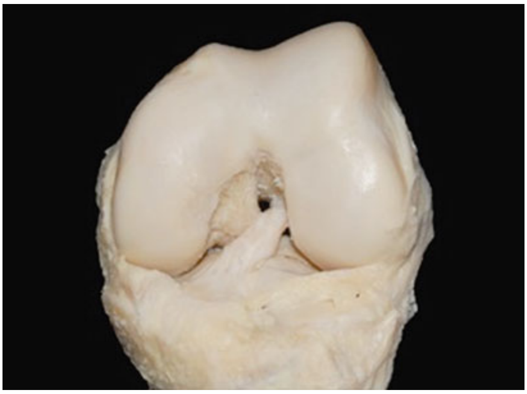

Fig. 3.1 ACL anatomy

Countless definitions can be found in the literature [19]. The definition by Johnson and Coen et al. that is frequently used defines the failure of reconstruction of the ACL as the following: the presence of recurrent instability when performing daily or sports activities or a stable, but painful, knee, with more than 10° motion loss after the surgical procedure [20].

Based on this definition, some authors recommend revision surgery for patients with instability and symptomatic objective laxity after the primary reconstruction of the ligament. The objective criteria include KT-1000 with an anterior-posterior laxity greater than 5.5 mm when compared with the contralateral knee or the presence of a positive pivot shift test [21].

Reasons for Failure in Primary Reconstruction of ACL

Various factors have been suggested as possible reasons for considering a primary ACL reconstruction "failed." It is critical to determine these factors prior to considering revision surgery.

The reasons for failure can be generally divided into three groups: recurrent instability, postoperative complications (such as infections, stiffness, and arthritis), and persistent pain [6] (see Table 3.1).

Table 3.1

Reasons for failure in primary reconstruction of ACL
Recurrent instability
Postoperative complications (such as infections, rigidity, and arthritis)
Persistent pain

Recurrent Instability

Recurrent instability is defined as the inability to restore stability in the sagittal and rotational plane after reconstruction of the ACL, leading to patient complaints [6].

Instability after reconstruction may be due to trauma, technical error, failure of initial diagnosis, early return to sport, or inadequate postoperative rehabilitation and failure of graft incorporation [14, 22, 23].

Technical errors have been shown to contribute to the failure of ACL reconstruction in 22–79 % of cases. This group includes improper positioning of the tunnels, improper graft choice, and failure to diagnose conditions associated with the ACL rupture [24–27].

Poor positioning of the femoral tunnel is the most common technical error and has been documented as the cause for failure of ACL reconstruction in 36 % of cases (see Fig. 3.2). In a series of cases, Van Dijck et al. demonstrated that improper positioning of the graft results in a greater number of meniscal and cyclops lesions after the primary ACL reconstruction [28].

Failure to diagnose conditions associated with ACL rupture also plays a fundamental role. Missed medial or lateral side laxity and/or malalignment of the lower limb can also contribute to graft failure. The presence of these factors can produce an increase in loads and stresses placed on the graft during the postoperative period, leading to laxity and early failure [6, 29, 30].

Although we grouped the causes of failure, we understand the importance of a multifactorial view of failure for ACL reconstruction. A previous study showed that the cause of failure diagnosed during the revision surgery was multifactorial in 31 % of cases [31, 32].

Fig. 3.2 Anterior position of the femoral tunnel

Postoperative Complications

The loss of range of motion is considered to be the most common cause for unsatisfactory outcomes after ACL reconstruction in many studies [33, 34]. Various factors have been described as possible causes for this complication, such as poor positioning of the graft, a prolonged period of immobilization, arthrofibrosis, excessive tension of the graft, cyclops, persistent pain, and the time between injury and surgery. The loss of extension is more common than the loss of flexion [33, 34]. The cause of this complication should be determined and, if possible, corrected before the revision surgery. The objective of treatment is an improved range of motion and knee function, which can be achieved through rehabilitation exercises and/or open or arthroscopic debridement of the knee.

The presence of persistent pain after ACL reconstruction can arise from various factors, including chondral injuries, meniscal injuries, neuroma pain from the graft harvest site, arthritis, patellofemoral pain, bruises of the bone that occur during initial trauma, and synovitis. However, the diagnosis in some situations is complex due to the multifactorial nature of the problem and the difficulty in differentiating the symptoms of recurrent instability and persistent pain reported by the patient [35, 36].

Diagnosis

History and Physical Exam

A detailed history is extremely important for the evaluation of a patient who is symptomatic after ACL reconstruction. It is through this history that most of the information will be collected and used for determining the possible cause of failure in the original surgery.

The mechanism of the injury reported by the patient can assist in the investigation of associated lesions and in determining the degree of energy of the trauma. Determining the time between injury and surgery, period of immobilization after the reconstruction and the presurgery range of motion can be useful in investigating a loss of motion [37]. Analysis of the medical records from the original reconstruction will provide information regarding the graft used, type of fixation, presence of associated lesions to cartilage/meniscus, whether a notchplasty was performed, and the physical examination under anesthesia. Other important information includes the rehabilitation program and possible postoperative complications, as well as time to and level of return to sports. With respect to return to sport, one should investigate if the expectations were realistic and if new trauma occurred following the original reconstruction [38]. Previous imagings, such as X-rays, magnetic resonance images, and arthroscopy photos, are also useful.

The physical examination of the patient's knee should be conducted after a complete history. During inspection, one should observe the alignment of the lower extremities in the sagittal and coronal planes. The presence of varus and/or valgus alignment of the lower extremity is important to evaluate the cause of failure of the original reconstruction and is fundamental to planning revision surgery. The presence of contractures in flexion or extension should also be noted. The presence of healed incisions about the knee

Fig. 3.3 Lachman test

Fig. 3.4 Anterior drawer test

provides clues on the type of graft and the fixation used in the previous surgery. The musculature of the lower limbs should be observed for atrophy. Gait should be evaluated for varus or valgus thrust due to ligamentous laxity [6]. Palpation of various anatomical structures of the knee should be performed to evaluate for painful areas and crepitation during flexion and extension of the knee.

The three physical exam maneuvers to evaluate the ACL are the Lachman test, the anterior drawer test, and the pivot shift test. A meta-analysis of studies focused on the clinical diagnosis of ACL rupture demonstrated that the Lachman test is the most sensitive and the pivot shift test the most specific, with both being indicated when there is a suspicion of rupture and/or re-rupture of the ACL [39].

The Lachman test performed in the supine position with the knee in semi-flexion is classified as grade 1 (0–5 mm), grade 2 (6–10 mm), and grade 3 (>10 mm) when compared with the healthy contralateral knee [6] (see Fig. 3.3).

The presence of previous injury to the ACL in the contralateral knee makes the evaluation more difficult. In cases where there is suspected rupture of the graft after ACL reconstruction and a previous injury to the contralateral knee, the use of records from previous evaluations is extremely valuable. Recently, Mulligan et al. investigated the utility and accuracy of the Lachman test when performed in the prone position to facilitate the test and proper stability of the thigh for larger patients and examiners with small hands. As the sensitivity and specificity of this test was 70 % and 97 %, respectively, it was concluded that the Lachman test performed in the prone position was a good alternative for examining patients with a suspected ACL injury when considered with other diagnostic criteria [40].

The anterior drawer test is performed with the patient in the supine position with the hip flexed to 45° and the knee flexed to 90° (see Fig. 3.4). It is graded according to the International Knee Documentation Committee [41] as normal (0–2 mm), nearly normal (3–5 mm), abnormal (6–10 mm), or severely abnormal (>10 mm), with the measurements based on the anterior translation of the tibia when compared with the contralateral knee [39]. This test should be performed with the patient's leg at neutral, internal, and external rotation, thus allowing an evaluation of both antero-posterior instability and the medial and lateral compartments.

The pivot shift test is the most specific test for diagnosis of ACL injury [39]. This test is graded, according to the IKDC [41], as normal, glide (+), clunk (++), or gross (+++) [6]. The pivot shift test evaluates the presence of rotational instability that may occur, for example, in sports with quick

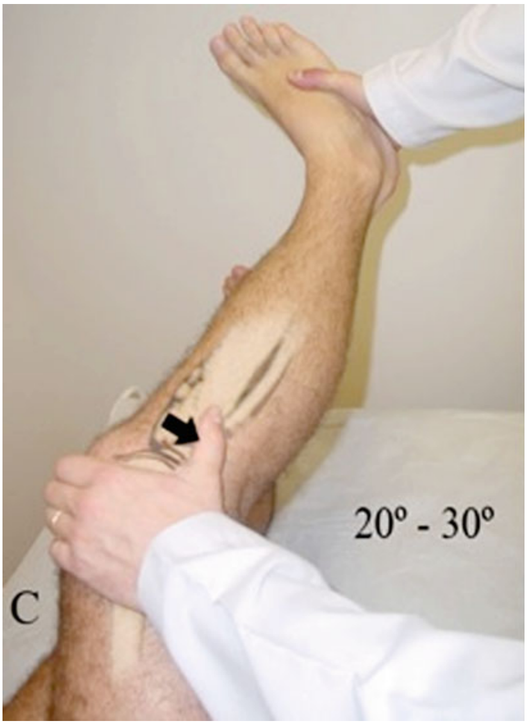

Fig. 3.5 Pivot shift test

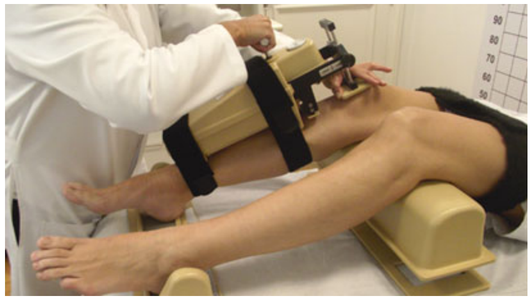

Fig. 3.6 KT-1000

changes in direction (see Fig. 3.5). Kocher et al. demonstrated that the Lachman test does not show a positive correlation with subjective evaluations after reconstruction of the ACL [42].

In the same study, the pivot shift test had a positive correlation with patient satisfaction, global function of the knee, and return to sports after reconstruction of the ACL [42]. However, the sensitivity of this test is influenced by various factors, such as the speed with which the maneuver is performed, the angle of hip abduction during the test, and the magnitude of the force applied by the examiner during the test [43].

Thus, in recent years, various authors have investigated options for objectively quantifying rotational instability of the knee [44–46]. Most of these were performed with the assistance of computerized navigation. Some authors even published studies demonstrating a high accuracy and agreement of these evaluation methods [45–47].

At present, most orthopedic surgeons use measurements of the antero-posterior translation of the tibia (KT1000/2000) and questionnaires on satisfaction and function of the knee to evaluate the stability of the joint and the success of the ACL reconstruction [48]. However, these evaluation methods do not necessarily guarantee that knee function was totally restored [49]. Moreover, they do not necessarily provide information with regard to the level of control and dynamic rotational stability. Thus, in future years, we should improve and develop objective systems for evaluating the rotational instability of the knee to better evaluate our patients.

For an objective evaluation of the isolated antero-posterior translation of the tibia, advances are already being made in terms of improvement in the various systems for measurement. The most commonly used system is the KT-1000/2000, which is accepted worldwide as a tool for measuring the antero-posterior translation of the tibia (see Fig. 3.6). The KT 1000/2000 has a high level of accuracy, even when compared with more precise systems of evaluation, such as computerized navigation [50]. Previous studies showed that the normal difference between measurements of the anterior translation of the tibia between the knees generally does not exceed 3 mm; a difference of 3–5 mm is considered to indicate a partial loss of ACL function, and a difference >5 mm is considered to indicate a total loss of function of the ligament [51].

Examination of the lateral and medial ligament complexes is essential prior to considering revision surgery. Failure to diagnose and treat associated ligament laxity can produce an increase in the load on the graft and subsequent graft failure. Injuries to the postero-lateral corner of the knee are the most commonly untreated

Fig. 3.7 CT scan post ACL reconstruction demonstrating massive expansion of the tibial tunnel requiring a two-stage revision

injuries, and have been reported in 10–15 % of patients with chronic insufficiency of the ACL [29]. Other structures, such as the medial collateral ligament, the posterior horn of the medial meniscus and the capsule, play an important role in the stability of the knee in ACL injuries and should be investigated thoroughly in the clinical examination of these patients [52]. The medial and lateral ligament complexes should be tested both with the knee flexed to 30° and in full extension. The postero-lateral corner should be tested using the external rotation recurvatum maneuver and the dial test at 30 and 90° of knee flexion [6]. The postero-lateral spin test is also helpful to evaluate the postero-lateral corner [53]. These tests should be performed preoperatively and also under anesthesia. Medial or lateral instability should be addressed at the time of revision ACL reconstruction.

Imaging

Radiographs including an antero-posterior view, lateral view, Merchant and Rosenberg views should be obtained in all patients. Hip to ankle radiographs should also be requested for patients with possible alignment abnormality, primarily in cases in which an osteotomy may be indicated [54]. Radiographs allow for the assessment of degenerative changes, tunnel position, tunnel enlargement, and prior fixation. Inadequate positioning of the tunnels can be visualized in the antero-posterior and lateral radiographs. Harner et al. described the ideal positioning of the tibial and femoral tunnels on plain XR [55]. The tibial tunnel, in the antero-posterior radiograph, should penetrate the surface of the joint at the center point of the tibial plateau. On the lateral radiograph, the authors suggest the division of the tibial plateau from anterior to posterior into four equal parts, with the ideal tunnel being positioned in the posterior third of the second quadrant. The femoral tunnel should be localized in the most posterior quadrant of Blumensaat's line.

Tunnel size should be evaluated to plan the revision surgery. Some authors have noted that revision surgery should be performed in two stages if tunnels are greater than 16 mm, as discussed in subsequent chapters [6] (see Fig. 3.7).

Magnetic resonance imaging and computerized tomography are used for preoperative planning.

MRI is used to evaluate meniscus, cartilage, and all ligaments. The advantage of computerized tomography is that bone and radio-opaque structures are highlighted which facilitates tunnel assessment, the need for hardware removal and the placement of revision tunnels.

Shen et al. have recommended the use of CT for preoperative planning of ACL reconstruction. We agree that although radiographs and MRI provide important information, CT can be very useful in determining precise tunnel size and location (see Fig. 3.7). Conventional and CT can assist in deciding preoperatively whether the original tunnels can be used or if their size as well as prior hardware require a two-stage procedure [56].

Conclusion

Revision ACL reconstruction is a complex procedure. A careful history, meticulous physical examination and detailed preoperative imaging is required. The cause(s) of failure should be determined prior to surgery if possible. Patient expectations must be managed since outcomes after revision ACL reconstruction are inferior compared to primary surgery. With the advent of improved imaging and surgical technique, we hope to increase the success rates of revision ACL reconstruction.

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4 Biomechanics and Etiology of ACL Graft Failure

Peter D. Fabricant, Moira M. McCarthy, Andrew D. Pearle, and Anil S. Ranawat

Introduction

Modern anterior cruciate ligament (ACL) reconstruction continues to have failure rates up to 13 % [1]. Failure of ACL surgery can be defined in many ways. For example, inability to return to sports, osteoarthritis, persistent pain, and loss of extension are disappointing results that occur even with successful stabilization of the knee after ACL reconstruction. The goal of this chapter is to review the biomechanics and etiology of ACL graft failure after ACL reconstruction. Clinically, graft failure is usually identified by recurrent instability. As such, this chapter will focus primarily on graft failure that results in persistent or recurrent instability after ACL reconstruction.

The etiology of ACL graft failure is varied. Multiple causes have been identified, however, in most cases, the cause is multifactorial. Timing of the failure relative to the index procedure can often help the treating surgeon to define the cause. Many authors define graft failure based on the temporal relationship to the index surgery. Early failures (<3 months) are typically related to loss of fixation, sepsis, and aseptic biological reaction. Graft failures are most common in 3–12 months postoperatively (midterm failures) and are often due to surgical technique errors related to impingement/poor tunnel placement, graft elongation secondary to creep and aggressive physical therapy, and graft failures secondary to unrecognized loss of secondary stabilizing structures. Trauma may be a cause of late failure (>12 months) but may occur at any phase of the postoperative period and may cause partial graft injury, elongation, or complete failure. The MARS cohort [2] is the largest cohort of revision ACL reconstruction cases to date, and have reported that the most common modes of failure are multifactorial (35 %), traumatic (32 %), technical error (24 %), and biologic (7 %). However, one must recognize that at every step of ACL reconstruction there is an opportunity for reconstructive failure. This chapter will review the biomechanics of the native and reconstructed ACL, and discuss the numerous potential failure mechanisms of ACL graft tissue.

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Mechanisms of Failure

Early

Mechanical Failure

Mechanical failure is the most common mode of early graft failure after ACL reconstruction, and is thought to represent 3–7 % of all failures [2]. Mechanical failures are often attributed to failure of fixation. Appropriate and adequate fixation is a critical step in ACL reconstruction. The goal of

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fixation is to maintain adequate tension and minimize motion between the graft and the bone tunnels for a minimum of 6–12 weeks to allow biologic incorporation [3, 4]. The three most common modes of fixation are aperture (e.g., interference screw), suspensory (e.g., cortical button), and hybrid fixation. Interference screws may be either metal or bioabsorbable and have statistically similar clinical results [5]. Screw pullout ranges from 230 to 715 N in biomechanical testing with stiffness ranging from 80 to 115 N/mm [6]. Fixation failure is more commonly tibial-sided with load to failure measurements approximately half of those in the femur [7–9]. It is speculated that graft pullout strength from the tibial tunnel requires less force than form the femoral tunnel due to its orientation along the force vector of the ACL (while the femoral tunnel is oriented oblique to the force vector of the ACL). Graft laceration may also occur with interference screw fixation whereby the screw threads lacerate the graft fibers, thereby weakening the biomechanical construct. This occurs more frequently with metal interference screws [6]. Suspensory cortical fixation may fail secondary to femoral cortical violation as well as failure to appropriately deploy the fixation device. Over time, suspensory fixation may be compromised due to bone tunnel enlargement resulting from graft-tunnel motion (which has been shown to be worse with soft tissue grafts), long femoral constructs, and aggressive postoperative range of motion therapy [10–12]. Additionally, material properties and implant design dictate fixation strength. For instance, with suspensory cortical fixation devices plastic deformation increases with longer loop length [13].

Sepsis

Septic arthritis following ACL reconstruction is a rare (0.3–1.7 % of failures) [2, 14, 15] but devastating complication that results in high morbidity and poor clinical outcome. Prompt treatment is crucial in order to minimize consequences of sepsis including graft failure, arthrofibrosis, and loss of articular cartilage. Postoperative infections can be classified by their temporal relationship to the index surgery as acute (<2 weeks), subacute (2 weeks to 2 months), or late (>2 months) with most presenting as acute or subacute infections [14]. The most probable cause of infection is contamination of the surgical wound or graft at the time of surgery. Infection may also spread from the extraarticular space (pretibial subcutaneous tissue) into the joint via the tibial tunnel. While *Staphylococcus* spp. are the most common microbial infections, *Streptococcus*, *Enterobacter*, gram-negative organisms, and polymicrobial infections also occur. Risk of infection increases with previous surgery, revision surgery, larger incisions, longer tourniquet time, and increased operative time [15]. Treatment goals of a septic ACL-reconstructed knee are to protect both the articular cartilage and the graft [14–16]. Chances of treatment success are largely dependent on early identification of infection, prompt arthroscopic debridement, initiation of targeted antibiotic therapy, and a favorable microbiologic organism [16]. However in many cases, the graft and associated fixation devices must be removed in the setting of delayed presentation, inadequate surgical debridement, inadequate antibiotics, or a virulent pathogen.

Aseptic Biological Failure

Graft incorporation is the biological indicator for success after ACL reconstruction and is imperative to a successful result. In certain settings, graft incorporation may not occur due to aseptic biological failure (7–27 % of failures) [2, 17]. Mechanical errors may occur due to inadequate fixation or inappropriate graft tensioning which may lead to compromise of graft incorporation [18, 19]. However, true biological failure is more commonly related to graft type (autograft vs. allograft), graft interface (soft tissue vs. bone plug), and patient immune response (e.g., graft vs. host disease vs. graft rejection). Autograft incorporation is faster and more complete than allografts due to immune response [20]. In addition, it is known that bone-tendon-bone grafts require less time to incorporate than soft tissue grafts due to bone-to-bone healing [4]. Finally, aseptic musculoskeletal graft reaction is a very rare failure mechanism and is believed to be an immunogenic response related mostly to allograft

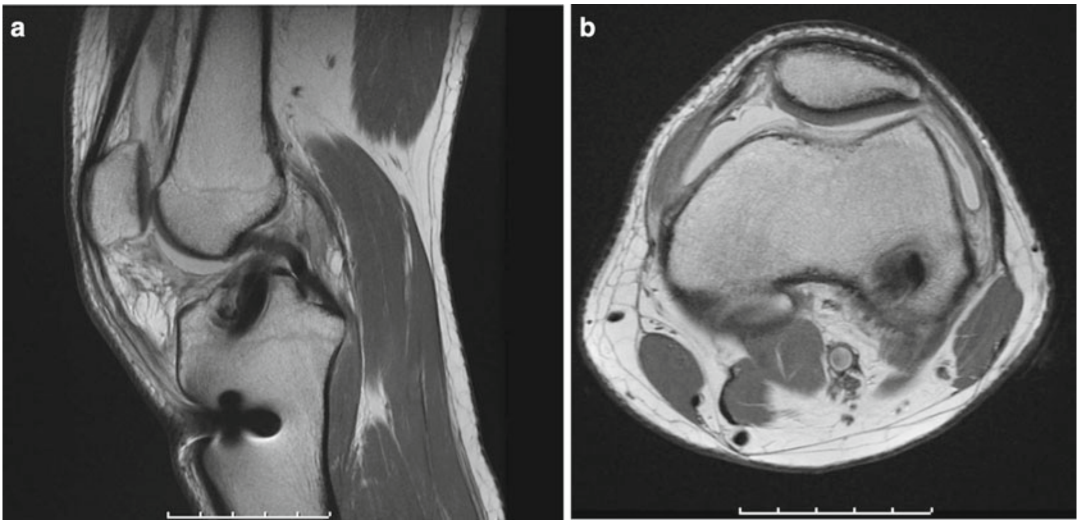

Fig. 4.1 T1-weighted sagittal MRI sequence (**a**) showing nonspecific thickening of synovium with tunnel widening possibly consistent with graft immune rejection. (**b**) An inflammatory medial parapatellar plica is noted on axial images

reconstruction and their preservative process but only after an extensive infection workup has been deemed negative [21] (Fig. 4.1a, b). The exact immunological mechanism has not completely been elucidated but it has been shown in other musculoskeletal allografts that these tissue are not as "privileged" as was once thought [22]. Each of these factors may affect revascularization and healing, and patients will present with instability in the absence of trauma.

Midterm

Tunnel Placement

Tunnel malposition is the most common recognized technical error during ACL reconstruction, accounting for 24–80 % of failures [2, 23]. Improperly placed tunnels may lead to poor graft kinematics, impingement, and ultimate failure of ACL reconstruction [24]. This has led to expanding interest in anatomic ACL reconstruction. Although either tunnel may be malpositioned, the femoral tunnel has historically comprised the majority of placement errors [25, 26]. Indeed, one of the most common etiologies of recurrent instability identified after ACL reconstruction is the central (vertical) placement of the femoral tunnel high in the intercondylar notch. This has been speculated to be due to the fact that the femoral tunnel had been dictated by the tibial tunnel in transtibial reconstruction techniques [27, 28]. Studies have shown that the transtibial positioning tends to lead to a high anteromedial and non-anatomic femoral tunnel position [29–31]. Anterior placement of femoral tunnels may lead to excessive strain in both flexion (when tensioned in extension) and extension (when tensioned in flexion). Vertical grafts that result from placing the femoral tunnel too central in the intercondylar notch do not constrain the knee under rotatory forces, so while anteroposterior stability may be intact, rotational stability is not (Fig. 4.2a, b). Several cadaveric studies have shown that there is improved stability, particularly in response to combined anterolateral rotatory loads, when the femoral tunnel is moved from a position on the "roof" of the intercondylar notch to a more anatomic position "down the wall" of the notch [32, 33].

Another common error is a posterior tibial tunnel leading to a vertical femoral tunnel, which came about early in the history of transtibial techniques. With newer techniques such as using an anteromedial portal for femoral tunnel placement and thus independent placement of the tibial

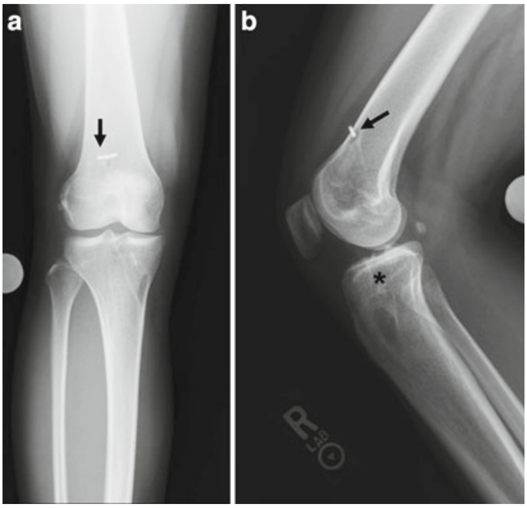

Fig. 4.2 AP (**a**) and lateral (**b**) radiographs reveal vertical graft orientation with suspensory fixation seen anteriorly and central in the femur (*arrows*). The tibial tunnel is placed posteriorly (*star*)

tunnel, excessive anterior placement of the tibial tunnel can be problematic. A cadaveric study using computer navigation and a mechanized Lachman and pivot shift showed that while keeping the femoral tunnel constant, placing the tibial tunnel further anterior on the tibial plateau afforded better control over the Lachman and pivot shift tests, but increased risk of impingement. It is therefore important to balance the risk of instability and impingement by placing the tibial tunnel in an anatomic position. Even with anatomic graft placement however, graft failure has been reported in 13 % of ACLR over the first 30 months postoperatively [1]. It is therefore important to understand that factors other than tunnel malposition can cause midterm ACL graft failure.

Impingement

As previously mentioned, it has been shown that anterior placement of the tibial tunnel improves knee stability in both the A-P and rotatory planes [34]; however, anterior tibial tunnels also lead to greater graft impingement in extension [35, 36] and excessive strain in knee flexion. It is important to recognize that while anterior placement of the tibial tunnel improves sagittal graft obliquity and improves stability and kinematics, excessive anteriorization of the tibial tunnel will lead to impingement and the resultant inability to extend the knee [34]. Graft erosion may also occur from tibial tunnel placement too medially or laterally, resulting from impingement with the intercondylar notch wall or PCL [37].

Nonanatomic placement of femoral tunnels may also lead to graft impingement. A cadaveric study was performed using computer navigation to evaluate femoral tunnel position on graft impingement [38]. Varying femoral tunnel positioning from AM to center to PL footprints resulted in significantly decreasing angles of impingement in extension, indicating that more anteriorly placed femoral tunnels are more prone to impingement in extension. Indeed tunnel positioning in the central region of the femoral and tibia footprint may be the most effective means of controlling stability and avoiding impingement in the ACL reconstruction.

Graft Elongation

For a successful reconstruction to maintain stability after leaving the operating room, graft tension must be maintained and protected. Instability in the absence of other causes of graft failure such as fixation failure, biological failure, tunnel malposition, or trauma should alert the surgeon to the possibility of graft elongation. Graft elongation, or creep, is defined as elongation due to non-recoverable stretch and loss of stiffness and may lead to gradual failure [39]. Greater graft elongation and creep may be due to decreased time of preconditioning grafts and inappropriate cycling of the graft prior to fixation. In vitro studies suggest that preconditioning grafts with a constant tensile load may be beneficial in preventing in vivo elongation [40]. In addition, overly aggressive early postoperative physical therapy prior to graft healing may also hinder incorporation or promote creep [41]. This occurs by graft motion and/or pullout. Soft tissue grafts have been shown to have a higher rate of failure due to creep when compared to BTB [42, 43] (Fig. 4.3).

Fig. 4.3 Coronal T1-weighted MRI sequence showing a vertical soft tissue graft resulting from a centrally placed femoral tunnel. Graft laxity and buckling are seen with nonlinear graft fibers (*star*)

Secondary Stabilizers

It is important to recognize and appropriately address all laxity in the secondary stabilizers of the knee to avoid excessive tensile forces and eventual ACL graft failure. Unrecognized associated ligamentous injury at the time of primary reconstruction accounts for around 15 % of ACL failures. With deficient secondary anterior stabilizers, the ACL graft will provide restraint for the first 6 months but increased demand activities will lead to a gradual recurrence of instability [44]. In a classic paper, O'Brien [45] reported on 80 primary ACL reconstructions and found that all of those with postoperative clinical instability had evidence of associated ligamentous instability. The most commonly unrecognized instability is posterolateral corner injury, followed by posteromedial injury and medial meniscus [45–48].

Injury to the posterolateral corner in an ACL-deficient knee results in increased instability. In a cadaveric study [49], the anterior tibial translation and anterolateral rotational instability of the knee were significantly increased after sectioning the ACL ($p<0.05$). Sectioning of the lateral collateral ligament further increased the anterolateral rotational instability. Subsequently sectioning of the popliteus complex increased the anterior tibial translation ($p<0.05$) but not the anterolateral rotational instability.

As with the lateral sides, the posteromedial aspect of the knee, which consists of the superficial and deep medial collateral ligament (MCL) and posterior oblique ligament, contributes to anterior knee stability [50]. Combined MCL and ACL deficiency were found to significantly increase anterior tibial translation relative to the ACL-deficient knee at flexion angles above 60°. The MCL is thus an important contributor to anterior stability at higher knee flexion angles. These associated ligamentous and meniscal injuries are important to recognize and treat appropriately to prevent ACL graft failure.

In addition to the lateral and medial side, medial meniscal deficiency is another common associated injury pattern. Ahn [51] reported on knee kinematics with ACL deficiency and medial meniscal injury and repair. Medial meniscal tear resulted in increased anterior-posterior tibial translation at all flexion angles except 90° ($p<0.05$) and the repaired medial meniscus showed a decreased anterior-posterior translation at all flexion angles except 60° compared to the torn meniscal state. This signifies the importance of recognizing and treating associated medial meniscal pathology. While the medial meniscus and status of the medial compartment is a crucial component of knee stability, the development and standardization of the mechanized pivot shift has enabled researchers to evaluate the rotational stability of cadaveric knees for biomechanical studies, rather than just A-P stability. In a cadaveric study using a Lachman and mechanized pivot shift, Ahn's results were confirmed in that the medial meniscus was a critical secondary stabilizer during Lachman examination, but the lateral meniscus was a more important restraint to rotatory loads during a pivoting maneuver [52]. In addition to secondary restraint, meniscectomized knees may lead to cartilage loss and resultant malalignment. In the setting of a meniscectomized knee with cartilage loss and malalignment, concomitant bony realignment procedures are required with ACL revision surgery (Fig. 4.4a, b).

Late

Trauma

Knee trauma following ACL reconstruction may be a devastating and unpredictable cause of graft

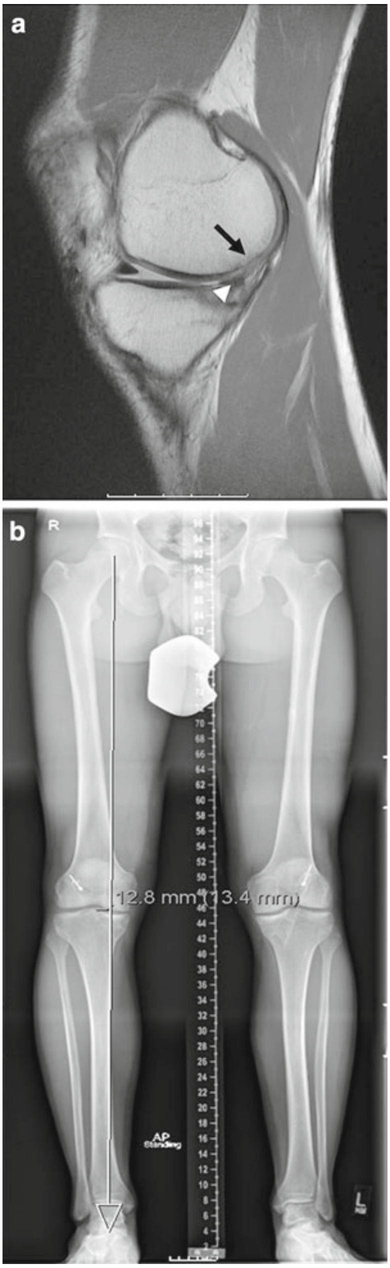

Fig. 4.4 T1-weighted sagittal MRI sequence (**a**) showing posterior chondral wear (*black arrow*) effects of prior meniscectomy (*white arrowhead*), and anterior tibial translation of a failed ACL reconstruction. Hip-to-ankle alignment radiographs (**b**) indicate right knee varus malalignment

failure, and accounts for 32–70 % of revision cases [2, 17]. Traumatic mechanism and force may be similar to the original injury with an audible "pop," laxity, hemarthrosis, and inability to walk, or may be from an event in which there was much less force than the original injury. Because of this, patients may present reporting only minor recent trauma; however, new onset instability or laxity after a period of functional stability indicates potential traumatic failure. Therefore minor trauma with subjective complaints of instability should not be ignored. Traumatic failures may occur early during graft incorporation from overaggressive physical therapy or premature return to athletic activity, or later after the graft has matured and the patient has returned to athletic activity (typically >1 year postoperatively). Once the graft has matured, the risk of reinjury is similar to that of the contralateral ACL. Early aggressive rehabilitation and premature return to sport may lead to reinjury. Postoperative bracing is a common practice with the goal of preventing reinjury. Some believe that there is an improvement in knee extension, decreased pain and graft strain, and protection from excessive force. A systematic review of 12 randomized controlled trials (RCTs) failed to show evidence that pain, knee range of motion, graft stability, or protection from subsequent reinjury was affected by brace use [53].

Conclusion

The purpose of this chapter was to review the biomechanics of graft failure. Most literature on this topic relates to technique-related issues in ACL reconstruction. Indeed, the most widely cited and well-studied reason for graft failure is tunnel malposition [54] and a large body of literature is devoted to the concept of "anatomic" placement of graft tunnels. In spite of this focus on refining tunnel position, graft failure is still found in up to 13 % of anatomic ACL reconstruction [1]. This suggests that while surgical technique is important, other factors that may be patient-specific (and minimally affected by surgical technique) may also have a role in graft failure. Indeed, in a recent meta-analysis of patients undergoing ACL reconstruction, the rerupture rate of the ACL graft was 6 % while the rupture rate of the contralateral, native ACL in these patients was 12 % [55]. The fact that patients who undergo an ACL reconstruction have twice the risk of tearing their contralateral ACL as their graft suggests that patient-related factors such as genetics, gender, alignment, bony morphology, and landing mechanics may have dominant roles in the etiology of failure after ACL surgery.

In summation, ACL graft failure may occur for a variety of reasons. Often the etiology is related to surgical technique or other factors that can be controlled by the surgeon. However, patient-related factors may also be important and may be difficult for the treating physician to modulate. It is important to consider all possible etiologies for new or slow-onset postoperative instability within a framework of chronology regarding the original reconstruction. Failures of fixation, infection, graft rejection, biological failure, overaggressive physical therapy, incorrect tunnel placement, instability due to graft creep, and attenuation of secondary stabilizing structures may all contribute to postoperative instability. Failure after 1 year is typically traumatic; however, trauma may occur at any phase of the postoperative period and may be similar to the original injury or may be from an event in which there was much less force than the original injury. One must recognize that at every step of ACL reconstruction there is an opportunity for reconstructive failure and by understanding potential pitfalls may be able to prevent reconstructive failures.

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5 Technical Causes of ACL Graft Failure

Andrew J. Blackman, Ljiljana Bogunovic, Steven Cherney, and Rick W. Wright

Introduction

Despite significant advances in the understanding of treatment of anterior cruciate ligament (ACL) injuries in recent years, the failure rate of ACL reconstruction is still significant. Recent prospective analysis of a multicenter cohort has shown failure rate after ACL reconstruction to be 3.0 % at 2 years [1] and a systematic review of randomized-controlled trials showed this rate to be 3.6 % at short-term follow-up [2]. Revision ACL reconstruction is clinically challenging and associated with worse clinical outcomes than primary reconstructions [3, 4], and a recent systematic review revealed a 13.7 % overall failure rate [5]. Avoidable technical errors, including tunnel malposition, inadequate fixation, and failure to address concomitant malalignment and/or ligamentous injuries, have been implicated in 53–79 % of primary ACL graft failures [6–8]. The following chapter reviews these technical causes of ACL graft failure.

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Tunnel Malposition

Proper tunnel placement is recognized to be one of the most critical factors in successful ACL reconstructions [9, 10] and much research has been devoted to determining ideal tunnel placement. Tunnel malposition is believed to be the most common technical cause of ACL graft failure [8].

Femoral Tunnel

The ideal femoral tunnel has traditionally been described as originating at the 11 or 1 o'clock position in the right or left knee, respectively, and as posterior as possible, with 1- to 2-mm of cortical bone comprising the back wall of the tunnel [11]. Recently, some have suggested placing the tunnel at the 10 or 2 o'clock position to improve rotatory stability [12]. Improper femoral tunnel position has been implicated in 80 % of cases in which technical errors contributed to ACL graft failure [8]. The femoral attachment of the native ACL is near the axis of rotation of the knee, so even small deviations in the placement of the femoral tunnel will cause large changes on graft length-tension relationships [13]. The two most common errors in femoral tunnel placement are tunnels that are too anterior or too high in the notch.

An anteriorly malpositioned tunnel (Fig. 5.1) is typically caused by failure to visualize and

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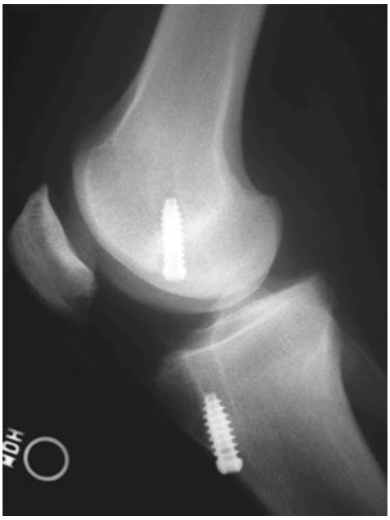

Fig. 5.1 Radiographic appearance of an anteriorly placed femoral tunnel. The tunnel should appear as posterior in the notch as possible

reference off of the posterior wall of the lateral femoral condyle, while instead referencing off the lateral intercondylar, or “resident’s”, ridge. Anterior placement of the femoral tunnel leads to a mismatch in graft tension in extension vs. flexion. If the graft is tensioned in extension, it will become tighter in flexion, leading either to loss of flexion or graft stretching [14]. If the graft is tensioned in flexion, it will become loose in extension and lead to unacceptable postoperative laxity. Anterior placement of the femoral tunnel will also lead to a graft with less sagittal plane obliquity, which may lead to decreased stability to anterior tibial translation [15].

A tunnel that is placed too high in the notch, i.e., too near the 12 o’clock position (Fig. 5.2), leads to a graft with less obliquity in the coronal plane, commonly referred to as a vertical graft. The coronally vertical graft maintains sagittal plane stability, but offers less resistance to rotatory forces and can result in a knee that remains rotationally unstable after ACL reconstruction [9, 16]. In addition, a graft that is vertical in the coronal plane causes impingement against the posterior cruciate ligament and increases graft tension in flexion [17], which may lead to loss of flexion and/or graft stretching.

The femoral tunnel can also be malpositioned posteriorly, which may lead to blowout of the back wall of the tunnel, which can cause difficulty in obtaining adequate fixation or, if unrecognized, fixation failure altogether.

Tibial Tunnel

The ideal position of the tibial tunnel is in the middle of the native ACL footprint. Visualization of this landmark requires adequate debridement of the ACL remnants and determining the precise center of the footprint can be difficult, so placing the center of the tunnel 7 mm anterior to the PCL and just lateral to the medial tibial spine has been suggested [11]. Improper tibial tunnel placement has been implicated in 37 % of cases in which technical errors contributed to ACL graft failure [8]. The tibial tunnel can be malpositioned in any direction with different consequences for each.

Anterior placement of the tibial tunnel (Fig. 5.3) has been researched most extensively and leads to impingement of the graft on the intercondylar roof with the knee in extension. This impingement can lead to loss of complete knee extension or progressive elongation and subsequent failure of the graft [18]. On a lateral radiograph with the knee in full extension, any portion of the tibial tunnel that is anterior to an extrapolation of Blumensaat’s line should alert the surgeon to the possibility of intercondylar roof impingement. A tibial tunnel that is too medial can lead to graft impingement against the PCL, whereas too lateral a tunnel can lead to impingement on the medial aspect of the lateral femoral condyle. In either of these cases, repetitive impingement can lead to progressive graft elongation, loss of flexion, and eventual failure. Finally, a tibial tunnel that is malpositioned posteriorly will lead to a graft that has decreased obliquity in the sagittal plane and, as is seen with an anterior femoral tunnel, decreased effectiveness in resisting anterior tibial translation [9, 11]. A posteriorly placed tibial tunnel creates a graft that is excessively lax in flexion, as well.

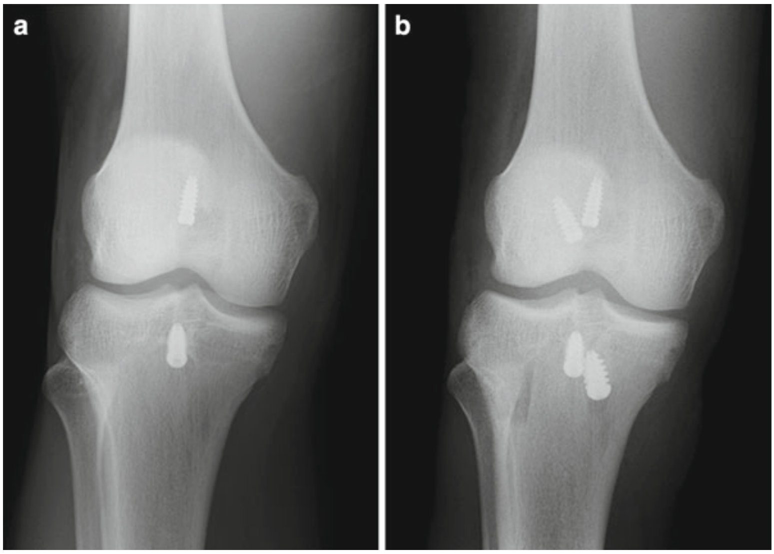

Fig. 5.2 (**a**) Radiographic appearance of a femoral tunnel placed near the 12 o'clock position in the notch, resulting in a vertical graft. (**b**) The subsequent failure was managed by placement of a new femoral tunnel near the 10:30 position, resulting in a more oblique graft

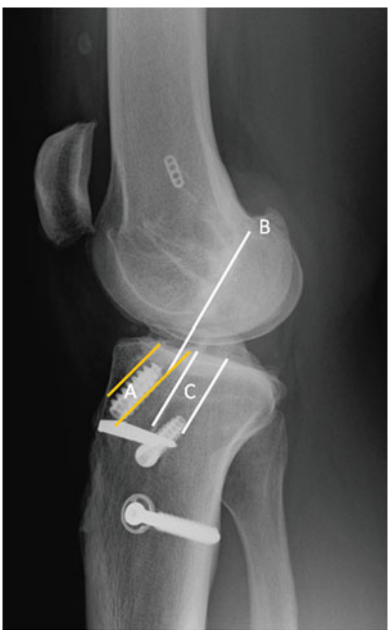

Fig. 5.3 Anteriorly malpositioned tibial tunnel (A), which is almost entirely anterior to Blumensaat's line extended (B) with the knee in full extension. The subsequent failure was managed with appropriate tibial tunnel placement (C) posterior to Blumensaat's line

Tunnel Preparation

Failure to adequately prepare the femoral or tibial tunnels may be an underappreciated technical cause of ACL graft failure. Tunnel drilling can leave sharp edges at the apertures that may impinge upon the graft after tensioning and fixation. At our institution, a shaver, angled arthroscopic rasp, or Gore-Tex smoother is routinely used to chamfer the tunnel apertures prior to graft passage.

Tunnel Enlargement

One technical cause of ACL graft failure that is specific to revision ACL reconstruction is failure to identify and manage tunnel enlargement, which can lead to both graft malposition and inadequate fixation [19]. It is important to critically evaluate preoperative radiographs for evidence of tunnel osteolysis (Fig. 5.4). A computed tomography (CT) scan should be obtained in

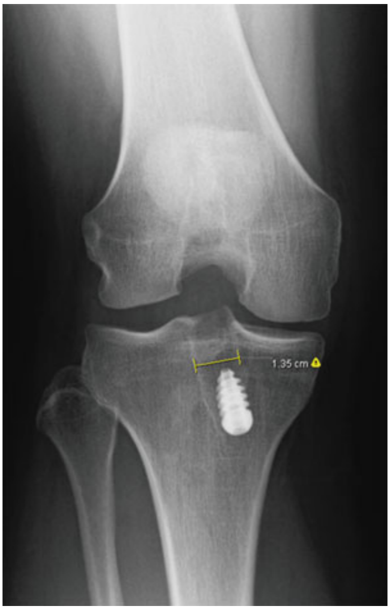

Fig. 5.4 Tibial tunnel enlargement in the setting of a failed primary ACL reconstruction

cases where further detail is needed. Many techniques have been described to allow for revision ACL reconstruction in the setting of tunnel enlargement including using larger bone plugs, tying bone plug sutures around a screw and washer, using an endobutton, and impacting allograft bone struts into the enlarged tunnel along the bone plug to obtain a press fit, among others [20]. Cases in which the degree of tunnel enlargement will prevent appropriate placement and fixation of the ACL graft should be treated in a staged fashion, with initial tunnel debridement and bone grafting. After a period of 3–6 months, a repeat CT scan will typically confirm incorporation of the bone graft and the second stage of the revision reconstruction can be carried out. In the Multicenter ACL Revision Study (MARS) cohort, bone grafting of enlarged tunnels was performed at the time of the revision in 3 % of patients for the tibia and 3 % of patients for the femur. It was performed as a staged procedure before revision reconstruction in 9 % of patients for the tibia and in 8 % of patients for the femur [8].

Graft Choice

The type of graft that is chosen for the primary ACL reconstruction can have a significant effect on the failure of the reconstruction. Studies attempting to compare allografts and autografts, both BTB and soft tissue, are numerous. Allograft reconstructions appear to undergo the same healing process as autografts, albeit at a much slower rate. At 6 months after surgery, allografts have decreased structural properties and slower incorporation [21], and animal models have shown that the center of the graft may heal incompletely [10]. These factors may lead to an increased risk of graft rupture.

Allografts need to be sterilized to prevent disease transmission and antigenic response in the host knee. Harvest, storage, sterilization, and processing techniques vary widely across tissue banks. Sterilization of grafts using ethylene oxide and gamma irradiation has been shown to cause increased clinical and mechanical failure, respectively [22]. Irradiated allografts have also been shown to develop laxity during follow-up at a higher rate than hamstring autografts, which may lead to increased failure rates [23]. These findings have led to a shift in practice that most allografts are fresh frozen specimens. However, a muted immune response still occurs to the donor tissue, which may cause tunnel enlargement [10], as well as changes in graft incorporation, revascularization, and remodeling [21].

Even after the initial healing period, allografts appear to fail at a greater rate than autograft counterparts in certain patients. In highly active patients under 50 years of age, BTB allografts have been shown to fail 2.6–4.2 times more frequently than in patients receiving BTB autografts and less active patients receiving allograft reconstructions [24]. Furthermore, allografts have been shown to fail more frequently in patients under 25 than BTB autografts [25]. Prospective, longitudinal, multicenter data also show allograft use to be an independent predictor of graft rupture [26]. Patients in the previously mentioned studies had undergone primary

ACL reconstruction. It remains to be seen if these findings hold true for revision ACL reconstructions.

When considering the differences in failure rate between BTB autograft vs. multiple bundle hamstring autograft, data are mixed. A recent Cochrane review and a prospective cohort study with 10-year follow-up suggest that the failure rates between the two types of autografts are the same [27]. However, another recent systematic review found a twofold increase in graft failure after hamstring autograft reconstruction compared to BTB [22], and hamstring autografts have been shown to fail more frequently in patients under the age of 25 [25].

To avoid increased risk of ACL graft failure, we recommend the use of autograft ACL reconstruction in all patients under the age of 40 who wish to pursue an active lifestyle postoperatively. Furthermore, although the existing literature is inconclusive, it suggests that BTB autograft may have the lowest graft failure rate, especially in patients under 25 years of age.

Graft Fixation

The fixation of the graft is the weakest part of the ACL reconstruction in the first 8–12 weeks, until the graft is fully incorporated [28], and has been implicated in 7 % of cases in which technical errors contributed to graft failure [8]. The tibial fixation site is usually weaker than the femoral fixation site [29]. Failure of the fixation sites can be multifactorial and may include poor host bone quality, interference screw divergence, suture or knot failure, graft-tunnel mismatch, or improper fixation sizing. Interference screws have been shown to provide acceptable femoral and tibial fixation in both BTB and hamstring grafts [30], provided several characteristics of the screw are met.

Biomechanically, using 9 mm diameter interference screws for tibial-sided bone plug fixation results in higher pullout strength than 7 mm screws [31], while interference screws longer than 20 mm have been shown to provide no significant increase in strength of the construct [32]. The clinical significance of these findings is undetermined, although the senior author has had good results with routine use of 9 × 20 mm interference screws for bone plug fixation on both the femoral and tibial sides. It is important to note that screws should not exceed tunnel length, which may cause intra-articular abrasion and weakening of the graft.

Interference screw divergence can lead to inadequate graft fixation and subsequent failure. The divergence angle is rarely a problem on the tibial side as the insertion site is under direct visualization. However, at the femoral fixation site, there has been much written about interference screw divergence in both BTB and hamstring grafts. The technical difficulties associated with placement of the screw lead to divergence of the screw from the ideal axis, which is parallel to the tunnel. Some studies have suggested that in BTB grafts, divergence as low as 10° leads to increased pullout [33], others have shown that divergence resulted in increased pullout only starting at angles greater than 30° [34, 35]. Regardless, care should be taken to ensure that the interference screw is directed as parallel as possible to the tunnel without damaging the graft itself.

The use of titanium endobuttons for femoral graft fixation carries with it specific risks for graft failure. Ideally, the button should be deployed and confirmed with intra-operative fluoroscopy. The proper position for deployment is directly against the femoral cortex. If the button is deployed in the substance of the quadriceps (Fig. 5.5), it can cause underlying muscle necrosis and eventual graft slippage before the graft can fully incorporate. Alternatively, if the button is deployed in the femoral tunnel's cancellous bone, there may initially be enough resistance to tension the graft intra-operatively. However, increased stress on the construct as the patient returns to activity may cause slippage through relatively soft cancellous bone and eventual graft failure [36].

Fig. 5.5 Deployment of the femoral-sided endobutton within the substance of the quadriceps

Graft Tensioning

Proper graft tensioning remains a difficult element in ACL reconstruction and one that may be an under-recognized cause of graft failure. Undertensioning a graft dooms ACL reconstruction in the immediate postoperative period. Grafts do not contract over time, and the clinical result will be an unacceptable amount of residual laxity [9]. On the contrary, overtensioning a graft can lead to loss of joint motion, increased pressures on articular surfaces, premature arthritic changes, decreased graft strength, myxoid degeneration, and infrapatellar contracture syndrome [37–39]. Thus, it is imperative that the graft be appropriately tensioned at the time of surgery.

The optimal method of graft tensioning is widely debated. Many different recommendations have been made [10, 40, 41]. The inherent stiffness of BTB grafts is 3–4 times higher than hamstring grafts, and as a result, some have suggested tensioning BTB grafts with less tension than with hamstring grafts [10]. It should be noted that although there are "ideal" tensioning parameters, there is still high intra- and inter-surgeon variability in graft tensioning [42, 43]. The senior author recommends tensioning the graft with full-strength one-hand pull with the knee in full extension and has not encountered significant problems with graft failure, motion loss, infrapatellar contracture, or progressive arthritis using this technique. It is also prudent to cycle the knee through a normal range of motion 15–20 times under tension in order to eliminate stress laxity, as well as check for isometry [4, 9, 10].

Failure to Address Malalignment

Failure to address lower extremity malalignment, particularly genu varum deformity, can lead to increased stress on the reconstructed graft and contribute to graft failure (Fig. 5.6). Failure to

Fig. 5.6 Genu varum in the setting of failed primary ACL reconstruction, which should be treated with limb realignment prior to, or concurrent with, revision ACL reconstruction

address concomitant limb malalignment has been implicated as a cause of failure in 4 % of failed ACL reconstructions requiring revision [8]. Varus malalignment is classified as primary varus, double varus, or triple varus [44]. Distinction between these different groups is important in the ACL deficient knee, as it determines whether correction of alignment will improve the success of ACL reconstruction. In the primary varus knee, tibiofemoral geometry and possible medial meniscus damage or cartilage wear results in the weight bearing line (WBL) crossing through the medial compartment. In the double varus knee the WBL crosses further medial within the medial compartment and damage to the lateral ligamentous structures leads to separation of the lateral tibiofemoral joint during gait [44]. This opening of the lateral tibiofemoral compartment is seen as a varus thrust during early stance phase [45]. In the triple varus knee the addition of posterolateral ligamentous insufficiency causes increased external tibial rotation and hyperextension in addition to the lateral tibiofemoral compartment separation and a far medial WBL [45].

Valgus high tibial osteotomy (HTO) is an accepted treatment option for patients with osseous varus alignment and medial compartment arthritis. The use of HTO has also been recommended in the double or triple varus ACL deficient knee in an order to protect the ACL graft. Multiple cadaver studies demonstrate increased force within the ACL with increasing varus alignment [46]. In order to protect the graft from excessive forces and potential failure, ACL reconstruction alone should not be performed in the varus knee in the setting of lateral joint opening or posterolateral ligamentous laxity. In the double varus knee, combined valgus HTO, either staged or concurrent, is recommended. In the triple varus knee, valgus HTO should be performed first followed by combined ACL and posterolateral corner (PLC) reconstruction if the patient has continued instability following the osteotomy [44]. In primary varus knees, valgus HTO has not been shown to enhance stability or protection of the graft from excessive forces and is not recommended in the absence of medial compartment arthrosis [47].

Failure to Address Concomitant Injuries

ACL tears are commonly associated with injury to other structures in the knee. In the multiligamentous injured knee, isolated ACL reconstruction fails to restore joint stability. Recognition and management of associated ligamentous injuries is important for successful ACL reconstruction. Failure to recognize and address these combined injuries can subject the ACL graft to increased forces and contribute to graft failure. Unaddressed ligamentous laxity has been implicated in 3 % of cases in which technical errors contributed to graft failure [8].

Posterolateral Corner

The most commonly missed concomitant injury is to the PLC. Failure to address the associated posterolateral rotatory instability will result in increased hyperextension and varus forces across the knee, which may contribute to ACL graft failure [48]. Recommended management of PLC injuries associated with ACL tears involves primary repair of the PLC or reconstruction with allograft or autograft [49].

Medial Structures

Injuries to the medial collateral ligament (MCL), oblique popliteal ligament, and posterior horn of the medial meniscus may occur concurrently with ACL tears. The posterior horn of the medial meniscus is an important secondary stabilizer to anterior translation of the knee [50–52]. The common longitudinal tear in the posterior horn leads to anterior tibial translation that is no different than that seen with total medial menisectomy [52]. The loss of stability associated with this type of meniscal injury increases forces experienced by the ACL graft and may predispose it to failure. Current data recommends concurrent repair of medial meniscal tears at the time of ACL reconstruction when possible. If the tear is deemed irreparable, an attempt should be made to preserve as much meniscal tissue as possible.

Multiple studies have demonstrated excellent outcome with nonoperative management of the MCL in combined ACL/MCL injuries [53–56]. In a prospective randomized study, patients with combined ACL and grade III MCL tears were treated with ACL reconstruction and MCL repair or bracing. At 27 months, there were no differences between the MCL repair and bracing with regard to patient outcome scores, postoperative stability, or return to activities [55]. In general, conservative treatment of MCL tears in combined ACL/MCL injuries can lead to successful ACL reconstruction and has not been associated with increased risk of graft failure.

Improper Notchplasty

Notchplasty, while controversial, can be an important component of successful ACL reconstruction. Notchplasty serves to improve visualization of the posterior wall and prevent graft impingement within the notch, especially during extension. The amount of notchplasty required is dependent on the anatomy of the patient. Patients with an A-frame or narrow notch will require more extensive resection.

The technique of notchplasty involves widening of the anterior portion of the intercondylar roof and medial edge of the lateral femoral condyle. This can be performed with an osteotome or a burr under good visualization. The resection should resemble a funnel, wider anteriorly and narrower posteriorly, as it is the anterior notch upon which the graft will impinge during extension [9]. Resection of the lateral femoral condyle should be carried out until the posterior wall of the condyle and the over the top position can be easily seen. Adequate visualization of the posterior wall serves to prevent anterior placement of the femoral tunnel, the most common technical error in ACL reconstruction and a cause of graft failure [8, 10]. Adequate notchplasty can be ascertained prior to graft passage by passage of a dilator or probe through the tibial tunnel. The knee is then carried through full range of motion and potential sites of impingement can be identified and rectified prior to graft placement. It is the current practice of the senior author to only remove enough bone from the notch to allow adequate visualization of the posterior wall of the lateral femoral condyle in most cases. However, in patients who have sustained non-contact ACL injuries, notch impingement may have contributed to failure of the native ACL, so the size and shape of the notch is closely evaluated and very narrow or A-frame shaped notches are more aggressively resected, even if it is not needed for adequate visualization.

Errors in notchplasty can lead to graft failure. Under-resection of the notch leads to impaired visualization, which can subsequently lead to improper tunnel placement. Failure to adequately widen the notch can also result in graft impingement. Grafts used in reconstruction are larger in size than the native ACL. Repetitive abrasion of the graft along the roof and/or medial aspect of the lateral femoral condyle with flexion and extension may weaken the graft overtime and increase the risk of failure. Over-resection during notchplasty is also problematic. A cylindrical, rather than funnel-shaped, notchplasty causes lateralization of the femoral tunnel and changes the isometry of the graft [9]. Resection of the posterior notch beyond what is needed for visualization of the femoral tunnel serves to only alter knee kinematics without reducing the risk of graft impingement. This change in knee kinematics has been shown to increase forces seen in the ACL graft, potentially predisposing it to failure [57, 58]. It is recommended that minimal bone be removed from the posterior notch.

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6 Indications for Revision ACL Reconstruction

James P. Leonard and Kurt P. Spindler

Epidemiology

The number of anterior cruciate ligament (ACL) reconstructions has increased substantially over the last 20 years [1]. The recorded number of ACL reconstructions in 1991 was approximately 63,000 cases [2]. Since then, the current estimated rates have ranged from 100,000 to 175,000 procedures a year [2, 3]. This growing trend is likely to continue given the general population's increasing pursuit of an active lifestyle, especially in the female athlete and aging populations. Concurrently, with a rising number of primary ACL reconstructions, combined with the high expectations placed on the surgically reconstructed knee by a high-demand population, the number of ACL reconstruction failures and candidates for revision ACL reconstructions is expected to increase as well. Estimates of patients that are candidates for revision ACL surgery have ranged from 3,000 to 10,000 patients annually [4], or between 3 and 25 % of primary ACL reconstructions performed [5].

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Failure of ACL Reconstruction

Definition

Defining an unsuccessful outcome or failure following an ACL reconstruction is a difficult task as no universally accepted definition exists. Unsuccessful results from ACL reconstruction have ranged from 3 to 52 % in the literature depending on the criteria used to define failure [6]. Historically, the rate of successful outcomes ranges from 75 to 90 % and is based on good to excellent results in functional stability, relief of instability symptoms, and return to normal activities of daily life [2, 7, 8]. However, these rates exclude the ability or level at which athletes are able to return to sport. Cheatham and Johnson [9] found that elite level athletes return to their preinjury activity levels only 60 % of the time with respect to sport intensity, frequency, and performance, despite having a knee that is objectively stable. A systematic review evaluating return to play following ACL reconstruction found 82 % returned to some type of athletic participation, but only 63 % returned to their preinjury level of activity and only 44 % returned to their competitive sport at final follow-up [10]. Fear of reinjury was the most cited reason for not returning to play or reducing their level of play. Thus, failure is dependent on the different expectations of either the surgeon or the patient.

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Table 6.1 Causes of ACL reconstruction failure

Cause of failure	Presentation	Associated factors
Recurrent instability	Early (<6 months)	Poor operative technique Failure of graft incorporation Premature return to high-demand activities Overly aggressive rehabilitation
	Late (>6 months)	Repeat trauma to the graft Poor graft placement Concomitant pathology not addressed Generalized ligament laxity
Complications	Stiffness	Global arthrofibrosis Poor preoperative range of motion Prolonged postoperative immobilization Intercondylar notch scarring Cyclops lesion Nonanatomical graft placement Graft overtensioning Complex regional pain syndrome
	Infection	Surgical contamination Multiple procedures
Comorbidities	Extensor mechanism dysfunction	Quadriceps muscle inhibition Loss of patellar mobility Inadequate rehabilitation
	Joint-related pain and arthritis	Chondral defects Postmeniscectomy pain

Source: Kamath GV, Redfern JC, Greis PE, Burks RT. Revision anterior cruciate ligament reconstruction. Am J Sports Med 2011; 39(1): 199–217. ©American Journal of Sports Medicine; Reprinted by permission of SAGE Publications

Classification

Patient complaints following an ACL reconstruction may include pain, swelling, stiffness, or mechanical symptoms of locking or giving way. From a surgical standpoint, complications following an ACL reconstruction can be categorized into recurrent instability, stiffness, persistent pain, and extensor mechanism dysfunction. On a more practical level, Kamath et al. categorized patient complaints into recurrent instability, postoperative complications, and comorbidities related to concomitant pathologic abnormalities or patient characteristics (Table 6.1) [7]. Being able to identify and compartmentalize a patient's complaint is extremely important in determining an appropriate treatment modality. Recurrent instability is a problem secondary to a failed graft, and for the most part will require a revision surgery. Non-graft-related conditions such as postoperative complications and concomitant pathologies do not usually require revision ACL reconstruction. Instead, these conditions necessitate more specific treatment for their problem.

Recurrent Instability

The primary goal of an ACL reconstruction is to restore the anterior and rotational stability of the knee following ACL injury. Continued or recurrent instability of the knee following an ACL reconstruction is most likely due to a deficient graft and is universally considered a surgical failure. The incidence of ACL graft failure and recurrent instability has been reported between 0.7 and 10 % of primary ACL reconstructions [11–14]. This scenario is the primary indication for a revision ACL reconstruction.

Table 6.2 Nonanatomic positioning of bone tunnels

Tunnel	Position	Results
Femoral	Anterior	Excessive strain (i.e., lengthening) in flexion/laxity in extension
	Posterior	Excessive strain in extension/laxity in flexion
	Central/Vertical	Rotational instability
Tibial	Anterior	Excessive strain in flexion/roof impingement in extension
	Posterior	Excessive strain in extension/impingement vs. PCL
	Medial	Impinges on medial femoral condyle/impingement vs. PCL
	Lateral	Impingement on lateral femoral condyle

Source: Reprinted from Allen CR, Giffin RG, Harner CD. Revision Anterior Cruciate Ligament Reconstruction. Orthop Clin N Am 2003; 34: 79–98; with permission from Elsevier

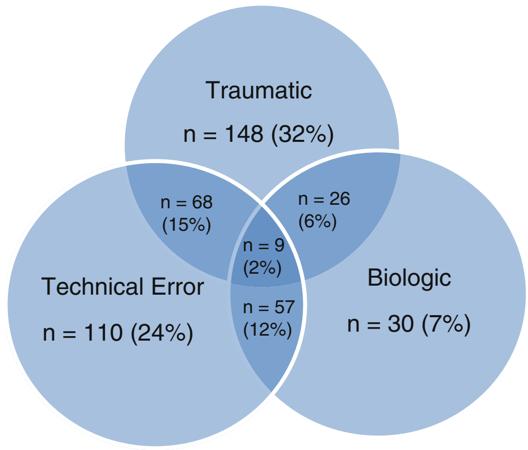

Fig. 6.1 Causes of ACL failure (from Wright RW, Huston LJ, Spindler KP, et al. Descriptive epidemiology of the Multicenter ACL Revision Study (MARS) cohort. Am J Sports Med. 2010; 38:1979–1986. ©American Journal of Sports Medicine; Reprinted by permission of SAGE Publications)

The mechanism of graft failure can be broken down into three categories: technical errors during primary procedure, insufficient biologic healing, and traumatic reinjury (Fig. 6.1). Most studies have identified technical errors as the most common etiology of graft failure, causing more than 50 % of the failures [5, 7, 15]. However, most of these studies identified one primary cause for failure and neglected any contributions from the other categories. ACL graft failure is a multifactorial process, with a significant interrelationship from each component. Recently, the MARS (Multicenter ACL Revision Study) group published initial results on their first 159 patients enrolled in this multicenter, prospective cohort evaluating failure modes in revision surgery. The study found isolated traumatic injuries to be the biggest indication, producing 32 % of the revision cases, followed by technical errors in 24 % of patients. Multiple etiologies were identified in 35 % of patients, with 55 % of cases describing some contribution of trauma to failure, and 53 % having a technical error component to their graft (Fig. 6.1) [16].

In addition to the MARS study, more recent studies are finding some history of trauma in most failed ACL grafts [17], with incidences between 24 and 100 % of revision ACL cases [7]. However, whether the traumatic event was the true initiator of the instability, or rather the result of an already deficient graft first noticed by the patient is sometimes difficult to ascertain. Injuries to the ACL graft can present early in the postoperative course, within 6 months of the primary procedure, or as a late presentation outside of 6 months. Although some patients may describe a traumatic event, reasons for early failure include poor surgical technique, delayed graft incorporation [14], loss of graft fixation [18], premature return to high-demand activities [19], and overly aggressive rehabilitation [20].

Traumatic rerupture after 6 months requires a force similar in magnitude to cause an original ACL tear [15]. With appropriate surgical technique and rehabilitation, long-term prospective cohorts have found the risk of graft ruptures to be the same as injuring the contralateral, "normal" knee with an incidence between 5 and 10 % at a minimum 5-year follow-up [17, 21, 22]. In fact, one systematic review found that the risk of ACL tear in the contralateral knee was double (11.8 %) the risk of ACL graft rupture (5.8 %) [23]. Risk factors for traumatic reinjury include surgical errors, young age, and participating in competitive pivoting, jumping, or contact sports. With increasing expectations of young athletes to return to high-level sports after ACL reconstruction, the number of traumatic reinjuries after ACL reconstruction is expected to increase.

Technical errors in ACL reconstruction include malpositioned tunnels, inadequate notchplasty, improper tensioning, and insufficient graft fixation. More than 70 % of technical errors are due to malpositioned tunnels [16, 24], with anterior femoral tunnel positioning the most common error. Positioning of the femoral tunnel is extremely important to knee function, as the origin of the ACL is close to the axis of rotation of the knee [8]. Small changes in the femoral attachment of the ACL have significant effects on the knee's biomechanics. Poor tunnel placement leads to excessive changes in graft length over the knee's range of motion, leading to plastic deformation and consequently loosening of the graft. An anterior femoral tunnel places increased stress on the graft in flexion, resulting in decreased flexion, pain with flexion, and stretching of the graft [15]. Similarly, a femoral tunnel too posterior increases the stress on the graft in extension, resulting in loss of extension, pain on extension, and stretching of the graft as well. Over time, both scenarios could result in deformation of the graft to the point of incompetency.

The femoral tunnel can also be incorrectly positioned in the coronal plane. A tunnel too close to the central axis of the femur, at the so-called 12 o'clock position, will result in adequate anterior restraint but poor rotational stability [25, 26]. Failure to control for rotation will result in continued instability episodes with cutting or pivoting activities. The femoral tunnel needs to be positioned more horizontally on the medial wall of the lateral femoral condyle to best control for anterior and rotation stability [27].

The effects of tibial tunnel positioning are more forgiving on graft tension than femoral tunnel positioning, but also play a role with potential impingement of the graft. Similar to femoral tunnel positioning, an anterior tibial tunnel will result in increased graft tension in flexion, whereas a posterior tibial tunnel will result in decreased tension in extension. In addition, an anterior tibial tunnel will cause impingement of the graft against the notch in extension, resulting in pain and/or decreased extension [28]. A posterior tibial tunnel will impinge against the PCL in flexion, causing pain and/or decreased flexion. Medial or lateral placement of the tibial tunnel may also cause impingement against the medial and lateral walls of the intercondylar notch [29]. The tibial tunnel position is not the only factor in graft impingement. Typically, the ACL graft is larger than the native ACL, so adequate space may not be available within the intercondylar notch. Even with ideal tibial tunnel position, a notchplasty may be required in some knees to open up the space available for the incoming graft to prevent impingement from occurring [30, 31]. Prevention of impingement is important, as repetitive friction from knee range of motion may cause persistent pain and swelling, as well as ultimately lead to graft failure and knee instability.

In addition to tunnel position, multiple other factors are involved in graft tension, including preoperative laxity, graft type, fixation type, and knee flexion angle at time of fixation [2]. Several randomized clinical trials have attempted to evaluate the effect of intraoperative graft tension on clinical outcomes after ACL reconstruction [32–35], but currently the optimum graft tension is unknown. Grafts that are undertensioned at the time of fixation are too loose, resulting in more knee instability postoperatively. Grafts with too much tension may result in decreased vascularization and delayed graft incorporation, myxoid degeneration, decreased graft strength, and overconstraining of the knee [36], which may potentially lead to osteoarthritis in the long term.

With recent emphasis on advanced rehabilitation protocols stressing early range of motion, it is imperative that graft fixation techniques be able to maintain graft tunnel position and tension until biologic incorporation has occurred [18]. Aperture fixation with interference screws gives the best fixation biomechanically [18, 37]. However, complications associated with their use include improper sizing of the bone plugs, osteopenic bone, divergent screw placement relative to the bone plug, and transection of the graft [18, 37–39]. With the increasing use of soft-tissue grafts, more suspensory types of fixation are being utilized with their own unique problems. Fixation points are farther from the joint, resulting in increased graft length, decreased stiffness, and increased displacement during cyclic loading [40]. The bungee cord effect and windshield-wiper effect described motion of the graft within the tunnel which can cause tunnel widening, loss of graft tension, and loss of graft fixation. Finally, with the increasing number of fixation devices available, proper surgical technique is important to avoid errors that may adversely affect graft fixation.

During an ACL reconstruction, secondary structures of the knee must also be evaluated and treated for a successful outcome. In a study of 80 ACL reconstructions, all patients who had postoperative clinical instability with giving way demonstrated evidence of associated ligamentous instability that had not been appreciated or addressed at the time of the primary surgery. Kamath et al. report that 3–31 % of ACL failures were due to missed collateral instability or concomitant malalignment [7], while Getelman and Friedman identified 15 % of revision ACL cases due to failure to address associated knee laxities [41]. Structures that need to be evaluated include the posterior horn of the medial meniscus, the posteromedial and posterolateral corners, and the overall alignment of the lower leg. The medial meniscus acts as an important secondary restraint to tibial translation, and increased forces are noted in the reconstructed ACL in the meniscus deficient knee [19]. Unrecognized injuries of the posterolateral or posteromedial structures result in unnatural high forces seen in the ACL graft as well, which result in gradual attenuation and eventual early failure [42]. Varus malalignment, either solitary or combined with medial compartment narrowing from complete or partial meniscectomy, may result in varus thrust in the limb, leading to repeated stretching and fatigue on the reconstructed ACL [43]. If identified early enough, these concomitant pathologies can be treated before the ACL graft becomes incompetent. However, once these injuries go unrecognized after the primary procedure, they are generally not discovered until the ACL graft has failed and revision ACL reconstruction is required.

Biologic failure of the ACL graft is failure of incorporation and ligamentization [44], resulting in an atonic, disorganized, and nonviable graft. This mode of failure should be considered in a patient with recurrent instability without a history of trauma and with no detectable technical errors, including injuries to secondary stabilizers. Graft incorporation involves a sequential, regulated process of necrosis, revascularization, cell repopulation, collagen deposition, and finally matrix remodeling [19]. Failure of this process is due to avascularity, immunologic reaction, and stress shielding. Still, very little is known about the biologic variables that affect the rate and extent of ACL graft incorporation. Several mechanical factors influence the vascularity to the graft and subsequent graft incorporation, such as intercondylar notch impingement, graft overtensioning, postoperative immobilization, infection, and immunologic reactions [37, 45, 46]. Thus, biologic healing of the graft can be optimized with appropriate surgical technique and postoperative rehabilitation.

Stiffness

Early studies of ACL reconstruction identified stiffness as the most common complication postoperatively, with high rates ranging from 24 to 35 % [47, 48]. Etiologies for stiffness include preoperative swelling or stiffness, infection, poor compliance with physical therapy, reflex sympathetic dystrophy, prolonged immobilization, impingement, scarring or capsulitis, and poor surgical technique. With the reduction of risk factors and accelerated rehabilitation protocols, stiffness as a postoperative complication has markedly decreased to as low as 0–4 % of cases [49–52]. Such modalities include ensuring full range of motion preoperatively, as well as immediate range of motion, immediate weight bearing, early quadriceps exercises, and patellar mobilization postoperatively. Surgical intervention is occasionally required should rehabilitation fail and includes manipulation under anesthesia, arthroscopic lysis of adhesions, or open lysis of adhesions [47, 48]. As mentioned previously, a malpositioned bony tunnel can result in stiffness and pain. If loss of range of motion and an intact, sometime tight, ACL graft are found in combination with tunnel misplacement, arthroscopic graft resection and arthrolysis may need to be considered if all other modalities have failed. Following surgical treatment, the knee should be treated with intensive physical therapy to regain full range of motion, and then consideration for revision ACL reconstruction, should the patient complain of knee instability.

Arthritic Pain

One of the elusive goals of an ACL reconstruction is to prevent or delay the development of osteoarthritis. However, multiple factors are postulated to be involved in the development of osteoarthritis after an acute knee injury. The initial hemarthrosis following a traumatic knee injury and the associated inflammatory response may initiate the arthritic pathway early on in the knee [53–55]. The associated structural damage from the injury, including bone bruises, articular cartilage damage, and meniscal pathology, may also affect the development of arthritis in the knee. Finally, recurrent episodes of instability that occur from the time of injury until the ACL reconstruction may result in further damage predisposing the knee to arthritis.

Several long-term, prospective studies have evaluated the effect of articular cartilage and meniscal injuries on outcomes following an ACL reconstruction. Ichiba and Kishimoto found lower knee patient-reported scores and higher osteoarthritis scores in patients with meniscal tears or articular cartilage damage following an ACL reconstruction [56]. Shelbourne and Gray demonstrated an inverse relationship between patient-reported knee scores and amount of meniscus removed during a meniscectomy [57]. Their group also recognized worse outcomes in patients with articular cartilage damage. Finally, Wu et al. found more subjective complaints, lower scores, lower performance on objective testing, and more arthritic changes on radiographs with patients who underwent meniscectomies compared to patients with intact menisci following their ACL reconstruction [58]. Thus, a successful ACL reconstruction with a stable knee may have an unsuccessful outcome because of the initial traumatic event or other associated pathologies. When evaluating a patient for revision ACL reconstruction, it is important to differentiate pain due to arthritis, meniscal, or articular cartilage injury from pain due to instability.

Extensor Mechanism Dysfunction

Extensor mechanism dysfunction encompasses a wide realm of complaints postoperatively, including anterior knee pain, quadriceps muscle weakness, patellar tendinitis, and donor site complications such as patellar fractures, quadriceps tendon rupture, and donor site pain. Anterior knee pain is one of the most common complications after an ACL reconstruction, with an incidence ranging from 3 to 47 % [2, 59, 60]. These complications can result in an unsuccessful outcome to an otherwise stable knee in an ACL reconstruction. Most of these problems can be prevented through proper surgical technique and postoperative rehabilitation protocols [61]. Physical therapy and rehabilitation are the treatment modalities of choice for these conditions, with surgery occasionally needed for problems such as patellar fractures or quadriceps tendon ruptures. Anterior knee pain related to the extensor mechanism in patients with a stable knee is not an indication for revision ACL reconstruction.

Determining Indications for Revision Anterior Cruciate Ligament Reconstruction

A thorough clinical evaluation is necessary to determine which patients are appropriate candidates for revision ACL reconstruction. The primary goal of a revision ACL reconstruction is to reconstruct a reruptured or incompetent ACL graft, with the goal to stabilize the knee, prevent further injury to articular cartilage and menisci, and maximize the patient's function. Patients who best fit these indications are patients complaining of instability with activities of daily living or athletic activities, together with the presence of anterior or rotational laxity on clinical examination.

History

A careful patient history is critical in successfully treating a failed ACL reconstruction. The primary goal is to differentiate a patient's primary complaint of pain vs. instability. A recent meta-analysis found that 32 % of ACL-reconstructed knees with autograft had positive findings on a Lachman test, and 22 % had positive findings on the pivot-shift test [62]. Therefore, a significant number of patients may have continued objective laxity but with satisfactory subjective outcomes. Instability or pain due to instability can be improved with revision ACL surgery, whereas arthritic knee pain, anterior knee pain, and donor site knee pain cannot. Other common patient complaints after ACL reconstruction include swelling, giving way, locking, noise, stiffness, or limp [63]. As mentioned previously, the time course of failure helps to determine the etiology of failure, with early failures in the absence of reinjury (less than 6 months) more likely the result of technical errors and late failures (more than 6 months) likely due to traumatic injury. A patient's activity level postoperatively must be evaluated and compared to their preoperative level of activity. It is important to note whether the patient ever returned to normal activities without instability symptoms, or if the patient has continued to have complaints of giving way in the reconstructed knee.

Physical Exam

In addition to the complaint of instability, patients must exhibit examination findings of anterior and/or rotational laxity to be a candidate for a revision ACL reconstruction. Some patients will describe a subjective perception of knee instability and giving way, with inability to trust the knee while performing pivot and/or twisting activities despite having a normal Lachman and pivot-shift examination [7]. However, without verifiable signs of knee instability, revision of the graft is unlikely to improve these patients' symptoms. Criterion for graft failures varies in the literature between greater than 3 mm and greater than 5 mm of side-to-side difference between the affected knee and the normal, contralateral knee utilizing the KT-1000 instrument. However, studies have shown the Lachman examination and instrumented laxity do not relate with patient-reported symptoms [64]. The pivot-shift examination, on the other hand, correlates well with patient-reported symptoms and function [63] as well as ACL insufficiency [65]. The combination of instability complaints and objective signs of ACL laxity are the two criteria essential to propose revision ACL reconstruction to a patient.

Diagnostic Imaging

Standard radiographs for clinical evaluation of a reconstructed ACL include standing anterior-posterior (AP), 40° posterior-anterior (PA) flexion weight bearing, lateral, and Merchant views. These views assess the type of hardware present, tunnel placement and size, and presence of osteoarthritic changes. They do not play a large role in determining which patients are appropriate for surgery, but may rule out patients if they demonstrate significant degenerative joint disease of the knee.

Similarly, an MRI is obtained for most patients for preoperative planning rather than for diagnosis of an ACL graft failure. The one instance would be patients complaining of instability that is difficult to examine because of the guarding or the size of the knee. Rak et al. demonstrated that an MRI is a useful modality to assess the integrity of the reconstructed ACL [66].

Post-surgical Expectations

Once a patient has been determined to be a candidate for revision ACL reconstruction, the goals and expectations of the surgery must be articulated to the patient. There is a paucity of data in the literature regarding outcomes after revision ACL reconstruction, with most studies being small, Level IV case series. Most studies demonstrate favorable results in terms of restoring stability. However, clinical outcome scores are consistently lower than those seen after a primary ACL reconstruction, and the return to preinjury activity levels is unpredictable [7, 67]. Thus, the goals of surgery are to allow a patient to return to activities of daily living without instability, with the understanding that return to sports may not be possible. Some authors have even gone as far to describe the surgery as a "salvage" procedure. It is also important to discuss with patients that the revision surgery cannot relieve concurrent pain secondary to extensor mechanism dysfunction or arthritic changes. Being forthright and counseling patients about the known results of a revision ACL reconstruction are important, as false expectations can lead to a subjective failure despite a technically successful procedure [68]. Patients who understand the prognosis and are still willing to undergo the procedure meet the final indication for a revision ACL reconstruction.

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7 Preoperative Planning for Revision ACL Reconstruction

Travis G. Maak, Demetris Delos, and Frank A. Cordasco

Introduction

The failed ACL reconstruction represents a significant clinical challenge to even the most experienced knee surgeon. More than 100,000 ACL reconstructions are performed yearly in the United States alone [1], and though satisfactory clinical outcomes range from 75 to 97 % [2–6], a significant minority of patients who undergo the procedure will experience recurrent instability and/or graft failure [6, 7]. Recurrent instability rates in the literature after primary ACL range from 1 to 8 % [8–10]. The actual rate of failure after ACL reconstruction, however, is difficult to pinpoint since no consensus definition exists and because recurrent instability after surgery is likely under-reported. Nevertheless, identifying the etiology of a failed ACL reconstruction is of the utmost importance when attempting to better understand the patient's overall condition and for the purposes of planning a potential revision surgery.

The most important reasons for failed reconstruction can be thought of in terms of three broad categories: technical, biologic, and mechanical (traumatic and unrecognized/untreated secondary instability) [11–13].

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Etiology of the Failed ACL Reconstruction

Technical Failure

The greatest percentage of ACL reconstruction failures are clearly due to technical deficiencies, which can account for over 70 % of all causes of failure [11]. Specific technical shortcomings include: poor tunnel placement (perhaps the most important reason), poor fixation, inadequate graft tensioning, inappropriate/inadequate graft material, and failure to address concomitant soft tissue or structural problems (such as meniscal, ligamentous, and articular cartilage lesions and/or malalignment) (Fig. 7.1) [11, 14]. Incorrect bone tunnel positioning is perhaps the greatest technical threat to success. On the femoral side, the margin for error is small: a tunnel placed too far anteriorly with the graft tensioned in extension can lead to excessive graft tension with knee flexion, while placement of the tunnel too far posteriorly may lead to excessive graft tension with knee extension. The former can lead to loss of knee flexion, whereas over-constraint in the latter scenario may lead to loss of terminal extension—both can result in excessive graft laxity [14, 15]. If the femoral tunnel is too vertical in the coronal plane (i.e., at the 12 o'clock position), it is likely

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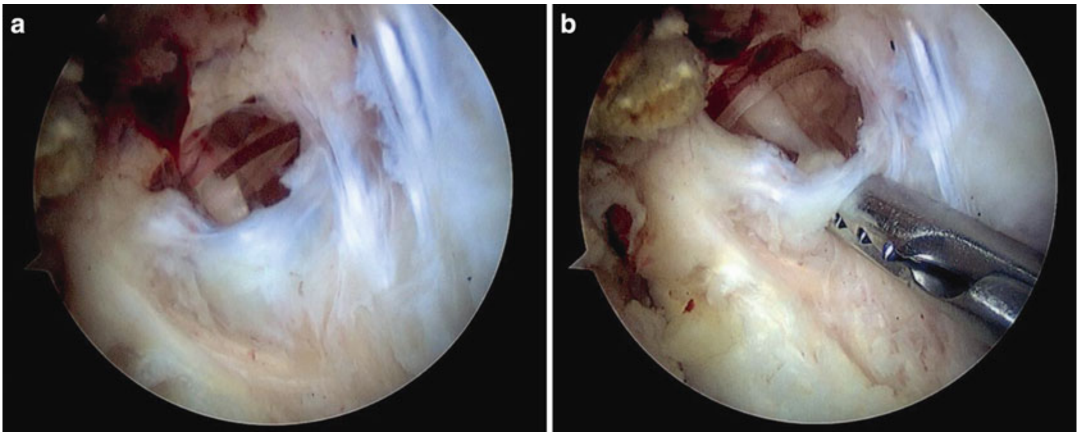

Fig. 7.1 (**a**) Arthroscopic visualization of failure and backout of previous bioscrew interference fixation of a tibialis anterior tendon allograft in the femoral socket. (**b**) Removal of this bioscrew was easily performed with an arthroscopic grasper demonstrating clear failure of fixation

that anteroposterior restraint will be improved but rotational stability will still be compromised after reconstruction, manifesting in a persistent pivot shift [16, 17]. Poor tibial tunnel placement has also been implicated in negative outcomes. A tibial tunnel that is too far anterior can lead to graft impingement with knee extension and excessive graft tension with knee flexion—one that is too far posterior can impinge against the posterior cruciate ligament (PCL) with knee flexion [15]. Excessive medialization or lateralization of the tunnel can result in the graft impinging upon the notch, chronic synovitis, and increased laxity [18].

Improper graft tensioning can also lead to ACL reconstruction failure. Under-tensioned grafts manifest in residual laxity after surgery, whereas over-tensioned grafts result in overconstraint of the joint and possible graft laxity over time. Ideal tensioning of the graft is complex and oftentimes clinically difficult to achieve. Factors that are important in tensioning include length of graft, the degree of tension applied, and the position of the knee at the time of tensioning [11, 19]. Graft type and graft fixation also play an important role in the success of reconstruction surgery. Grafts that are too small (e.g., some autologous hamstring tendons), or of poor quality, may lead to compromised results. Graft selection is an important step in successful ACL reconstruction and should be carefully considered in the preoperative stages. Prior history of severe patellar tendonitis or Osgood–Schlatter disease can compromise graft quality. Likewise, fixation failure due to bone block advancement (in the case of BTB) grafts), screw divergence, or loss of fixation with interference screws may negatively affect the intended outcome [11].

Biologic Failure

Infection after ACL reconstruction is relatively rare, with a rate of 0.58 % identified in one large retrospective series [20]. In that same series, hamstring autograft demonstrated a higher rate of infection (1.44 %) than BTB autograft (0.49 %) or allograft (0.44 %). Infection after ACL reconstruction presents a unique clinical problem and treatment options must be tailored to each patient. Successful outcomes after treatment of the infection with graft retention are possible; however, clinical results and motion are frequently negatively affected [21–24].

Stiffness after ACL reconstruction is often due to arthrofibrosis and usually affects extension more than flexion. There are several factors that have been associated with postoperative stiffness and arthrofibrosis including: early ACL reconstruction performed prior to restoration of complete range-of-motion after the initial ACL injury, excessive postoperative immobilization, Cyclops lesions, inappropriate graft tensioning, and non-anatomical graft placement [14, 25–27]

Another biologic cause of failed ACL reconstruction is poor graft incorporation. Patients with failed graft incorporation often present with clinical instability despite no history of trauma and no evidence of technical error [28]. Poor vascularity, failure of cellular repopulation of the graft, poor remodeling, and aberrant loads may all contribute to failed graft incorporation [12].

Mechanical Failure

The true incidence of traumatic failure after ACL reconstruction is not completely known and likely varies depending on the graft used [29, 30]. However, for the purposes of identifying etiologic causes it is useful to narrow traumatic failures to those that occur early (<6 months after surgery) and those that occur late (≥6 months after surgery). Early failures are often associated with aggressive physical therapy that overstresses the surgical fixation before incorporation has occurred [31]. Late failures are usually due to mechanisms similar to those involved in the initial ACL injury. It is believed that patients who have undergone well-performed ACL reconstructions with appropriate grafts are at no higher risk of re-rupturing the reconstructed ACL than the contralateral native ACL, though return to competitive sports and young age have been identified as potential risk factors [29, 32–34].

Unrecognized Concomitant Injury

A final category of causes of failed ACL reconstruction is unrecognized or untreated concomitant lesions of the knee such as meniscal injuries, articular cartilage wear (arthritis) or defects, posterolateral or posteromedial instability, and malalignment. All of these entities can negatively affect outcomes and potentially lead to failure. Needless to say, any revision procedure must address these problems prior to or during revision ACL reconstruction in order to optimize the chance at successful revision.

Patient Evaluation

History

As with all orthopedic conditions it is imperative that a careful history be performed. The nature of the symptoms and their onset (especially in relation to the index procedure) can provide significant clues to etiology. Frequently, the patient's constellation of symptoms can be used to help identify whether the primary issue is pain, instability, or stiffness. Furthermore, the timing of these symptoms and signs in relation to the index procedure can help identify potential causes since failure that occurs within 6 months of the index procedure is often due to technical reasons and failure that occurs late may be caused by traumatic re-rupture, arthritic degeneration, or lack of graft incorporation.

Previous clinic notes, imaging studies, and intraoperative photographs may be helpful to better understand the clinical picture and should be reviewed, if possible. It is also useful to attempt to retrieve the index procedure operative report in order to identify the type of graft and hardware utilized and to understand how the tunnels were made (i.e., trans-tibial versus anteromedial portal, etc.).

The patient should be asked the circumstances behind the index procedure. How did the original injury occur? Was the index surgery delayed to allow motion recovery? Was there recurrent instability prior to surgery? Were there any postoperative wound healing issues? What postoperative rehabilitation was performed? At what time interval did they resume agility training, and when were they released for sports participation? What was the level of activity and overall knee performance after the index procedure? Did the patient return to sports? Was the return at the prior level of performance? Finally, it is important to discuss the patient's desired level of activity and the expectations regarding possible surgical versus conservative management. Revision ACL reconstruction is a complex procedure and outcomes are less predictable than after primary reconstructions. Furthermore, rehabilitation after surgery can be more difficult. Patients should be counseled on all these factors and realistic expectations regarding operative and non-operative treatment should be clarified prior to making a final decision.

Physical Examination

Physical examination first begins with observation. Gait and lower extremity alignment should be carefully evaluated. Malalignment, excessive varus, or valgus with or without thrust may be indicative of a more complex structural problem that should be addressed prior to any revision ligament procedure. Inspection of scars can aid in preoperative planning and may suggest the type of graft used as well as the previous surgical approach. The integrity of the skin and overall muscle tone should also be reviewed. Thigh circumference should be compared with the contralateral limb in order to detect atrophy. Knee range-of-motion is evaluated, preferably with a goniometer, and evidence of stiffness should be recorded. Likewise, extensor mechanism dysfunction should be identified if present. Strength testing should also be performed.

A complete ligamentous exam including examination of the ACL, medial collateral ligament (MCL), lateral collateral ligament (LCL), PCL, as well as the posterolateral and posteromedial corners is necessary. ACL examination should include the Lachman, anterior drawer, and pivot shift tests. Varus and valgus testing at 0° and 30° should be performed to evaluate the collaterals. The posterior sag sign, posterior drawer, and the quadriceps active tests are used to evaluate the PCL. The Dial test or posterolateral spin test at 30° and 90° of knee flexion should be performed to test for posterolateral rotatory instability. The anterior drawer test with the tibia in external rotation can be used to test for increased anteromedial translation, a possible sign of posteromedial corner lesions.

Radiographic Evaluation

Plain radiographs including standing anteroposterior (AP) and lateral views as well as Merchant and Rosenberg [35] (45° posteroanterior (PA) weight-bearing) views are recommended. Standing AP and lateral views are used to inspect the femoral and tibial tunnel positions, hardware position, joint spaces, and overall alignment. The Rosenberg view is useful to evaluate the notch as well as the joint spaces in the medial and lateral compartments with the knee flexed [35]. A single standing hip-to-ankle alignment view may be used to draw out the mechanical axis from the center of the femoral head to the center of the talus to better evaluate lower extremity alignment. Any significant deviation from the mechanically neutral axis may require a concomitant or staged osteotomy. Plain radiographs that demonstrate osteolysis or bone defects should prompt further evaluation with a computed tomographic (CT) scan. CT scan is useful for more precisely evaluating the bone quality, architecture, tunnel position, and tunnel widening, which may require bone grafting as part of a staged procedure

MRI is often performed to review the integrity of the previous graft, the menisci, the articular surfaces, and the other ligaments and tendons about the knee. The degree and quality of signal in the graft is carefully evaluated, since increased signal may be indicative of graft impingement [36, 37]. MRI can also be used to look for loose bodies that are not visible on radiographs. Recent translation episodes may manifest in bone edema patterns that can also be seen on MRI.

Surgical Approach

Skin Incision

The data collected during a meticulous preoperative patient assessment and radiographic evaluation will aid in developing a preoperative plan and surgical approach. During the physical examination, careful inspection of the skin and myofascial envelope of the knee will help guide new skin incision placement. The positioning of

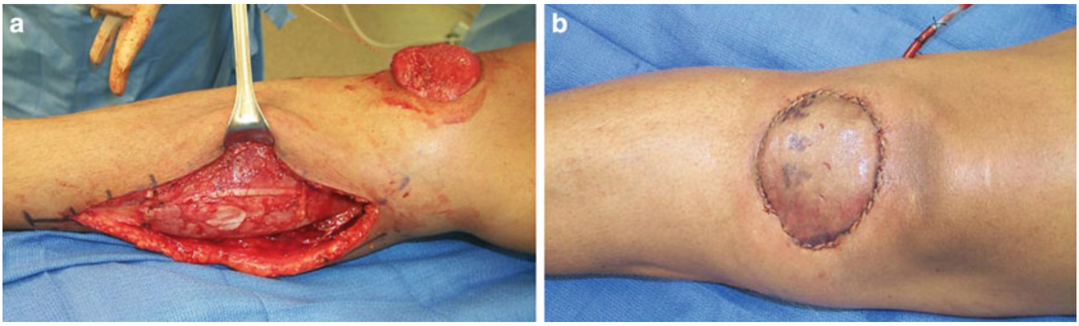

Fig. 7.2 (**a**) Skin necrosis and infection following BTB autograft required mobilization of a medial head gastrocnemius flap to facilitate soft tissue coverage. (**b**) Split-thickness skin grafting following flap placement resulted in effective coverage of the soft tissue defect

the requisite skin incisions should include consideration of: (1) revascularization of dermal tissue, which is directly related to the time elapsed since previous surgical intervention, (2) potential incorporation of previous incisions without compromising surgical exposure, and (3) if new incisions are required for adequate exposure these should maximize skin bridges as bridges less than 7 cm may increase the risk of skin necrosis (Fig. 7.2) [37]. In this setting, the use of allograft tissue can reduce surgical dissection and thereby minimize the risk of wound complications. In the case of prior infection with poor quality or severely compromised soft tissues overlying the patella or tibia, plastic surgery consultation should be considered as a gastrocnemius flap may be required to prevent wound complications.

Tunnel Widening

Tunnel widening can cause a significantly increased degree of difficulty during ACL revision surgery due to complications secondary to bone loss and compromised fixation. While adverse clinical outcomes have been associated with tunnel widening, preoperative planning is critical to improve revision ACL reconstruction outcomes [38]. Femoral tunnel widening represents a specifically difficult problem due to impaired arthroscopic access, as compared to the superficially accessible tibial tunnel. Particular focus should be placed on preoperative radiographic evaluation of the previously placed tunnels. Plain radiography, CT, and MRI should be used to evaluate the dimensions of the tunnels (Fig. 7.3a–d). These dimensions can aid in selecting the preferred surgical option, including jumbo plug placement, divergent tunnel placement, stacking screws, matchstick or bullet grafting, or two-staged grafting and reconstruction (Fig. 7.3e–h) [38].

Implanted Hardware

Recent advances in arthroscopic ACL reconstruction have resulted in a wide variety of fixation techniques. Specific hardware options range from aperture fixation with metallic and biologic interference screws to suspensory and double-cross pin fixation [39–41]. Knowledge of these various options is critical for the revision surgeon as removal or incorporation of the prior hardware may be necessary during the revision surgery. Many of these implants require specific removal instrumentation that should be available at the time of revision ACL reconstruction.

Optimal tunnel placement should not be compromised to avoid prior hardware. Removal of prior hardware should include meticulous excision of soft tissue and bone that may impede access to the hardware. Use of curettes, burrs, or small osteotomes may be required for adequate excision. If removal of a screw is required, care

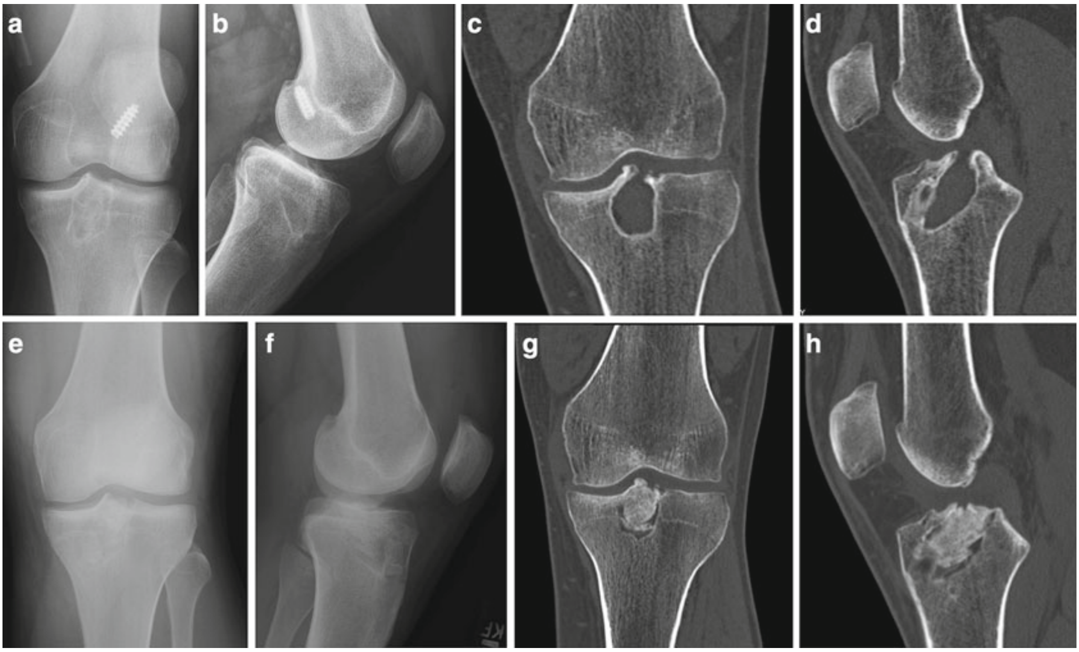

Fig. 7.3 (**a**) Anteroposterior (AP) and (**b**) lateral plain radiographs demonstrating tibial tunnel widening (**c**) Coronal and (**d**) sagittal CT images confirming and more accurately delineating tibial tunnel widening (approximately 18 mm). (**e**) AP and (**f**) lateral radiographs following removal of hardware and staged bone grafting of tibial and femoral tunnels. (**g**) Coronal and (**h**) sagittal CT images obtained demonstrating tibial tunnel graft fill and incorporation

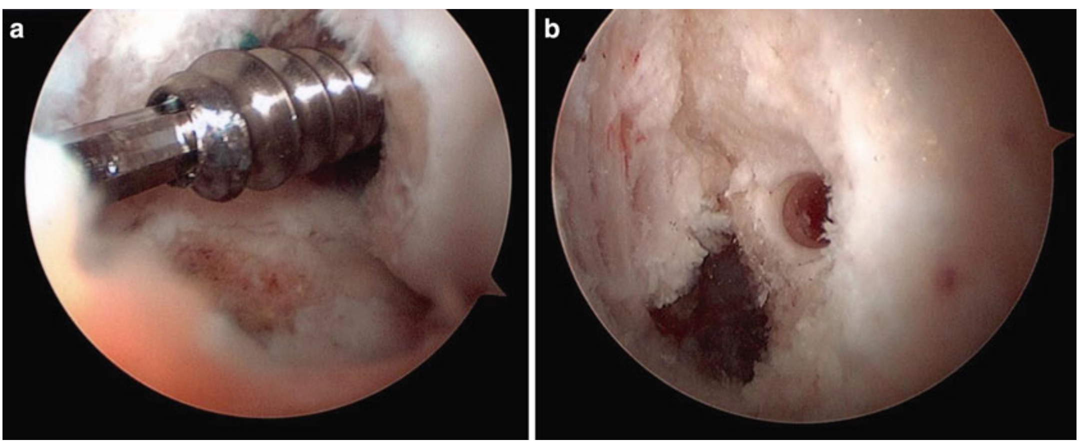

Fig. 7.4 (**a**) Traumatic rupture of previously well-positioned ACL graft may require removal of prior hardware prior to tunnel and socket drilling. Care should be taken to fully seat the appropriate screwdriver into the screw and thereby atraumatically remove the interfering hardware as shown in this arthoscopic image. A cannulated guide wire may also be used to ensure that the screw does not disengage and move freely within the knee joint. (**b**) Following complete hardware removal, the previous socket may be re-reamed in the absence of tunnel widening as in this case

should be taken to confirm the correct screwdriver size and fully seat the screwdriver prior to removal (Fig. 7.4). A stripped metallic screw may be removed using an oversized screwdriver and direct impaction technique using a hand mallet, a reverse threaded screw removal instrument, or over-drilling with a coring reamer. Stripped biologic screw removal may be performed with

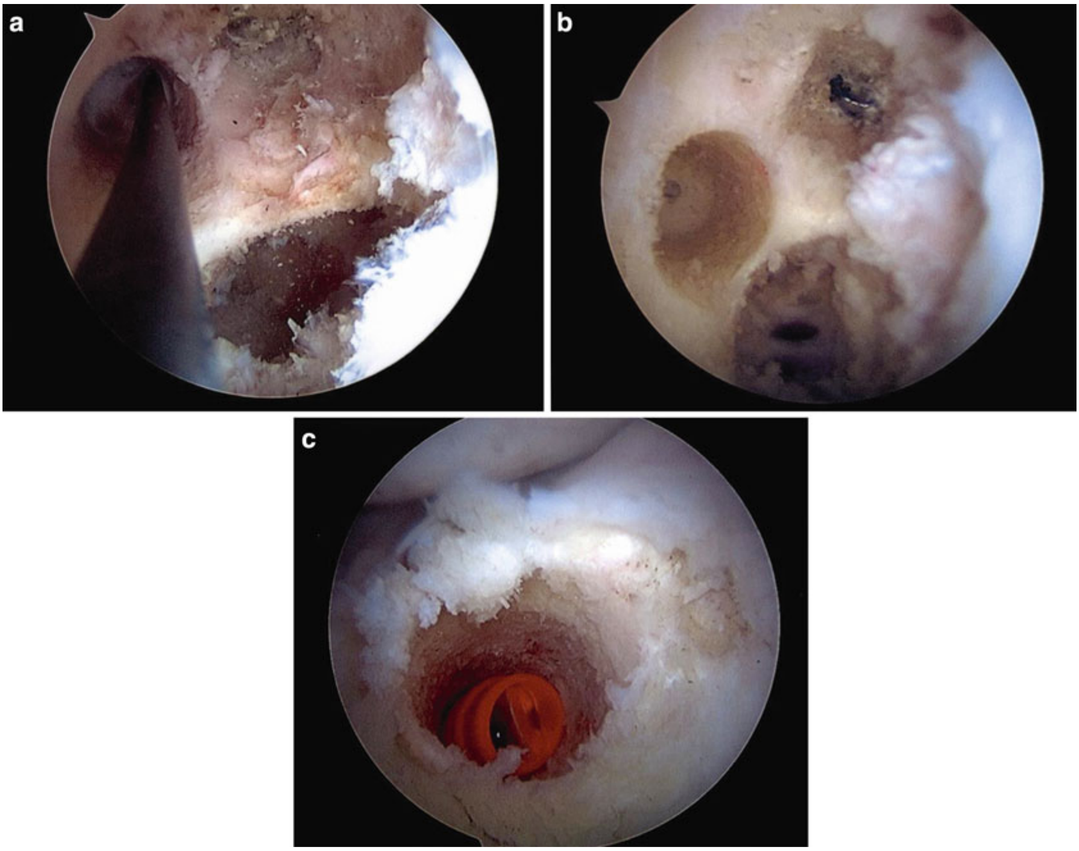

Fig. 7.5 (**a**) An anteromedial portal technique may be used to create a new revision femoral socket position without requiring hardware removal or bone grafting if the previous socket was not placed in the desired position as in this case. The guide wire can be seen arthroscopically placed in the new revision socket at the 10:30 position immediately below the previous vertical socket position. (**b**) Reaming of the femoral socket and guide wire removal demonstrates the new, divergent tunnel. (**c**) A prior well-placed tibial tunnel may be re-drilled following hardware removal and in the absence of excessive tunnel widening as in this arthroscopic image

direct drilling since metallic drills can effectively remove the softer, biologic screw. In these settings, removal of prior hardware may cause an additional increase in bone loss with subsequent tunnel widening. This situation should be considered prior to surgery and may result in the need for two-staged bone grafting and reconstruction. Removal of suspensory fixation is rare because these implants do not typically compromise new tunnel placement. Metallic staples may be removed with an implant-specific staple removal device or a small osteotome if necessary.

In some cases, prior hardware does not compromise optimal revision tunnel placement and can be retained. Varying the trajectory of the femoral and tibial tunnels, while maintaining the optimal footprint position, can potentially avoid the need for hardware removal. The revising surgeon should be comfortable with multiple tunnel placement techniques including trans-tibial, anteromedial, two-incision drilling, and "all-inside" techniques (Fig. 7.5) [42]. In this setting, the retained hardware may serve to reduce potential bone loss and enable increased fixation as in the case of stacking screws [38].

Prosthetic Ligaments

Although synthetic ligaments are rarely used in ACL reconstruction surgery due to significantly increased failure rates, these ligaments may be encountered during revision ACL reconstruction [43]. These synthetic ligaments should be considered as hardware, and thus should be completely removed prior to revision reconstruction. Incomplete removal may result in an inflammatory response that can compromise the revision graft as well as increase the risk for chondrolysis and synovitis. Effective removal may be accomplished using curved gouges and osteotomes to resect the prosthetic ligament.

Graft Selection

Identification of the graft that was used during the index reconstruction will significantly affect graft selection for the revision ACL reconstruction. Prior autograft harvest during the index surgery will reduce the options available to the revision surgeon. For example, prior bone-patellar tendon- bone (BTB) autograft harvest may eliminate ipsilateral harvest in the revision setting. Additionally, knowledge of a previously failed graft type may predispose the revision surgeon to alter the revision graft selection. For example, if an Achilles allograft was used for the index ACL reconstruction, an autograft BTB may be a more appropriate selection for the revision graft due to a reduced rate of re-rupture [44]. Consideration of preoperative tunnel widening may also influence the graft selection, as a jumbo plug will require a large quantity of bone from the selected graft.

Many graft options are available to the revision surgeon including: synthetic grafts, autografts, and allografts. Synthetic grafts, however, have been associated with significantly higher failure rates and therefore are not suggested in this setting [43]. Autograft options include: hamstring, quadriceps-patella, iliotibial band, and BTB. These grafts have a clear benefit of reduced time to incorporation and no concern for disease transmission or immune reaction. The BTB autograft also has an added benefit of dual osseous aperture fixation with low re-rupture rates [44]. Therefore, this graft option should be highly considered if the index reconstruction was performed using an allograft or hamstring graft. Nevertheless, donor site morbidity remains a concern, specifically in the setting of bone harvest as with quadriceps-patella or BTB.

Graft availability must also be considered and may be compromised by prior harvest during the index ACL reconstruction. In this vein, contralateral BTB harvest and ipsilateral BTB re-harvest have been previously used. Ipsilateral BTB re-harvest has been associated with higher complication rates [45]. Contralateral BTB harvest has not been associated with significant complications and is an excellent graft source as mentioned above, but may lead to donor site morbidity and patellar tendonitis in the donor knee for the first postoperative year [46]. Additionally, MRI data has demonstrated reconstitution of the central third of the patellar tendon following BTB harvest at 1 year [47]. However, the biomechanical properties of re-harvested grafts are currently unknown, and histologic data of this graft at the bone-tendon interface have documented largely scar tissue [46]. The current authors do not advocate the use of re-harvested BTB due to the availability of other alternatives with fewer potential shortcomings.

A widely available alternative graft option is allograft tissue. Multiple allograft options exist including: Achilles tendon, quadriceps-bone, BTB, anterior/posterior tibialis, and iliotibial-band allografts. These allograft options provide advantages to the previously discussed alternatives including: reduced operative time, minimally invasive surgical incisions, and elimination of donor site morbidity. In addition, no restriction exists on the quantity or availability of graft tissue. This advantage is particularly important in the revision ACL reconstruction setting given the increased potential for bone loss and compromised fixation. The primary disadvantage to allograft tissue is the concern regarding the higher failure rate noted following primary reconstruction particularly in younger patients and athletes (Fig. 7.6) [48]. In the adolescent athlete and the majority of adults under the age of 40–45, the senior author prefers an autograft source. If BTB had been the graft choice prior to failure, contralateral BTB, quadriceps autograft, or hamstring autograft would be possible graft

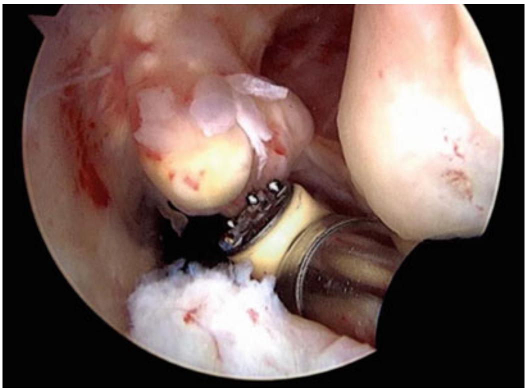

Fig. 7.6 Arthroscopic image demonstrating interval rupture of the previously placed allograft used during the index ACL reconstruction. Complete debridement of the remaining graft tissue should be performed to fully delineate the prior tunnel apertures and identify the necessary landmarks for revision tunnel positioning

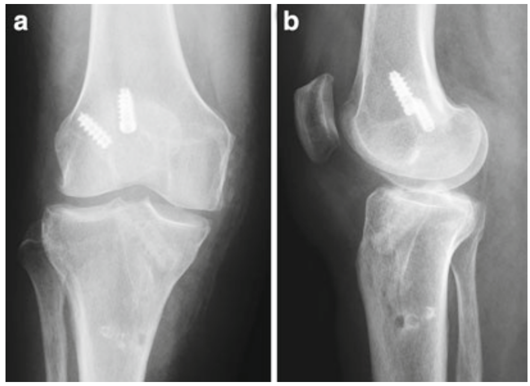

Fig. 7.7 (**a**) AP and (**b**) lateral plain radiographs demonstrating previous and newly revised femoral and tibial socket positions. Note the vertical nature of the prior femoral socket and tibial tunnel as visualized by the prior interference screw and tunnel shadow position, respectively. Additionally, note the new increased obliquity of the revision femoral socket and tibial tunnel, which was obtained using a divergent tunnel technique through the anteromedial portal

options for the revision. Allograft use in this setting would not be preferred as a general rule, but would be considered in the older adult with lower functional demands. The disadvantages of allograft tissue must also be considered prior to selection of this graft option including: immunologic inflammatory reaction, potential disease transmission, increased cost, and increased time for graft incorporation.

Tunnel Placement

Errant femoral and tibial tunnel placement is the most common cause of ACL reconstruction failure, specifically anterior femoral tunnel placement. Therefore, accurate and optimal placement of the revision tunnels is of paramount importance and should not be compromised by prior hardware or poorly positioned tunnels.

Preoperative evaluation of tunnel position is a crucial component of revision ACL reconstruction. Prior operative history regarding the surgical approach (trans-tibial, anteromedial portal, two-incision) provides important insight into the tunnel trajectory during the index surgery and serves to guide the optimal revision ACL reconstruction surgical approach. Radiographic imaging should serve to confirm the approach as well as allow meticulous evaluation of hardware and tunnel placement. Interference screw and tunnel orientation can be visualized on plain radiographs as well as CT scan and MRI. Co-linear screw placement is more likely associated with a trans-tibial approach, while divergent hardware placement may be more consistent with an anteromedial or two-incision approach (Fig. 7.7).

Multiple scenarios exist regarding tunnel placement in the revision setting including: well-positioned tunnels with graft rupture or incompetence, poor femoral tunnel position and adequate tibial tunnel position (or vice-versa), and also poor position of both tunnels. If an appropriately placed tunnel is present, the hardware can be removed (if necessary) and the tunnel can be re-drilled. All fibrous material should be removed from the tunnels to ensure adequate fixation and optimal graft incorporation. Following hardware removal and debridement, a large osseous defect may be present and various revision techniques may be required to ensure adequate graft fixation. The techniques previously discussed for femoral tunnel widening should be considered preoperatively and the instrumentation should be available. Tibial tunnel bone grafting may also be required.

An alternative to re-drilling a well-positioned tunnel is divergent tunnel placement within the same footprint. Using an anteromedial portal or two-incision approach allows independent coordination of tunnel placement, which may obviate the need for hardware removal or tunnel bone grafting. For example, if the index surgery utilized a trans-tibial approach with an appropriately placed femoral socket, the revision surgeon may consider an anteromedial drilling technique to maintain optimal footprint position while creating a new tunnel at an altered angle. It is for this reason that the revision surgeon should carefully evaluate all preoperative imaging and physical examination findings to identify the potential cause of failure. Particular focus should be placed on screw and tunnel position to allow preoperative preparation for revision tunnel placement.

If a poorly positioned tunnel is identified preoperatively, the revision surgeon should plan placement of the new tunnel in a more optimal position. The prior tunnel may not compromise this optimal position. However, if the prior tunnel significantly overlaps the new, revision tunnel, then a separate technique must be used. Alternate techniques in this setting include utilization of a smaller graft and tunnel to reduce potential tunnel violation or the techniques previously discussed for tunnel widening.

These techniques can also be employed for the tibial tunnel. A new convergent tunnel can be created with the same tibial footprint if necessary. Bone grafting of the anterior tibial tunnel may be required in the setting of bone loss. Finally, a native tunnel may be drilled if at least one tunnel diameter is present between a poorly positioned tunnel and the desired revision tunnel. Notably, particular focus should be placed on the tibial aperture. Posterior graft displacement may occur if communication exists between the apertures of the old and new tibial tunnels [49]. In this setting, the revision surgeon should consider a two-staged revision ACL reconstruction consisting of bone grafting followed by revision reconstruction at 6 months.

Planning for Graft Fixation

Advances in arthroscopic instrumentation have provided a wide array of graft fixation options from aperture fixation with interference screws to suspensory fixation with cortical ligament buttons, staples, or screws. The specific hardware selected should be dependent upon the degree of bone loss that is present following femoral and tibial tunnel creation and the integrity of the posterior femoral wall. Interference screw fixation can be effectively employed for bone plug grafts in the setting of an intact posterior femoral wall with minimal bone loss or a graft jumbo plug that is able to compensate for an osseous defect. However, the revision surgeon should consider the potential for secondary cortical fixation if fixation is not ideal, particularly on the tibial side where back-up fixation is used routinely. A two-incision technique with cortical fixation may be considered in this setting with the use of an outside-in interference screw. The aforementioned tunnel widening techniques may also be utilized for intraoperative fixation including stacked screws, matchstick grafting, etc.

Summary

Preoperative planning for revision ACL reconstruction requires a complete history, physical examination, and imaging assessment. A detailed description of the index ACL reconstruction should be obtained. Careful evaluation of these factors should aid to identify the primary, and often secondary, cause of surgical failure. This information will allow the surgeon to develop a careful management algorithm to optimize surgical outcome including consideration of skin incision placement, tunnel widening, implanted hardware, graft selection, tunnel placement, and graft fixation. However, unanticipated complications may be encountered intraoperatively despite a complete preoperative evaluation and treatment plan. Therefore, the revision surgeon must maintain a degree of surgical flexibility and consider potential alternative options to account for these complications. Alteration of the graft type, surgical approach, and fixation method must be planned for. Nevertheless, the various difficulties inherent to revision ACL reconstruction can be offset by a meticulous preoperative plan.

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8 Graft Selection for Revision ACL Reconstruction

Jeffrey Wilde, Asheesh Bedi, and David W. Altchek

Introduction

When planning a revision ACL reconstruction, one of the most important considerations is the graft choice. Despite the prevalence of revision ACL reconstruction, there is no universally agreed upon graft choice. Ideally, the graft selected should allow for early, active rehabilitation and have similar structural and biomechanical characteristics to the native ligament. It should allow for secure fixation, permit rapid biologic incorporation, and have limited donor site morbidity [1, 2]. In the young and active population who has sustained recurrent ACL injury despite technically well-positioned tunnels, the senior authors have favored the use of autograft. Patellar tendon autograft remains a preferred option in the absence of significant tunnel widening, while quadriceps autograft may be a robust option to address larger but well-positioned tunnels. This chapter will focus on the qualities of the different graft sources available (autografts, allografts, and synthetic grafts) along with the advantages and disadvantages of each.

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Allografts (Table 8.1)

The increased availability of allografts in the United States has led to a significant increase in the utilization of these tissues in orthopaedic surgery. The American Academy of Orthopaedic Surgeons (AAOS) asserts that over five million musculoskeletal allografts have been utilized by surgeons in the past decade, while the data from the American Association of Tissue Banks (AATB), a voluntary organization that sets accreditation standards for tissue banking, reports that demand for musculoskeletal grafts has grown from nearly 700,000 grafts in 2001 to approximately 1.5 million distributed in 2007. Allografts are frequently used in revision ACL reconstruction, especially if autograft options are limited or compromised by the initial procedure. The Multicenter ACL revision study (MARS) demonstrated that 54 % of surgeons used an allograft at the time of revision reconstruction compared to only 27 % who utilized an allograft at the time of the initial reconstruction [3]. Within the MARS cohort, 50 % of the allografts were BTB, followed by tibialis anterior (23 %), Achilles tendon (12 %), and tibialis posterior (11 %) [3]. Other

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Table 8.1 Advantages and disadvantages of allografts

Advantages	
•	Becoming more widely available
•	Wide variety of tissue options
•	Decreases the morbidity of the reconstruction by avoiding graft harvest
•	Decreased operative time, no autograft harvest is required
•	The allograft makes a single-staged procedure possible in large bony defects
Disadvantages	
•	Expensive
•	Slower and incomplete incorporation
•	Risk of disease transmission
•	Risk of immunologic rejection and subsequent prolonged inflammation
•	Biomechanical properties of the tissue may be compromised due to the sterilization techniques
•	Inferior results found with objective stability testing compared to autografts

available options include the quadriceps tendon (QT), hamstring tendons, peroneus longus tendon, and fascia lata. The increased utilization of allograft for revision surgery can likely be attributed to a number of different factors, including more effective sterilization techniques, better organization and distribution of the tissues, and increased confidence in the strength and stability of the grafts [4–6]. Allografts are often appealing during revision ACL reconstruction because they avoid potential complications associated with hamstring or patellar tendon graft harvests, including donor site pain, patellar fracture, patellar tendon rupture, saphenous nerve injury, and persistent extensor mechanism or hamstring weakness [7–15]. In addition, large allografts are readily available and can fill expanded tunnels in the setting of revision ACL surgery, thereby allowing a single-stage reconstruction and avoiding the need for bone grafting and a staged procedure. Allografts can be harvested with a bone block as well (AT, BTB, or QT), which may allow for increased flexibility in revision cases where significant bone loss is encountered and allow for bone-to-bone fixation. Nevertheless, the benefits of allografts must be weighed against the potential disadvantages, including an increased cost, limited availability, slower graft incorporation, and the possibility of disease transmission or an immunologic response to the graft [16]. Most importantly, however, the increased rate of failure with allograft ACL reconstruction in a young and active population is a critical consideration, and may be of even greater consequence in a population that has already experienced a previous failure [17]. In this regard, it has been the senior authors' preference to avoid the use of allograft for revision ACL reconstruction in this population, as the surgeon-controlled variables of technical accuracy and favorable biological properties of the graft should be prioritized.

Disease Transmission

One of the major concerns regarding the use of allografts is disease transmission. The true incidence of infection related to allograft knee surgery has yet to be determined. Nevertheless, the reported incidence is significantly less than 1 % (0.0004–0.014) [18, 19]. Despite a low incidence, however, there have been reports of transmission of human immunodeficiency virus (HIV), hepatitis B and C viruses (HBV and HCV), group A streptococcus, and Clostridium species [20–25]. The overall risk of viral transmission is lower and most cases have occurred prior to the discovery of the pathogen or before effective screening techniques were available to identify the pathogen. Currently, it is estimated that the risk of contracting viruses like HIV and HCV from an allograft is on the order of 1 in 1,667,600 [26].

Screening and Sterilization Techniques

All cells or tissues that are intended for transplantation into a human recipient are under strict regulations and any institution involved with recovering, processing, or storing these tissues must register with the FDA's Center for Biologics Evaluation and Research and is strongly encouraged to seek accreditation from the Board of Governors of the AATB [18]. The FDA and the AATB mandate that all graft tissue be screened for HIV 1 and 2 antibodies, HIV-1 DNA by polymerase chain reaction (PCR), HBV surface and core antigen, HCV antibody, human T-cell lymphotropic virus types 1 and 2 antibodies, and syphilis antibodies. Additionally, the development of newer testing methods such as advanced nucleic acid testing (NAT) have increased safety by allowing for screening for human transmissible spongiform encephalopathies and has significantly decreased the window period associated with the conventional antigen and antibody testing [19, 27–29].

Prior to procurement of the tissue, allograft donors are initially screened with an exhaustive review of the donor's medical and social history as well as with postmortem examinations for signs of infection. Typically, donor tissue is procured under aseptic technique in the operating room. Blood as well as samples from the allograft tissue are cultured as part of the initial screening process. Several sterilization techniques have been used in an attempt to eradicate bacteria, viruses, and spores from the donor tissue. There is no single standardized approach to sterilizing the graft tissue. Currently, there are two commonly employed processes for sterilization: gamma irradiation (GI) and chemical processing. GI can effectively be used to eradicate bacteria with doses of only 1.5–2.5 mrad. Unfortunately, it requires as much as 4.0 mrad to render HIV inactive and often even higher doses are necessary to eliminate spores [30]. Because GI results in the generation of free radicals that ultimately kill the pathogens, these free radicals can also affect the structural integrity of the graft itself. Fideler et al. studied the effects of GI on BTB allografts. The study found a 15 %, 24 %, and 46 % reduction in all biomechanical properties after exposure to 2.0, 3.0, and 4.0 mrad, respectively [31]. Ethylene oxide (EO) was shown to be an effective external sterilization technique, but had poor tissue penetration and had been associated with intra-articular reactions with chronic synovitis. Consequently, it has not been used in the past 10 years [18, 19, 29, 32]. There are several novel chemical sterilization processes available to process allografts. Some of the commonly used proprietary tissue sterilization techniques include Clearant Process (Clearant, Inc., Los Angeles, CA), Allowash XG (LifeNet, Virginia Beach, VA), Biocleanse (Regeneration Technologies, Inc., Alchua, FL), and Tutoplast (Tutogen Medical, Inc., Alchua, FL). While each manufacturer uses a slightly different technique, proprietary sterilization generally includes soaking the graft in a solution. The tissues are then placed in a centrifuge and spun with or without an agent such as H_2O_2 or alcohol. This may be followed by a second rinse and then the tissues are irradiated prior to deep freezing. Deep freezing has not been demonstrated to alter the biomechanical properties of the tissue, but it doesn't substantially contribute to the sterilization process since some viruses, like HIV and HCV, are not destroyed at these temperatures. Unfortunately, no independent testing or validation of these proprietary sterilization techniques has been performed to characterize their efficacy or effect on the biomechanical integrity of allografts.

Healing and Incorporation of Allografts

Graft healing and biologic incorporation warrant significant consideration when comparing allografts to autografts for revision ACL reconstructions. Both graft types undergo the same healing process of "creeping substitution" that begins with an initial period of avascular necrosis followed by revascularization and host synovial cell proliferation. Jackson et al. found that the donor DNA was replaced by host DNA by 4 weeks as a result of this process [32, 33]. While the mechanisms of integration may be similar, the literature has demonstrated that allografts undergo this process at a much slower rate than autografts. This was again confirmed by the work performed by Malinin et al. [34]. This study evaluated nine ACL allografts and one autograft that were retrieved at autopsy or at the time of revision surgery to evaluate extent of graft cellular replacement and remodeling at different graft ages. The age of the specimens ranged from as early as 20 days to 10 years post implantation. The examination of the entire allograft 2 years after implantation revealed that the center portion of the grafts remained acellular. The study found only one sample to have complete cellular replacement at 3.5 years postoperatively. This led the authors to conclude that complete remodeling and cellular replacement will occur in allografts, but it may require 3 or more years for complete incorporation [34]. This delayed integration may contribute to the overall decrease in the biomechanical properties of the allograft. Jackson et al. [35, 36] demonstrated that autografts had better stabilization of AP translation, twice the maximum force to failure strength, an increase in cross-sectional area, and a more rapid conversion of large diameter collagen fibers to small diameter fibers. Ultimately, the allografts demonstrated a greater decrease in biomechanical properties, an overall slower rate of incorporation, and a prolonged inflammatory response when compared to the autografts [35, 36]. For these reasons, the senior authors have avoided the use of allografts for ACL reconstruction, particularly in the revision setting in which a recurrent failure may be catastrophic to an athletic career. In a population with a previous reconstructive failure, the technical graft position, graft fixation, time-zero biomechanics, and biology must be optimized to offer the greatest chances for a favorable structural and clinical outcome in a potentially adverse host environment.

Clinical Outcomes

Clinical studies evaluating revision ACL allograft reconstructions have demonstrated reasonable outcomes, though they remain inferior to autografts for primary and revision ACL reconstruction in a young, active population [17]. Several studies also support the basic science findings that allograft incorporation is delayed and the biomechanical properties of the allograft are inferior to those of autografts [34–36]. In a prospective study of revision ACL reconstruction, Noyes and Barber-Westin evaluated 65 patients who received BTB allografts and 20 patients with autogenous BTB grafts [37]. Overall, 33 % of the allografts failed compared to 27 % of the autografts. Additionally, KT-2000 testing showed that 53 % of the allograft cohort and 67 % of the autograft group had less than 3 mm of displacement [37]. Similarly, Grossman et al. [38] compared 30 revision ACL reconstructions that used allografts (29 BTB and 1 AT) with 6 patients who had BTB autografts transplanted at the time of the revision reconstruction. The allograft group demonstrated increased laxity during instrumented knee testing compared to autografts (3.21 vs. 1.33 mm, respectively) [38]. Uribe et al. [39] reviewed 54 patients who underwent revision ACL reconstruction. Of the 54 patients, BTB allografts were used in 35 % of the cases while autologous hamstring grafts were used in 65 %. There was no subjective difference found between the two graft types, but the allografts did demonstrate decreased stability on KT-1000 testing compared to the autografts [39]. Battaglia et al. [40] reported on 63 patients who underwent ACL revision reconstruction, 40 of which were performed with autologous grafts and 23 with allografts. The overall failure rate was 25 % in the autograft subset compared to 30 % for the allograft group [40]. Based on the currently available literature, allografts present a greater risk of structural failure after ACL reconstruction and the senior authors would not advocate their use in the revision setting unless other viable autograft options have been compromised.

Table 8.2 Advantages and disadvantages of autografts

Advantages
• Eliminates the risk of disease transmission
• Eliminates the risk of graft immunologic rejection
• Faster and more complete biologic incorporation
• Decreases cost compared to allografts
• Better results with objective stability testing when compared to allografts
Disadvantages
• Fewer tissue options available
• Autograft tissue may not be available for revision reconstructions
• Increased morbidity related to autograft harvest
• Patient may refuse autograft harvest

Autografts (Table 8.2)

Despite the increasing utilization of allografts, autografts continue to be the graft of choice for primary and revision ACL reconstructions. Despite the donor site morbidity, autografts have considerable advantages over allografts. Autografts carry no risk of disease transmission or immunologic rejection. Additionally, they have a faster and more reliable biologic integration than allografts, which may be of particular importance in a revision surgery with an impaired healing environment in a previously repaired knee.

Currently, there are several options for autograft harvest sites for primary and revision ACL reconstructions. The most commonly used grafts are the BTB and hamstring tendons for primary ACL reconstruction, while the quadriceps tendon (QT) may be another favorable option for revision surgery in the setting of tunnel expansion or previously harvested grafts. Autologous grafts can be harvested from either the ipsilateral or contralateral limb depending on patient preference and what tissue was used during the primary reconstruction.

BTB Grafts

The central third of the patellar tendon along with bone plugs from the tibia and patella are considered the gold standard by many surgeons. Because of the presence of the bone plugs, BTB grafts allow for bone-to-bone healing within the tunnels and have been shown to provide a faster and more reliable incorporation of the graft than tendon-to-bone grafts [41–43]. Integration of the bone plug begins with osteonecrosis at the graft-tunnel interface. This is followed by creeping substitution of the host bone into the graft and rapid incorporation into the surrounding host bone. At 3 weeks, the bone plug is surrounded by dense fibrous tissue and by 6 weeks the bone plug has undergone complete integration into the host bone [42].

Another advantage of the BTB grafts is that they allow the flexibility to adjust the graft size to match the tunnel size. Depending on the size of the patellar tendon, up to a 12-mm width graft can be taken while still retaining an appropriate amount of tendon on either side of the harvest site. While size may be a limiting factor for the patellar harvest site, the tibial bone plug can be widened or lengthened to fill large bony defects that are often present in revision cases.

BTB autografts have some negative characteristics that have been cited in the literature, such as risk of graft-tunnel mismatch, anterior knee pain at the harvest site, and patellar fracture. Despite the ability to adjust the bone plug size to fit the defect, the BTB graft soft tissue component cannot easily be lengthened or shortened, unlike soft tissue grafts like hamstring and QT grafts. This mismatch may be particularly evident with previously prepared tunnels or when the femoral tunnel is placed in an anatomic position on the lateral wall of the femoral notch, which effectively reduces the intra-articular graft length compared to a more conventional over-the-top position. Therefore, if the graft is either significantly shortened or lengthened in comparison to the size needed for the reconstruction, the surgeon must be prepared with alternate fixation options to solve this graft-tunnel length mismatch [44–46].

Significant anterior knee pain is a well-known problem associated with BTB autografts, with occurrence rates as high as 40–60 % [47–52]. Although there are some conflicting results in the literature when comparing hamstring to BTB grafts regarding the incidence of anterior knee pain, the incidence of anterior knee pain is likely higher in the BTB group. Roe et al. [51], in a study with long-term follow up, noted that significant anterior knee pain persisted even at 7 years postoperatively and was more common and more severe in the BTB group compared to the hamstring autograft group [51]. Additionally, the incidence of donor site symptoms of any kind was more than doubled in the BTB group compared to the hamstring tendon group. The BTB group was also more prone to develop a slight extension deficit over time [51].

The risk of a patellar fracture is a rare complication that may occur in approximately 1 % of ACL reconstructions with a BTB autograft [53, 54]. The surgeon can decrease the risk of a patellar fracture by ensuring that the harvested bone plug is no more than half the length of the patella and by avoiding cross-hatching and making angled cuts with depths no greater than 10 mm. Most commonly, the fractures occur in the vertical orientation and ultimately do not disrupt the extensor mechanism. These fractures can usually be treated conservatively with nonoperative management. Occasionally, transverse fractures occur, but are usually the result of postoperative trauma. These fractures generally require repair because the fracture is at risk of displacement and compromising the function of the extensor mechanism.

Special consideration must be given in pediatric patients before utilizing a BTB autograft for a reconstruction. There is concern that using a BTB graft in a patient with open physes may cause an angular deformity due to placement of the bone plug across the physis or recurvatum deformity secondary to tubercle apophyseal injury. Consequently, the location of the graft within the physis is of significant importance because a centrally positioned physeal defect may result in premature closure but is much less likely to cause an angular deformity. There is less of a risk of this deformity in the tibia where the graft tunnel is placed more centrally in the physis, whereas, the femoral tunnel is often drilled more obliquely. In addition, tunnel obliquity affects more total volume of the physis, which can result in a larger disruption of the growth plate. A BTB graft is at a greater risk of a large physis disruption because of the thickness of the graft ends. An animal study demonstrated that the larger the cross-sectional area of the physis that is affected, the greater the chance of a growth disturbance. The same study found that there is an increased risk of partial physeal closure when greater than 7 % of the physis is disrupted.

Re-harvested BTB has also been used in revision ACL reconstructions. Currently, there are conflicting data regarding the success of this graft in revision ACL reconstruction. Colosimo et al. [55] found that 11 patients had good or excellent results and 2 patients had fair results after undergoing a revision ACL reconstruction with a re-harvested BTB graft. Mean follow up was 29.4 months and postoperative KT-1000 testing demonstrated an average side-to-side difference of 1.92 mm. There was no loss of range of motion in any of the patients and only 1 patient reported moderate patellofemoral problems. Based on these results, the authors concluded that a reharvested BTB graft is a viable option for revision ACL reconstruction [55]. O'Shea and Shelbourne also reported good subjective and objective results in a group of 11 patients with a mean follow up time of 49 months [56]. In contrast, Kartus et al. [57] demonstrated a higher rate of complications and poorer functional scores in the patients who underwent reconstruction with a re-harvested BTB graft in comparison to cases where the contralateral patellar tendon was used for graft harvest. Of the 12 patients with a re-harvested BTB graft, 1 had a patellar fracture 2 weeks postoperatively and another suffered a patellar tendon rupture 6 months postoperatively [57]. Liden et al. [58] noted similar results in a 10-year follow up study of 14 patients with re-harvested BTB reconstruction. MRI studies at 10 years following the re-harvesting procedure demonstrated that the patellar tendon at the donor site had not normalized. Additionally, Lysholm, IKDC, and KT-1000 scores as well as single leg hop and knee-walking testing noted no significant difference between results at 2 years and 10 years postoperatively. Overall, the results were considered to be poor at both postoperative timepoints [58]. As with the study by Kartus et al. [57], the two major complications noted in this cohort were one patellar fracture and one patellar tendon rupture.

The senior authors have favored the use of native BTB graft when available for revision ACL reconstruction. This graft is particularly favorable in the setting of well-positioned tunnels without considerable expansion or in the setting of newly prepared tunnels in a primary or staged reconstruction.

Hamstring Grafts

Hamstring autograft has been used successfully in revision ACL reconstructions for many years. In a recent study, Salmon et al. [59] reported on 57 revision ACL reconstructions using 4-strand hamstring autografts with an average of 89 months of follow up. Of the 50 knees reviewed, 5 (10 %) had objective failure of the graft. In the remaining 45 patients knee function was normal or nearly normal in 33 cases (73 %). Fifty percent of the knees had less than 3-mm of translation with the remaining 50 % having 3–5 mm [59].

Typically, both the gracilis and the semitendinosis tendons are harvested and then doubled and combined to create a 4-strand graft, though some authors have noted using 5- and 6-strand grafts to improve the graft strength when sufficient length is available. Currently, there are numerous fixation devices available for soft tissue grafts such as cortical suspensory fixation devices and aperture interference fixation devices.

One significant advantage to using the hamstring graft is the avoidance of the potential side effects inherent with BTB grafts, especially anterior knee pain and patellar fracture. This may be particularly important in patients who perform a significant amount of kneeling or squatting during work. In a 9-year follow up study, Wipfler et al. [60] found that hamstring autografts had better kneeling, knee walking, single leg hopping, and IKDC scores compared to BTB grafts. Leys et al. [61] found that the hamstring autograft group had better results regarding the incidence of osteoarthritis, motion loss, single leg hop, and kneeling pain postoperatively, but the study found no difference in IKDC scores [61].

The most commonly reported disadvantages to hamstring grafts are related to size, the propensity of the graft to develop laxity, the ACL agonist function of the hamstring muscle-tendon units, and the delayed healing of tendon-to-bone compared to bone-to-bone. Hamstring grafts can often be small and cannot be adjusted or customized to match existing tunnel dimensions, which are frequently greater than 10 mm in diameter. In the revision setting, incomplete tunnel fill with these grafts is unfavorable and likely increases the risk of failure and incomplete healing and the tendon-bone interface. The occurrence of laxity is generally related to the number of graft strands used in the reconstruction. In 2010, a systematic review found, in two studies, that 2-strand hamstring grafts developed laxity over time when compared to BTB grafts [62]. Whereas, only 1 of the 4 4-strand hamstring grafts analyzed was found to have a significant difference in laxity when compared to BTB grafts.

Soft tissue-to-bone healing has been found to be a slower and less reliable process than bone-to-bone healing [42, 63]. Unlike bone-to-bone healing where there is direct incorporation of host bone into the bone plug, soft tissue-to-bone healing requires a slower process of fibrovascular scar tissue maturation at the graft-tunnel interface. Eventually, the fibers organize into a perpendicular orientation, which takes approximately 12 weeks [43]. The presence and number of these fibers directly correlates to the pullout strength of the graft [64–66]. Unfortunately, the slower healing process and compromised pullout strength place these hamstring grafts at increased risk for structural failure in the early postoperative period.

Lastly, the native hamstring also acts as a protective force for the ACL. One study by Withrow et al. [67] demonstrated that increasing hamstring force during the knee flexion landing phase decreased the peak relative strain in the ACL by >70 % compared with the baseline condition ($p = 0.005$). Neither a constant hamstring muscle force nor the absence of a hamstring force significantly changed the peak strain in the ACL relative to the baseline condition [67]. Consequently, a weakened hamstring from graft harvest will not likely increase the peak strain on the ACL, but it may affect the ability of the hamstring to properly protect the ACL by reducing the total strain on the ligament and thereby compromising the reconstruction.

Quadriceps Tendon

Ipsilateral and contralateral quadriceps tendon has been used in revision ACL reconstruction and is a robust autograft option, particularly in the setting of considerable tunnel expansion. The quadriceps tendon is a thick tendon and can be harvested with a bone plug from the superior pole of the patella. The thickness of the graft lends to a stronger graft with a large cross-sectional area that can fill well-positioned but expanded sockets, often permitting a single-stage reconstruction with autograft in the revision setting. A relative benefit of the QT graft is that it is easily customizable in terms of both thickness and length and offers the benefit of bone-to-bone healing on one side of the graft. Currently, there is little in the literature regarding the use of QT in revision ACL reconstructions. One study looked at 21 knees with ipsilateral QT grafts for a mean follow up of 49 months. Of the 21, 8 knees had less than 3 mm of translation, 7 knees had 3–5 mm of translation, and 4 knees had more than 5 mm of translation on knee laxity testing. On pivot shift testing, 10 had a grade 0 pivot shift, 7 had a grade I, 3 had a grade II, and 1 had a grade III [68].

The senior authors have favored the use of quadriceps autograft for revision ACL reconstruction, particularly in those cases in which BTB graft has been previously utilized and/or in the setting of well-positioned but expanded tunnels. In these cases, QT autograft affords the potential for excellent tunnel fill, bone-to-bone fixation, and the favorable biology of autograft healing.

Synthetic Grafts

Previously popular in the 1980s, synthetic grafts were occasionally used as the primary graft material or as an adjunct support to autologous graft tissue in ACL reconstructions. Three devices were most commonly used in the United States: the Gore-Tex ligament (W. L. Gore and Associates, Flagstaff, AZ), the Stryker Dacron ligament (Stryker Corporation, Kalamazoo, MI), and the Kennedy Ligament Augmentation Device (3M Corporation, Minneapolis, MN). Poor performance of the synthetic grafts compared to biologic grafts in several long-term studies has largely limited their use. Complications such as premature rupture, prolonged inflammatory response to the graft material, recurrent knee effusions, synovitis, and painful hardware were all implicated in the use of synthetic graft material [69–73]. Consequently, synthetic grafts should not currently be used for primary or revision ACL reconstructions, leaving the biologic grafts as the primary graft options.

Clinical Considerations when Selecting the Graft

The relative strengths of both allografts and autografts are given in Table 8.3. In addition to understanding the performance profile of various grafts, there are a number of clinical factors that must be considered when choosing the appropriate graft for a revision ACL reconstruction (see Table 8.4).

Table 8.3 Relative strengths of graft choices

Graft type	Average load to failure (*N*)
Allografts	
Double anterior tibialis [74]	4,122
Double peroneus [75]	2,483
Double post tibialis [74]	3,594
Achilles [76]	1,470
Tibialis [76]	1806.7
Autografts	
Double semitendinosis [77]	2,330
Single semitendinosis [78]	1,216
Double gracilis [77]	1,550
Single gracilis [78]	838
Double gracilis/double semitendinosis [79]	3,000
BTB [78]	2,900
Quadriceps [80]	1,075

Table 8.4 Clinical considerations when selecting the graft type

- Cause of failure of primary reconstruction
- Previously used graft type/Available autograft tissue
- Type and location of previously used hardware
- Bone quality
- Condition of the patellofemoral joint in the ipsilateral and contralateral knees
- Size of bony defect
  - Necessity of multistaged procedure?
- Individual preferences of the patient

Cause of Primary Reconstruction Failure

Determining the cause of failure is not always simple, because there is rarely only one factor that contributes to the failure of the primary reconstruction. Currently, errors in surgical technique account for the majority of primary ACL reconstruction failures. Several factors may contribute to poor graft healing and a compromised biological environment, including multiple knee surgeries, large bony defects, previous infections, or the chronic use of steroids or nonsteroidal anti-inflammatory medications. Consequently, given the slower incorporation time of the graft, allografts are not recommended in situations where the healing environment may be significantly compromised. In contrast, primary ACL reconstruction failures as a result of grossly malpositioned tunnels, inadequate fixation, or trauma may not significantly affect the healing properties of the knee, allowing the surgeon to consider more graft options. The senior authors have favored the use of autograft whenever possible in the revision setting to maximize the potential for a biologically favorable environment for graft healing and maturation.

Other Considerations

The surgeon should evaluate the patellofemoral joint in both the ipsilateral and contralateral leg. The presence of significant patellofemoral degeneration may preclude the use of BTB and QT as viable options for harvest. The use of these grafts can result in postoperative extensor mechanism weakness and may exacerbate the symptoms of the patellofemoral syndrome. This could hinder the rehabilitation process and slow the patient's recovery. In this situation, if other autografts are not available, an allograft may be the best option.

Finally, it is important to take into consideration the personal preference of the patient. Patients should be informed of the risks and benefits of each graft type and should be allowed to participate in the decision-making process.

Conclusion

There are many different graft options now available to orthopaedic surgeons. The risks and benefits of each graft type must be carefully considered prior to selecting a graft for a revision ACL reconstruction. Generally, autografts are the preferred graft for revision ACL reconstructions due to their more rapid and complete incorporation into the host tissue. There are risks and benefits to all the autograft tissues available, and these should be discussed with the patient to select the most reasonable option for the reconstruction. Additionally, with the presence of a large bony defect or significant tunnel expansion, a two-stage procedure with an autograft is generally preferred by the senior authors over a single-stage approach with an allograft with suboptimal socket position. Allograft tissue is used if there are limited autograft options available or if autograft use is relatively contraindicated secondary to patellofemoral pathology. Finally, synthetic grafts have a high rate of failure and are associated with significant complications, and therefore have no current role in primary or revision ACL reconstruction.

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9 How to Handle a Poorly Placed Femoral Tunnel

Konsei Shino, Alberto Gobbi, Norimasa Nakamura, Anup Kumar, and Tatsuo Mae

Existing Tunnel Position and Tunnel Enlargement

The existing tunnel position can be classified using 3D computed tomograms (CT) and the conventional radiographs (lateral view in maximal extension, 45° posteroanterior weight-bearing radiograph) as:

1. *Correct*: The existing femoral tunnel is placed optimally and can be reused for the revision ACLR.
2. *Completely incorrect*: The existing tunnel is placed in a completely incorrect position and the new tunnel can be created without contacting the old tunnel.
3. *Partially acceptable*: The existing tunnel communicates with the new correctly placed tunnel, which leads to an enlarged tunnel [1].

It is important to consider the "divergent tunnel" concept while planning the revision tunnel to approach the anatomical femoral or tibial foot print from several extra-articular orientations [2, 3]. If the angle or position selected for drilling differs from that used for the index procedure, one can select the proper site for tunnel placement and then diverge away from the original tunnel with minimal overlap. This allows the surgeon to address a malpositioned tunnel and avoid preexisting hardware that might be difficult to remove.

Presence of Hardware

The presence of hardware may interfere with the new tunnel creation, hence it is important to identify the type and location of the existing hardware; metallic hardware can be easily identified on a plain radiograph, a bio-absorbable screw can be identified by the sclerotic bone margin surrounding the fixation device. It's important that the hardware is identified (type and manufacturer) in order to prepare instruments for removal. Intraoperative considerations for hardware removal and dealing with any bony defects should be anticipated and the surgeon should be prepared to deal with any such issues prior to surgery. Metal fixation should be removed only if needed. Biodegradable interference screws

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(IFSs) can be drilled through; however, the debris should be carefully washed out of the joint to avoid an inflammatory response. Newer biocomposite screws can be difficult to drill, and they can also fracture into small pieces which must be removed. If hardware removal will require excessive bone loss, the preferred approach may be to leave the hardware in place and change the orientation of the tunnel while maintaining an anatomic aperture [4].

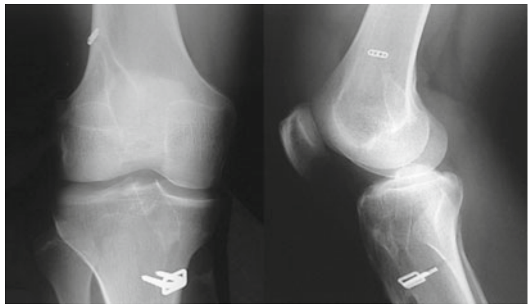

Fig. 9.1 Tunnel widening

Technical Problems Related to Femoral Tunnel Revision

There are several potential problems related to femoral tunnel revision. These situations are discussed below.

1. The existing femoral tunnel is too anterior.
   An anterior femoral tunnel can cause limitation in flexion and is frequently related to the trans-tibial technique. The hardware can often be left in place if it is out of the way, allowing for the preparation of a new tunnel in the anatomic position. In this situation, a second IFS can often be placed because the anterior fixation is out of the way. If hardware blocks creation of a new tunnel or prevents placement of a second IFS, the primary screw can be removed and replaced by a new screw, or suspensory fixation can be used.
2. The existing femoral tunnel is close to the anatomic position, interfering with the new tunnel.
   In this situation, we recommend creating a new tunnel close to the existing tunnel with overlap. We prefer to use a graft with a bone plug on the femoral side, such as BTB autograft or achilles tendon allograft. With a larger bone plug, the tunnel can be filled and good fixation can be obtained with a screw.
3. The existing femoral tunnel is too big and it is impossible to create a new tunnel.
   A two-stage procedure is indicated when the femoral tunnel is very large, generally over 16 mm (Fig. 9.1). We recommend a first stage by impacting either a cylindrical iliac crest autograft or a prefabricated allograft cylinder (Fig. 9.2). CT scan is then obtained at 3–6 months to evaluate the bony fill of the graft, and when incorporation is adequate, revision ACL reconstruction can be undertaken.
4. It is impossible to remove prior hardware or create a new tunnel.
   This is an uncommon situation and one should consider an over-the-top procedure if this is encountered. The graft can be taken over the top of the lateral femoral condyle and fixed through a lateral incision. Alternatively, the divergent tunnel concept can be useful in this situation if it is possible to bypass the hardware and recreate the anatomical ACL femoral footprint.
5. Revision after failed double-bundle reconstruction.
   (a) Both tunnels are in the wrong position and cannot be reused.
   If both the tunnels are completely incorrect and cannot be reused, then a two-stage procedure is considered because of the high risk of fracture. In the first stage, bone grafting is done by impaction of a cylindrical iliac crest autograft or allograft. If CT scan at 3–6 months shows a good bony fill, the second stage of the procedure of revision ACLR can be performed.
   (b) One of the tunnels (Anteromedial or Posterolateral) can be reutilized.
   Leaving the reusable tunnel, the other new tunnel is created after removing the

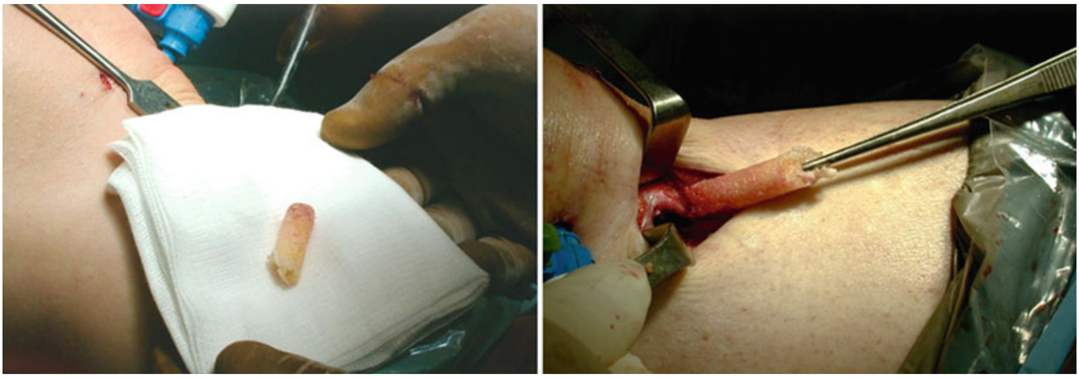

Fig. 9.2 Bone graft as cylinder

hardware (if necessary) and a single-bundle ACLR is performed, as indicated.

(c) The two tunnels are too close or there is a breakage of the wall between them.
In such a situation we would consider a single-bundle revision, a two-stage procedure, and/or a suspensory fixation, as indicated.

Finally, preoperative patient education is extremely important prior to a revision procedure and the expectations of the patient should be modified. Revision ACL surgery represents a salvage procedure and the patient should be counseled that the outcome is not likely to be as good as a primary procedure. The goal of surgery is to provide a stable pain-free knee. Return to sport is another goal, but is less predictable. In many cases, the status of the articular cartilage and meniscus are major factors in determining return to sport.

Over-the-Top Technique

Femoral tunnel creation is a key to revision surgery. In some cases, due to compromised bone, it can be very difficult to create a new femoral socket. In addition, the effectiveness of femoral bone grafting has not been well elucidated in the literature [5]. In cases with severe tunnel widening on the femoral side, it may be impossible to create a new tunnel in a single-stage procedure. In such situations, we recommend considering the over-the-top of the lateral condyle procedure for femoral fixation [6].

Case Example of Over-the-Top Femoral Fixation in Massive Bone Loss

The patient was a 42-year-old competitive Judo player who presented with reinjury after single-bundle ACL reconstruction with semitendinosus autograft at 11 years previously. Computed tomography revealed massive bone resorption around the original femoral insertion site (Fig. 9.3a, dotted line). Revision surgery was planned using a BTB graft. Arthroscopic inspection after debridement of soft tissue revealed that the bony surface area behind the enlarged femoral tunnel aperture was insufficient for creating a new tunnel without overlapping (Fig. 9.3b, c). We therefore switched to go over-the-top of the lateral condyle via the posterior capsule for fixing the graft to the femur (Fig. 9.3d, e). On the tibia, we created a new tibial tunnel from the tibial cortex more medial than the previous one to the same aperture, as it was properly located in the center of the anatomical attachment site. Thus the wall of the new tunnel was mostly composed of fresh cancellous bone, as shown by intra-tunnel arthroscopic observation (Fig. 9.3f). The patient was able to be back to strenuous activity by 8 months post-surgery without any complaints of knee instability.

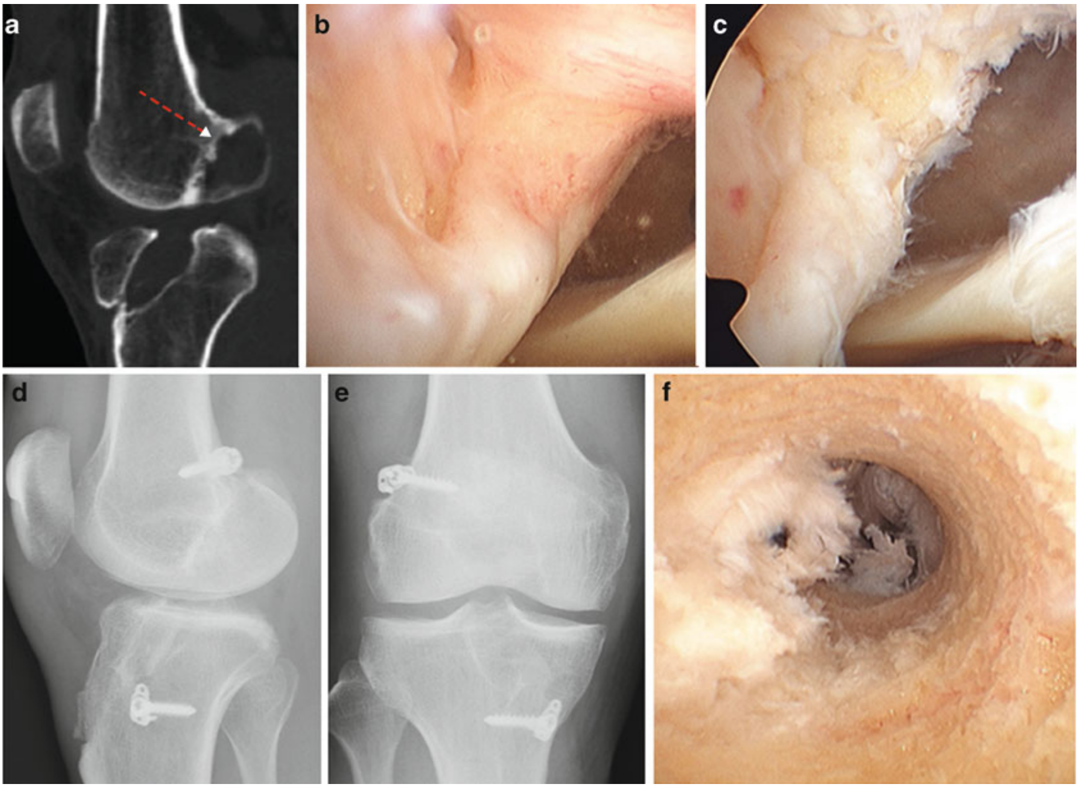

Fig. 9.3 An illustrative case with bone absorption. (**a**) CT of the right knee before revision. Note the severe bone absorption around the anatomic femoral attachment (*dotted line*); (**b**, **c**) postoperative lateral (**b**) and AP (**c**) radiograph showing femoral graft fixation over top of the lateral condyle; (**d**) arthroscopic view of femoral tunnel aperture from anterior medial portal; (**e**) after debridement, posterior wall consists of fatty tissue without bony structure; (**f**) intra-tunnel view of the newly created tibial tunnel. Note most of the wall surface is composed of cancellous bone

Anatomic Rectangular Tunnel (ART) Technique

We developed the anatomic rectangular tunnel ACL reconstruction (ART ACLR) with a BTB graft to mimic natural fiber arrangement inside the native ACL and to minimize tunnel size aiming at reducing the space between the graft and tunnel walls [7–9]. The ACL femoral attachment area is of crescent shape, less than 10 mm in width, and located at the superior–posterior margin of the lateral wall of the notch, as shown in published studies [10–14]. The technique makes it possible to create the tunnel aperture inside the attachment area. A tunnel aperture within the thicker cortical area of the femoral attachment area may be more robust, and may potentially reduce the tunnel widening [15].

When planning to use a 10-mm wide BTB graft for revision, the procedure is advantageous not only to avoid overlapping tunnels in case of improperly placed tunnels from the previous surgery but also to leave more space between the old and new tunnels. The cross-sectional area of the tunnels of 50 mm^2 (5×10 mm) in ART ACLR is less than that in a conventional 10-mm round tunnel technique of 79 mm^2. Since tunnel encroachment would hypothetically be less of a problem, we presume the ART ACLR technique could be more easily applied as a one-stage revision procedure after failed primary ACLR.

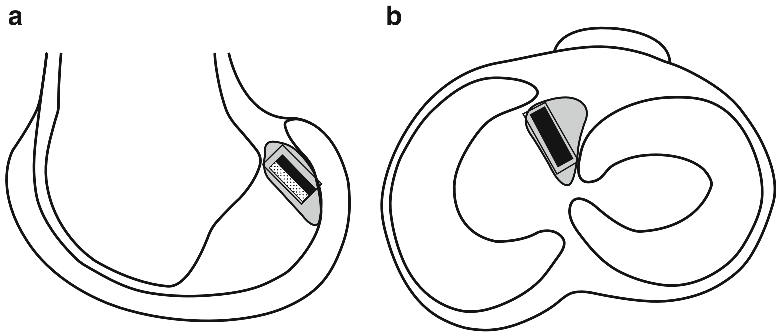

Fig. 9.4 Intra-articular tunnel apertures of the femur (**a**) and the tibia (**b**) in anatomical rectangular tunnel ACL reconstruction (ART ACLR). (**a**) Note the tendinous side of the bone plug (*black-painted area*) located posteriorly superiorly in the femoral tunnel; (**b**) the tibial tunnel is almost filled with the tendon (*black-painted area*)

Surgical Principles for Anatomic Rectangular Tunnel Technique

The principles are to (1) create parallelepiped tunnels with rectangular apertures inside the anatomic attachment areas (Fig. 9.4), (2) avoid overlapping tunnels or staged operations (Fig. 9.5), and (3) accept the preexisting tunnel apertures if they were in the anatomic attachment areas.

The patient is positioned supine with the thigh in a leg holder. The anteromedial portal is used for viewing and the far anteromedial portal for instruments [16]. The femoral tunnel is created using an all-inside technique through the far anteromedial portal with the knee flexed beyond 140°. If the knee cannot be flexed beyond 140°, this step can also be accomplished in outside-in fashion via a small lateral thigh incision. The tibial tunnel is created through the anteromedial cortex to the anatomic intra-articular insertion. Two continuous 5-mm tunnels along the long axis of the attachments are created and then dilated with a 5 × 10 mm dilator into parallelepiped tunnels [8].

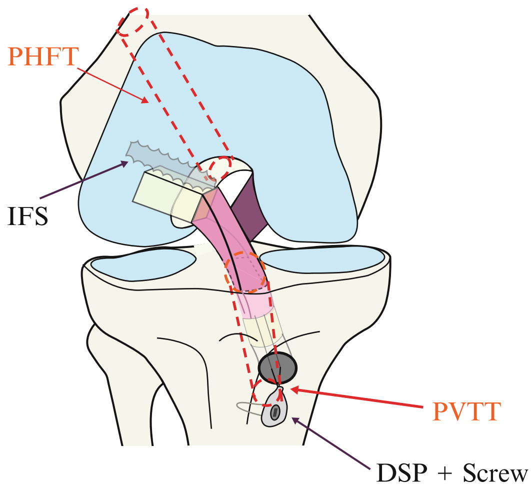

Fig. 9.5 Schema of revision rectangular tunnel ACL reconstruction with (BTB) graft. The bone plug is fixed to the femur with a 6-mm IFS, whereas tibial fixation is achieved with a modified pullout suture technique using the DSP (Double Spike Plate) and a screw. With this procedure, the new anatomical femoral tunnel can be properly placed in most cases without overlapping tunnels despite the previous high and anterior femoral tunnel (PHFT) leading to a vertical graft. In most cases, a new tibial tunnel is created with the same aperture as the previous vertical tibial tunnel (PVTT), whereas the direction is changed

Technical Considerations for Anatomic Rectangular Tunnel Technique

1. For graft choice
   With this procedure, autogenous or allogeneic tendon grafts with or without bone plugs may be used. As some of us are located in Japan, where allogeneic tissues are not readily available, our primary graft choice for revision is a BTB graft from the contralateral knee or from the ipsilateral knee if it was not used for the primary ACLR. However, the BTB graft may

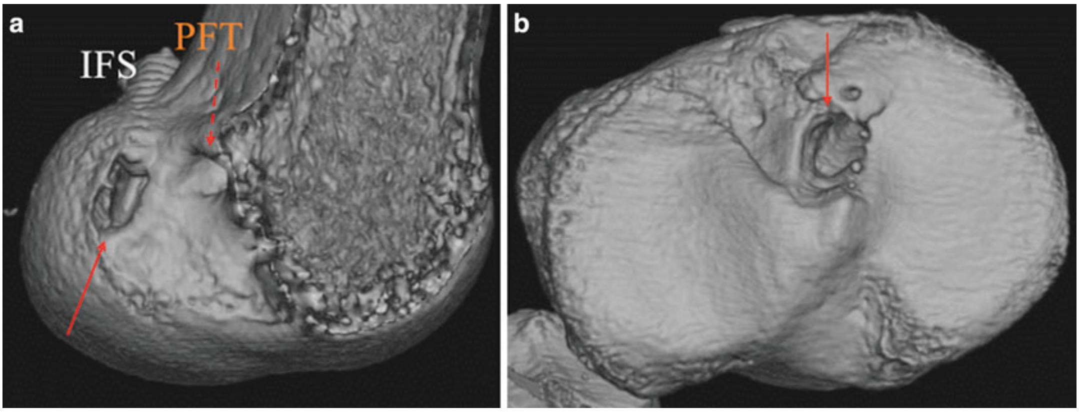

Fig. 9.6 3D CT pictures of Case 1 after the revision ACLR showing tunnel apertures: (**a**) femur; (**b**) tibia. Note the previous femoral tunnel aperture (PFT) located high and anterior (**a**). Also note the reused tibial tunnel aperture situated properly

not be appropriate for every patient. For example, some judo wrestlers would not accept graft harvest from the contralateral knee. For these patients, the ART technique could be used with semitendinosus tendon (SMT) if the double- or triple-bundle procedure could not be applied because of preexisting tunnel(s) [17]. In contrast, rugby or American football players may be candidates for a BTB graft harvest from the contralateral limb.

2. With previous properly placed tunnels
   After ART ACLR with a BTB graft reconstruction, the revision can be performed as the primary ART ACLR using any type of graft: two double-looped SMT grafts, quadriceps tendon-bone (QTB), or the contralateral BTB graft (Fig. 9.6, Case 1).
   For failure cases following double-bundle ACLR, a new rectangular tunnel can be easily created by dilating previous two tunnels along the long axis of the ACL attachment areas. However, for those with widened femoral tunnel that is frequently seen after use of soft tissue grafts including SMT, the extra space might be filled with an IFS of greater than 6 mm.
3. With improperly placed previous tunnels
   If the distance between the aperture rim of the previous femoral tunnel and that of the new tunnel is 5 mm or greater, the new femoral tunnel is created as in the primary ACLR. If the distance is less than 5 mm, however, the divergent tunnel can be used either by changing the approach to inside-out through the far anteromedial portal or outside-in through a lateral femoral incision.
   On the tibial side, a tunnel placed too anteriorly is easily revisable by creating a new tunnel behind the previous one. With the tunnel placed properly in the attachment or malpositioned by 1 cm or less posteriorly, a divergent tunnel technique should be applied to obtain a new posterior tunnel wall of fresh cancellous bone using or to avoid merging the two tunnels. This should help the graft to heal to the tunnel wall and resist anterior tibial force. When the posterior malpositioning exceeds 1 cm, however, the previous tunnel may be filled with a bone graft or its substitute.
4. For graft fixation
   Femoral fixation is achieved with a 6-mm IFS (Fig. 9.5), although additional cortical suspensory fixation may be considered if the fixation is questionable due to the previous tunnel or poor bone quality. Tibial fixation is achieved with a modified pullout suture technique using DSP (Double Spike Plate; Smith-Nephew Endoscopy, Andover, MA) and a screw. This technique makes it possible to fix the graft

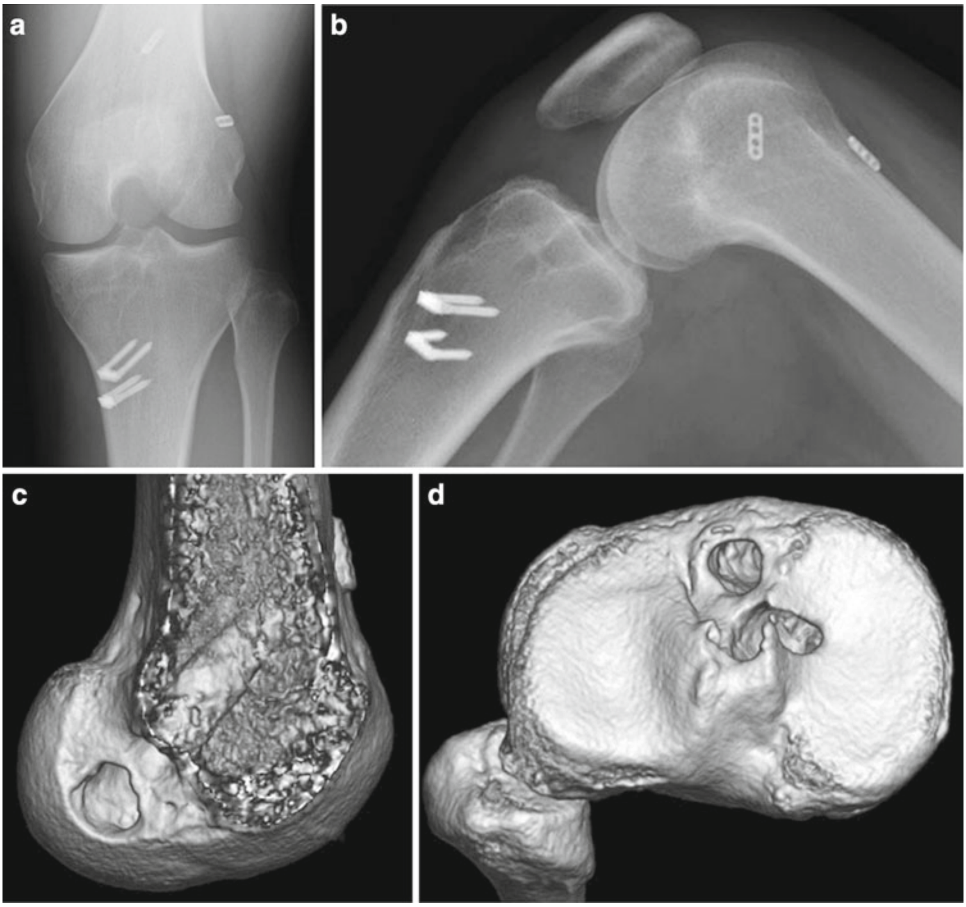

Fig. 9.7 Plain radiographs of Case 2 showing improperly placed non-anatomical two tunnels in the femur and the tibia: (**a**) P-A and (**b**) lateral. 3D CT pictures of Case 2 showing improperly placed non-anatomical two tunnels in the femur (**c**) and the tibia (**d**)

under a predetermined amount of tension [18]. We prefer to apply the initial tension of 10–20 N to the graft after meticulous in situ pretensioning with a tensioning boot.

Postoperative Rehabilitation

The knee is immobilized in 10° flexion for 1 week with a brace for BTB grafts. After that, passive and active ROM exercises are followed. Partial weight-bearing is allowed 2–3 weeks postoperatively followed by full weight-bearing at 4–5 weeks. Full extension or flexion exceeding 130° is not permitted until 5 weeks. Jogging is recommended at 3–4 months. Return to strenuous activity is not allowed until 6 months.

Illustrative Cases

Case 1 with a previous surgery of single-bundle ACLR with hamstring tendon graft via high/improper femoral tunnels and a central/proper tibial tunnel (Fig. 9.6).

A 17-year-old girl who had undergone a single-bundle ACLR was suffering from persistent instability of her left knee. She underwent the revision with ART ACLR using the BTB graft, and the instability was resolved.

Case 2 with a previous double-bundle ACLR with hamstring tendon graft via improper femoral and tibial tunnels created by trans-tibial tunnel technique (Figs. 9.7–9.9).

A 21-year-old female collegiate athlete who had undergone a double-bundle ACLR using hamstring tendons was suffering from loss of

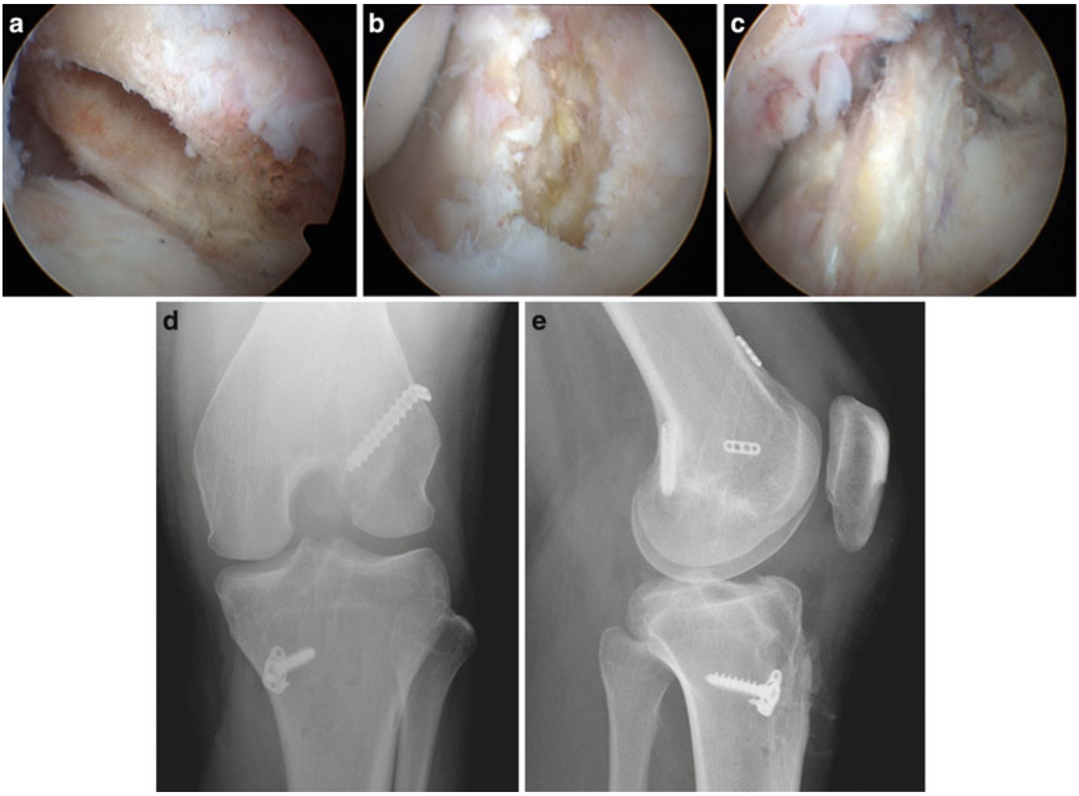

Fig. 9.8 Intra-articular tunnel apertures of the femur (**a**), the tibia (**b**) and a BTB graft in proper place (**c**) in the revision rectangular tunnel ACL reconstruction for Case 2. Radiographs of Case 2 after revision rectangular tunnel ACLR (**d**, **e**). The femoral fixation was achieved with a 6-mm interference screw (IFS) installed in outside-in fashion. The tibial fixation was accomplished with a modified pullout suture technique using DSP (Double Spike Plate; Smith-Nephew Endoscopy, Andover, MA) and a screw. The two endo-buttons which had been used at the time of the previous surgery are left in situ

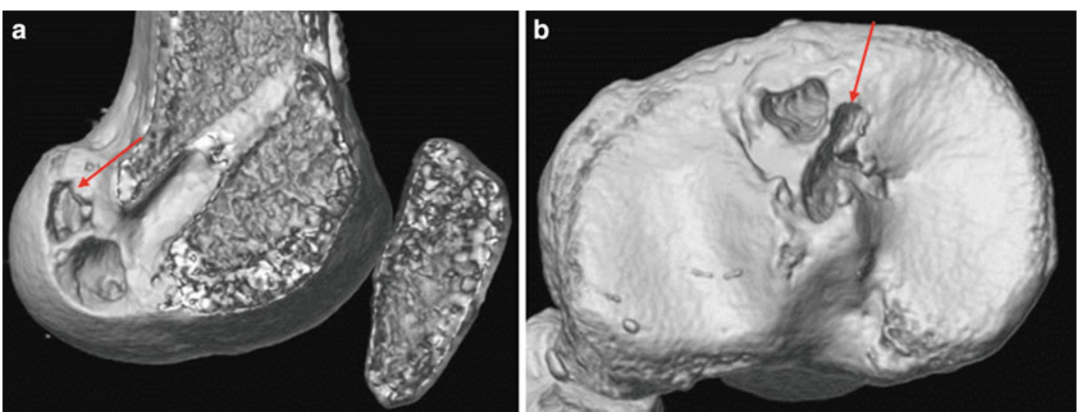

Fig. 9.9 3D CT pictures of Case 2 after the revision ART ACLR showing the new two tunnels in the femur (**a**) and the tibia (**b**) (*arrows*)

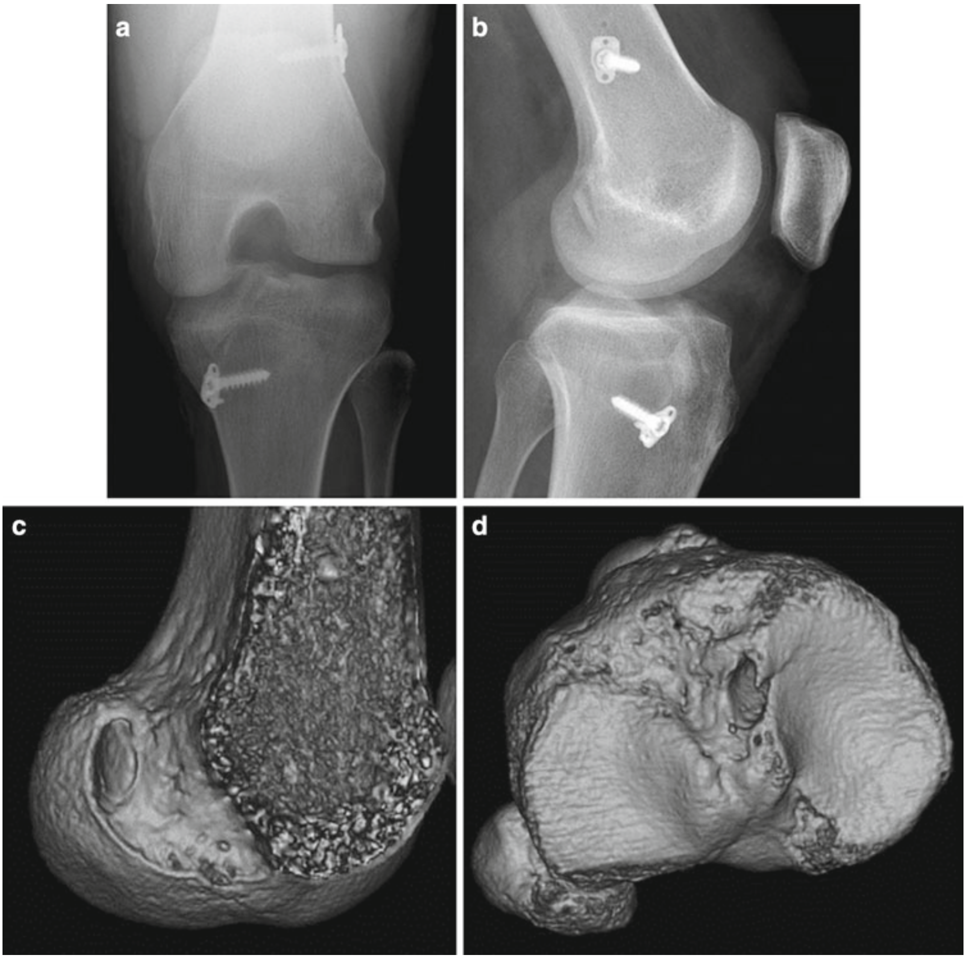

Fig. 9.10 Radiographs of Case 3 after revision rectangular tunnel ACLR (**a**, **b**). The femoral fixation was achieved with a pullout suture technique using DSP (Double Spike Plate) and a screw instead of a 6-mm IFS. The tibial fixation was accomplished with the same procedure as the primary one. 3D CT pictures of Case 3 after the revision ART ACLR showing the two tunnels in the femur (**c**) and the tibia (**d**). Note the new tunnels are exactly the same as the previous ones located in the anatomical attachment areas

motion in her left knee. The restricted range of motion from 40 to 90° did not allow her to walk. First, she underwent arthroscopic release of the arthrofibrosis as well as excision of malpositioned grafts in the notch. Three months later, the revision ART ACLR using the BTB graft was performed. She returned to cheerleading at 7 months postoperatively.

Case 3 with a previous ART ACLR with BTB graft via proper femoral and tibial tunnels (Fig. 9.10).

A 20-year-old male collegiate athlete who had undergone left ART ACLR by one of us with a BTB graft 8 months prior, tore the graft while performing a cutting maneuver. The revision ART ACLR using the contralateral BTB graft was performed.

Results of Anatomical Rectangular Technique

The ART ACLR technique made it possible to create a femoral tunnel in the anatomic attachment area in 30 of the 31 patients who underwent revision in one of our practices between 2004 and 2008. The tibial tunnel was successfully created within the tibial attachment area in 29 of the 30 patients, whereas the remaining one required bone grafting to fill out the previous tunnel because of its posterior location. None of the patients underwent staged surgeries [19].

Of the 18 patients followed for a minimum of 24 months, none reported giving way, subjective instability or loss of motion. One had retorn the graft at 28 months. Quantitative anterior laxity measurement with KT-1000 showed the mean side-to-side difference at maximum manual force improved to 1.1 ± 1.4 mm with a range from −1 to 4 mm. One had sustained a tear of the revision graft, and underwent a second revision ACLR with the QTB graft [19]. These results support our use of the rectangular tunnel technique for managing the femoral side in revision ACL reconstruction.

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10 How to Handle a Poorly Placed Tibial Tunnel

Jón Karlsson and Kristian Samuelsson

Introduction

The new paradigm of anatomic reconstructive techniques has led to new technical challenges. An ACL revision may be a simple and relatively straightforward procedure in cases where the original tunnels are in a markedly incorrect location, i.e., far away from the native footprints. In such cases, the previous bone tunnels and fixation material can often be left in situ. When the bone tunnels are correctly placed the procedure is easier if the original tunnels can be utilized. However, bone tunnel widening may play an important role in such cases. Difficulties arise when the bone tunnels are neither good nor bad, i.e., the location is close to correct. Then a two-stage procedure may become necessary, in most cases with bone grafting of the old tunnels. This requires approximately 4–6 months to ensure incorporation of the new bone in the tunnel for secure fixation. Preoperative planning is important and every experienced knee surgeon dealing with revisions must always be prepared for the so-called plan B. Today, most ACL revisions are performed as a one-stage procedure. This chapter will focus on issues relating to the tibial tunnel in revision ACL surgery.

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ACL Failure and the Tibial Tunnel

The tibial ACL footprint is fan-shaped and consists of the functional bundles of the native ACL named after their placement on the tibia, the anteromedial (AM) and the posterolateral (PL) bundles. The tibial footprint of the ACL varies in shape from oval to triangular [1]. The tibial footprint is the largest part of the ACL and it is 350 % larger than the midsubstance ACL and 120 % larger than the femoral footprint [1]. The AM bundle can be confluent with the anterior horn of the lateral meniscus and is centered 13–17 mm from the anterior tibial edge [2]. The PL bundle can be confluent with the posterior root of the lateral meniscus and is centered 20–25 mm from the anterior tibial edge and 7–8 mm anterior to the PCL [2]. This anatomy is not only complex but it also varies between individuals and therefore there is room for incorrect placement.

Since the native ACL does not impinge, neither will an anatomically placed graft. Therefore, many of the impingements and damages that occur to other structures in the knee joint are a direct consequence of non-anatomic placement of the graft. Historically, the most common placement was high in the intercondylar notch on the femur and posterior in the tibial footprint which created the so-called vertical graft. The placement on the femur was a consequence of the placement on the tibia, as the graft would otherwise impinge against the notch during full extension of the knee. But the posteriorly placed ACL could impinge against the PCL.

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Preoperative Planning

After reviewing the history, physical exam, and all imaging studies, one or more of the following scenarios must be considered: the already existing bone tunnels are in anatomic position, the bone tunnels are in a non-anatomic position and/or there is significant bone loss because of tunnel widening (Table 10.1). In general, the success of the revision relies heavily on the planning. As little as possible should be improvised.

Anatomically Placed Bone Tunnels

Anatomically placed bone tunnels are usually easily revised, as in most cases they are simply reused after hardware removal. However, tunnel widening may be a problem and should be addressed by utilizing bone plugs, careful choice of graft material, stacking of screws (Fig. 10.1), or prior bone grafting.

Non-anatomically Placed Bone Tunnels

Malpositioned Bone Tunnels That Do Not Interfere

Non-anatomic bone tunnels that do not interfere with the new revision bone tunnels can be left alone, and the primary fixation devices are removed only when necessary. Major malposition of the tibial tunnel is most often too posterior with a femoral tunnel high in the notch, the so-called vertical graft. In case of too anterior loca-

Table 10.1 Preoperative algorithm

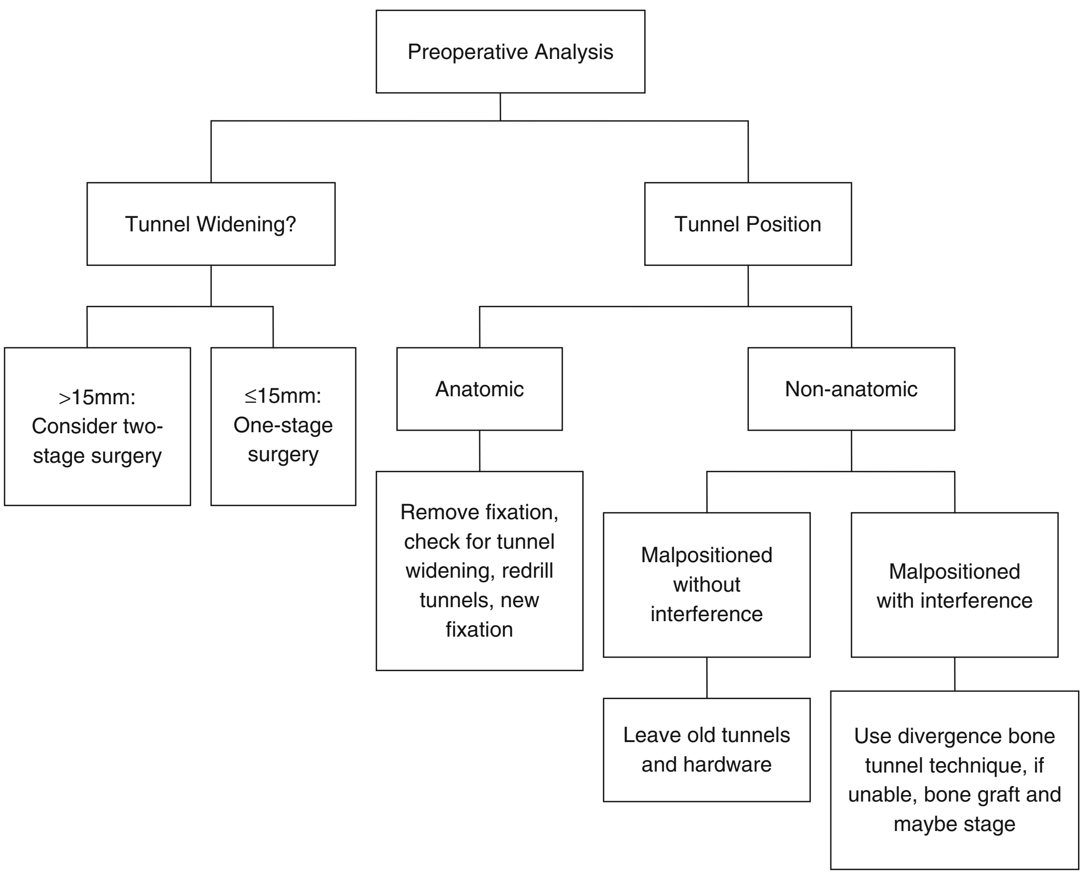

Fig. 10.1 Radiograph of stacked screws in the tibia bone tunnel in mildly expanded bone tunnel. Reprinted from ref. [3] with permission from Elsevier

tion of the tibia bone tunnel, there is risk of notch impingement and loss of full extension. In both cases, it is fairly easy to perform a revision ACL reconstruction as the material and bone tunnels are usually severely malpositioned and do not interfere with the new anatomically placed bone tunnels (Figs. 10.2, 10.3, and 10.4). This "divergent tunnel" concept allows the surgeon to address severely malpositioned bone tunnels and avoid preexisting hardware that is often difficult—and unnecessary—to remove.

Malpositioned Bone Tunnels That Interfere

Difficulties arise when the non-anatomic bone tunnels overlap with the new revision tunnels. This often presents a major challenge as it can cause potential complications such as inferior fixation strength and fracture. Several methods can be used to cope with this difficulty.

Divergence of the new and old bone tunnels is essential. However, the intra-articular entry point should always attempt to exit at the native footprint of the ACL. This can result in convergence and a "figure-eight" defect (Fig. 10.5) [3].

Fig. 10.2 Too anteriorly placed previous bone tunnel that does not interfere with the new anatomically placed tibial bone tunnel

Fig. 10.3 Malpositioned too anterior tibial bone tunnel and "high" femoral bone tunnel

In these cases, the small bone bridge between the bone tunnels is often inadequate for secure fixation and there is little good-quality bone to allow

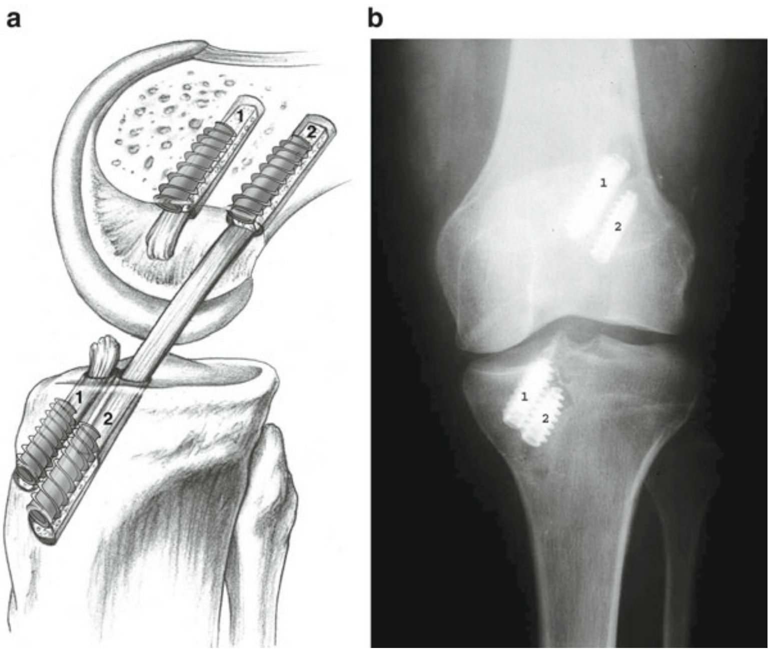

Fig. 10.4 Severely malpositioned bone tunnels and hardware that do not interfere with the new bone tunnels and fixation. (1) Index hardware; (2) revision hardware. Figure (**a**) reprinted from ref. [3] with permission from Elsevier; Figure (**b**) reprinted form ref. [4] with permission from AAOS

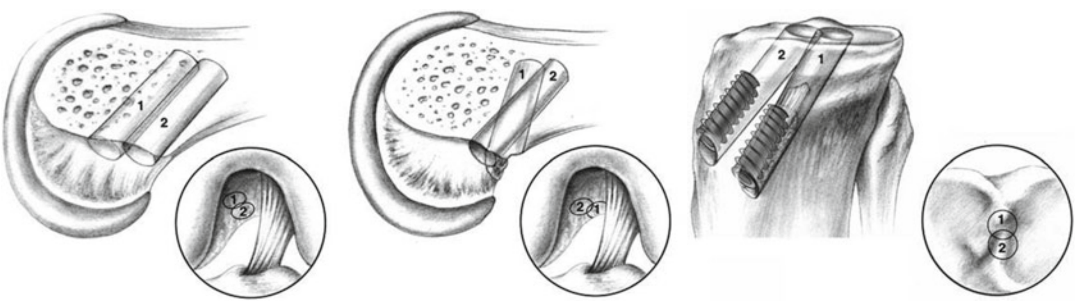

Fig. 10.5 The so-called figure-eight after anatomic ACL revision reconstruction with a prior malpositioned tunnel. Reprinted from ref. [4] with permission from AAOS

graft-bone healing. There are several available methods to address this dilemma:

- Bone grafting with large autologous bone plugs and/or bone chips from the iliac crest.
- Utilization of bioactive implant material such as moldable calcium phosphate cement [5].
- Utilization of an ACL tendon graft with a large bone plug such as an autograft quadriceps tendon or allograft Achilles tendon.
- Utilization of extra-cortical fixation instead of aperture fixation in order to avoid stress on the small bone bridge between the bone tunnels.
- Divergent extra-articular tunnel orientation as the tibial footprint can be approached from multiple angles by using different starting points, even from the lateral side of the tibia (Fig. 10.6) [6].

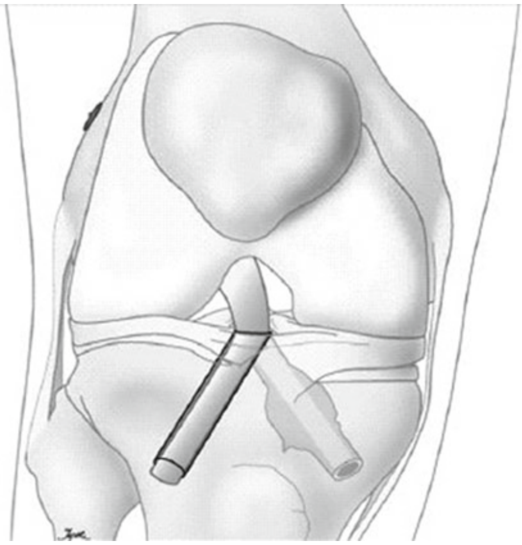

Fig. 10.6 Lateral tibial tunnel can be utilized in severe cases where there are difficulties creating a divergent bone tunnel due to tunnel widening and near anatomical position. Reprinted from ref. [6] with permission from WB/Saunders Co.

Tunnel Widening

Surgical options for a one-stage revision are more limited when the tibial bone tunnel exceeds 15 mm or is very close to the planned new tunnel (Fig. 10.7). The main reason is that the tunnel widening will compromise secure fixation. Bone grafting can be performed in a two-stage procedure if necessary.

Operative Technique

Surgical Set Up

The preoperative plan, including the type of reconstruction, graft type, hardware removal, and the need for bone graft should be planned before the surgery is started. Preoperative planning is of the utmost importance. In case hardware needs to be removed, multiple screw drivers must be available. A set of special instruments must be available as well, if either metal or biodegradable fixation devices need to be removed. The patient is set up as in a primary ACL reconstruction; however, the preparation/draping of the iliac crest should be performed if necessary. The procedure is started by arthroscopic evaluation of the knee joint, and the first step is to expose the tibia footprint remnant [3].

Bone Grafting

The original bone tunnels must be carefully evaluated for expansion, as one of the most difficult problems is a widely expanded tibial tunnel. An expanded tunnel will not only limit graft options, but will also make the fixation less secure. In cases of marked tunnel expansion, bone grafting of the original tibia tunnel may be necessary. The fixation in the tibia may never be less than optimal. Expanded tunnels can also make it impossible to locate the new graft correctly and allow for sufficient native bone for graft-bone interface and healing. As previously mentioned, if the tibial bone tunnel is wider than approximately 15 mm, a two-stage reconstruction should be performed.

One should start with removal of all soft-tissue remnants from the new bone tunnel in order to secure the fixation and the incorporation of the new graft. The tibial tunnel should be visualized in its entire length using the arthroscope to ensure that all soft-tissue has been removed and there is no tunnel overlap.

If the decision is to bone graft due to overlapping tibial tunnels, tunnel widening, or compromised bone quality, bone grafting can be performed by choosing bone chips harvested from the iliac crest or as a larger solitary bone block. Of course, one could also choose allograft bone grafts to minimize harvest site morbidity, or use a mixture of autogenous cancellous graft obtained from the iliac crest and allograft cancellous bone. Also, allograft bone chips or struts, the result of the preparation of the BTB graft, can be used. In case of an extensive tunnel widening, iliac crest harvest either using dowel or cancellous graft is preferred together with a two-stage reconstruction.

There are also alternative graft sources that reported good results, such as OATS (osteo-

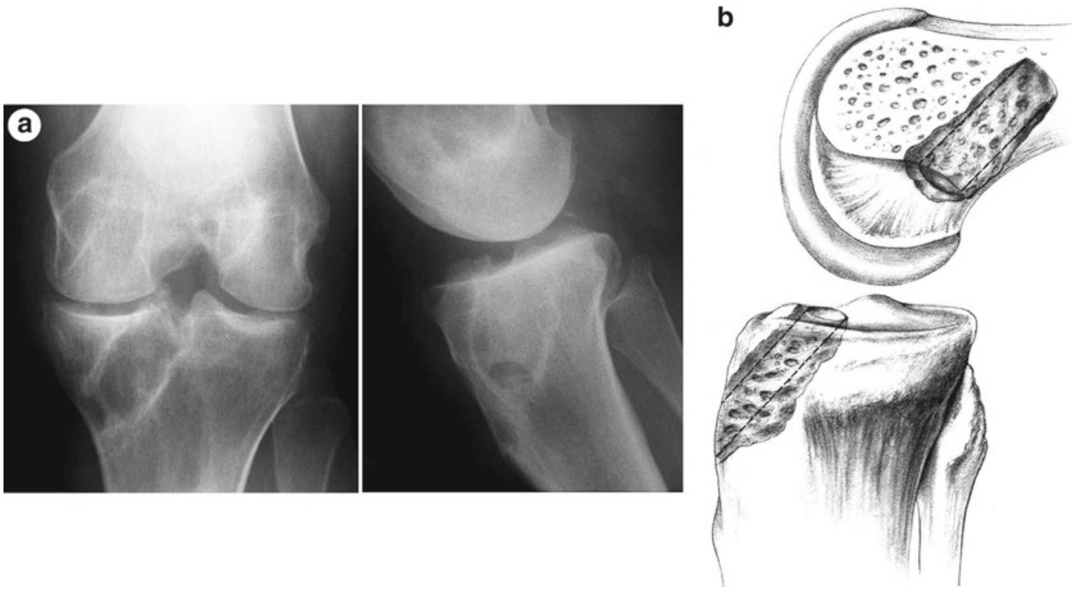

Fig. 10.7 Radiograph (**a**) and illustration (**b**) depicting a large tibial defect and tunnel widening. Figure (**a**) reprinted from ref. [3] with permission from Elsevier; Figure (**b**) reprinted from ref. [4] with permission from AAOS

chondral autograft transfer system) [7]. The OATS can be harvested either from the iliac crest or the medial tibial metaphysis. The OATS plug should ideally be of 1 mm greater diameter than the tunnel to secure press-fit fixation within the tunnel. Allograft dowels that allow large sizes (over 10 mm) are available and are a valid alternative to smaller bone chips. Commercially available dowels, including calcium phosphate as bone void fillers, are a new and interesting option but still unproven in large series of patients [7].

Repeated radiographs, preferably CTs, are recommended during the healing phase in order to confirm adequate consolidation of the tunnels. This should be done in both two-stage and one-stage ACL revisions, the former to confirm timing of next surgery and the latter to guide in the postoperative rehabilitation. Bone grafting procedures usually require at least 4–6 months for complete incorporation. Currently, most ACL revisions are performed as a one-stage procedure, often using interference screw fixation in the tibial tunnel.

Creation of the New Tibial Tunnel

During preparation of the new tunnel, the drill guide is traditionally set at 50–55°. This can be easily adjusted depending primarily on the location of the old bone tunnel and the angle of the new tunnel. Graft length and where the new tunnel is drilled from ("lateral tunnel" concept) may also play a role here. The divergent tunnel concept should be utilized to redirect the new tibial tunnel away from the primary and avoid overlap. The tunnel may approach the previous tunnel inside the joint, as the tunnel progresses further away from the joint, creating an intact part of normal bone for adequate graft fixation, especially close to the tibia cortex. The variable-angle ACL guide should be directed to enter the tibia in a new location in order to secure adequate fixation, while it enters the joint in the appropriate position. Furthermore, the angle can be increased or decreased to create either a longer or shorter tibial tunnel or more medially divergent tunnel, if needed. Thus a new angle, between 45 and 60° may be useful in order to avoid drilling into the primary tunnel. The guide wire should enter at the center of the tibial ACL footprint which is approximately at the level of the posterior edge of the anterior horn of the lateral meniscus. This means that the new tunnel is approximately 7–8 mm anterior to the PCL. The extra-articular entry site is approximately 2–2.5 cm below the joint line and approximately 1–2.5 cm medial to the tibial tubercle. The exact location, however, depends on the location of the primary bone tunnel. An “extreme” medialization is sometimes used in order to avoid the primary tunnel. This may be dangerous, as a too medial tibia tunnel may undermine the medial tibial plateau cartilage and can even lead to major cartilage damage and possibly blow-out and cartilage fracture. After the guide wire has been advanced into the joint, the position should be confirmed. If the guide wire has deviated and encounters the primary tunnel, it should be replaced. It can be wise to leave the guide wire in situ if not ideally positioned and drill the new one close to it, often using a new angle. This avoids the second wire following the path of the first. It is very important that the guide wire does not break into the old tunnel, which will lead to deviation from the planned path. The guide wire can be drilled into the femur to secure it. Another problem is preexisting hardware that interferes with reaming of the tibial tunnel. If possible, it is wise to leave the hardware in place in order not to create large cavities in the proximal tibia.

If the two tunnels overlap, the old metallic screw may be replaced by a bioabsorbable screw that can be drilled through, at least partially, which means stacking the old and new interference screws. Planning for a conventional interference screw fixation at the tibial tunnel, the new tunnel is reamed and then inspected using the arthroscope inside the tunnel. In case of residual soft-tissue inside the new tunnel, it should be carefully removed using shaver and/or curette. The tunnel should be cleaned from all residual soft-tissues, in order to obtain optimal screw fixation of the revised graft.

One of the challenging situations is the “too-posteriorly” placed tunnel. If it is much too posterior, then a new anterior tunnel in an anatomic position can be used. However, when the original tibial tunnel has been placed somewhat too posterior, there is concern that the new and more anteriorly located tunnel will converge into a massive tunnel. In these cases, preoperative planning is crucial and bone grafting may be necessary. Double-tunnel technique is another option in this situation. In the double-tunnel technique the “too-posterior” tibia tunnel is used for the posterolateral (PL) tibial bundle and thereafter a new independent anteromedial (AM) tibial tunnel is created.

Bioabsorbable and biocomposite fixation devices are often difficult to remove as they may break and are commonly left in situ. Biocomposite screws may be very useful to partially fill too large or confluent tibial tunnels. Metal interference screws must be removed if they are in the way, but may be replaced by biocomposite screws and can then be drilled through. Replacement of a metal screw with a biocomposite screw followed by overreaming is often a very useful technique. Sometimes sequential reaming is needed, starting with a smaller reamer (for instance 5.0 mm) and then progressing to larger reamers.

Graft Fixation

After creation of the tibia tunnel, the next step to consider is the fixation. Adequate and secure fixation is critical to ensure a stable graft. Bone quality must be assessed and in some cases bone grafting is necessary. The surgeon must also be prepared to alter the plan during surgery, i.e., be knowledgeable in several different techniques and technical details. Sometimes allograft with a large bone block or BTB autograft from the opposite knee may be useful. In case of a minor mismatch, a biocomposite or stacked screw can be useful. In the case of a major graft-tunnel mismatch, an allograft with a large-sized bone block is preferable such as Achilles tendon allograft with a large piece of the calcaneus. In such cases, it is important to note the shape and possible osteoporosis of the bone block as some allografts originate from osteopenic donors. Another option is to use synthetic dowels or separate allograft bone plugs or biocomposite screws that can partially fill the old tunnel. All of these techniques may provide adequate supplemental fixation for interference screws.

Interference screw fixation can also be complemented by the use of a screw and a post for a supplemental fixation. Secure intra-tunnel fixation using a new interference screw is preferred, taking into consideration the bone quality and possible need for bone supplementation. The exact type of interference screw is based on the surgeon's preference and experience [8]. The threshold to add a supplementary screw outside the tunnel and a post should be low in all revision cases and we use back-up fixation frequently, depending on the case [7].

When tibial fixation is performed, the rotation of the bone plug is not crucial, some surgeons prefer to have the cancellous side of the bone plug fraction posterior and the cortical side anterior. The interference screw is usually placed anterior to the bone plug and the cortical bone anteriorly which may provide better fixation. If there is concern regarding the initial strength of the interference screw fixation, the size of the screw may be increased or a screw and post added outside the tunnel, as mentioned above.

Conclusion

Revision ACL reconstruction is always a surgical challenge. Depending on the location of the original tunnels, the procedure can vary from easy and straightforward utilizing the old—correctly placed—tunnels or difficult due to loss of bone, tunnel widening, and less than adequate fixation. There are many ways to deal with the tibial tunnel during ACL revision, and the key to successful revision surgery is thorough preoperative planning by a surgeon who is well prepared with several intra-operative options.

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Fixation in Revision ACL Reconstruction

11

Nathan A. Mall, Wendell M.R. Heard, Nikhil N. Verma, and Bernard R. Bach Jr.

Introduction

Anterior cruciate ligament (ACL) injuries are common, and their number may be increasing as more young athletes play sports year round. Many ACL tears are reconstructed by surgeons who perform less than ten of these procedures per year [1]. Technical errors are often cited as the most common cause of ACL reconstruction failure [2, 3]. Other authors have found that it is a combination of factors that most commonly leads to failure, with traumatic injuries being the most common single reason for disruption of a reconstructed graft [4]. The goal of ACL reconstruction is to return individuals to recreational or competitive sports. However, continued participation in sports does risk re-injury and possible need for revision surgery.

Revision reconstructions often require creativity to create anatomic tunnels and fixate a graft given the limitations of retained hardware or tunnel malposition from the index procedure. There are several technical pearls that are outlined in this chapter that can help the surgeon in revision situations and aid in understanding the indications for single stage revision reconstruction vs. staged bone grafting followed by revision ACL-R. In performing revision surgery, relevant considerations include identification of the cause of failure, evaluation of the index procedure tunnel position and retained hardware, and strategies for graft selection, staging of the reconstruction, and the focus of this chapter, graft fixation.

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Basic Considerations

Clinical history is a key determinant in etiology of failure of the index procedure. The patient may describe a specific injury mechanism suggesting traumatic graft re-rupture, vs. atraumatic episodes of increasing instability suggesting graft malposition or biologic failure. During the physical examination, the range of motion is an important factor to assess prior graft placement as malposition may result in loss of terminal extension or full flexion. Radiographs, including an AP standing radiograph of the knee, full extension lateral to assess for impingement and tibial slope, standing long leg cassette to assess alignment, and a patellofemoral view, should be used for the initial assessment of the knee and to assess graft position and tunnel widening. Radiographic parameters of appropriate graft

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position have not been well defined, however. Advanced imaging may be required to assess the integrity of the graft and presence of concomitant pathology. CT scan with 3D reconstruction can more accurately define tunnel position and provide a more accurate measure of tunnel widening when present.

Advanced Imaging

Radiographs have been shown to adequately assess bone tunnel width and area [5] in comparison with advanced imaging [6]. Recently, studies have been relying on MR Imaging to assess tunnel size and shape [7–11]. A recent study by Marchant et al., however, demonstrated poor ability to identify tunnels using X-ray and MRI as well as poor inter and intra-observer reliability for both radiographs and MRI. MRIs can determine the position of bioabsorbable implants that cannot be seen on plain radiographs, however. While most patients will typically undergo MRI to evaluate for articular cartilage damage or meniscus tears, this is not always necessary. Interestingly, CT scans only demonstrated moderate reliability [12]. The senior authors' opinion is that plain X-rays are generally adequate for assessing the location and the general size of the prior tunnels, and MRI can be used to determine graft integrity and presence of concomitant pathology. However, if the tunnels appear expanded, a CT scan can provide valuable information quantitating the amount of expansion, facilitating a pre-operative decision regarding primary vs. staged reconstruction.

Need for Bone Graft

The indications for bone grafting are not absolute and vary based on the surgeon's preference and comfort with other fixation techniques discussed in this chapter. In general, indications for bone grafting include tunnel widening, or tunnel malposition preventing anatomic tunnel placement during revision reconstruction. There are multiple theories regarding the cause of tunnel widening, including the use of allografts, soft tissue grafts, bioabsorbable fixation, and the placement of the fixation. Other potential factors include inflammatory cytokines, synovial fluid circulation, and graft motion or delayed healing. Some authors state that bone grafting should be used if the diameter of the tunnels is greater than 100 % of the original tunnel or more than 16–20 mm in any one dimension as seen on radiographs or advanced imaging [13]. However, this is not absolute. If the tunnels are vertical and will not interfere with anatomical placement of the graft at the time of revision, then new tunnels can be drilled and standard fixation can be used. In some cases, however, partial overlap of tunnels may complicate revision anatomic tunnel placement or graft fixation. In these situations, bone grafting of the index tunnels can be performed at the time of revision surgery or a staged procedure can be undertaken based on surgeon preference, the quality of the bone, and the size of the tunnel expansion and its associated fracture risk. If a single stage revision is indicated, freeze dried allograft bone dowels can be used to fill the defect, facilitate new tunnel drilling, and improve graft fixation [14].

Graft Sources as It Relates to Fixation Needs

Graft choice in revision surgery is dependent on multiple factors including the type of graft used at index procedure, failure mechanism, patient age, patient activity level, and tunnel size. Graft options include ipsilateral or contralateral bone patellar bone autograft, ipsilateral regenerated bone patellar bone autograft, bone patellar tendon bone allograft, hamstring autograft (4, 5, or 6 strand grafts), hamstring allograft, quadriceps tendon autograft, Achilles allograft, and tibialis anterior allograft. Each of these grafts may require different graft fixation techniques as outlined below. The authors' preference is to use primary ipsilateral bone patellar tendon bone autograft if available. The senior authors do not use regenerated ipsilateral BTB autograft despite some available support in the current literature.

If BTB autograft has been used previously, our preference is to use BTB allograft or contralateral BTB autograft depending on the patient's age and athletic status. In our opinion, BTB allograft is well suited for revision situations as secure bone to bone fixation can be achieved in most cases and bone blocks can be enlarged to accommodate larger tunnel sizes without increasing morbidity.

Hardware Removal

The need for hardware removal is based on the reconstruction technique used by the treating surgeon and the position of the previous tunnels. In most cases, an attempt is made to perform the revision surgery without removal of previous hardware if possible. Leaving hardware from the prior procedure in place avoids the creation of bone defects that may compromise revision fixation. The revising surgeon should request the operative records from the original reconstruction to assure the appropriate tools are available for hardware removal, even if pre-operative planning suggests the hardware will not affect the new tunnels. Retrieving the operative report can also aid the surgeon in understanding through which portal the hardware was placed and can facilitate removal of screws and prevent stripping of the screw.

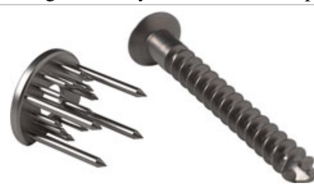
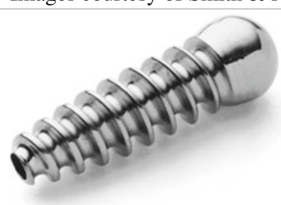
In the case of staple fixation, different manufacturers create staples of differing widths and therefore the appropriate extractor can improve the speed and ease of removal and decrease damage to the tibial cortex. If the appropriate extractor is not available, then the surgeon can attempt to stack osteotomes under the staple to gently force it out of the bone. However, levering can cause tibial bone loss that can compromise tunnel placement or fixation. Stacking osteotomes should be performed using the widest osteotome that will fit between the spikes of the staple. The next widest osteotome should then be slid on top of the first, and so forth.

During pre-operative planning the surgeon should assess whether or not hardware will need to be removed. Hardware can be left in place and can be used as a "blocking screw" if the old tunnel and new tunnel have similar starting points and the screw is not metal. The prior screw will essentially "block" the drill from proceeding towards the old tunnel and will do the same with the graft and subsequent interference screw if this is the fixation method used. However, the surgeon should be cautious of forcing the guidepin or reamer in close proximity to previous hardware as it may result in shearing of the guidewire or tunnel malposition. Previously placed bioabsorbable or biocomposite screws and bioabsorbable soft tissue fixation pins are often left in place and can be drilled through. Metal cross fix devices (Arthrex, Inc. Naples, FL) are difficult to remove and new tunnels should avoid this if possible. The company does not make an extraction tool. Also, bone mulch screws (Biomet, Warsaw, IN) typically result in a significant amount of bone loss with extraction and can lead to a stress riser that may prevent single-staged revisions.

Fixation

There are a multitude of fixation devices currently on the market, most of which have performed well enough in the laboratory setting to justify their use. Table 11.1 lists the most common fixation devices currently being used. Most authors agree that the normal ACL will undergo forces of up to 500 N during activities of daily living, and thus, the graft fixation construct should be able to withstand forces of greater than 500 N (Table 11.2). Surgeons must be aware of the theoretical disadvantages of each of the available devices as they can be accentuated in the revision setting. In addition, the surgeon should be prepared to use an alternate method of fixation if the preferred or planned method of fixation fails to achieve adequate strength. Patients undergoing revision ACL reconstruction can have decreased bone mineral density, wider tunnels, remaining graft within prior tunnels that overlap with new tunnels, prior hardware that has been removed which weakens the surrounding bone, or remaining hardware that should be avoided. Each of these must be considered when choosing the graft and the fixation device for that graft in the revision setting.

Table 11.1 Manufacturer and images of various fixation devices obtained from manufacturers' websites

Intrafix DePuy Mitek, Inc. Raynham, MA	 Image courtesy of DePuy Mitek, Inc.
Bone Mulch Screw Biomet/Arthrotek Warsaw, IN	 Image courtesy of Biomet Orthopedics, Inc.
WasherLoc BioMet/Arthrotek Warsaw, IN	 Image courtesy of Biomet Orthopedics, Inc.
Endobutton Smith & Nephew Andover, MA	 Images courtesy of Smith & Nephew, Inc.
RCI Screw Smith & Nephew Andover, MA	 Image courtesy of Smith & Nephew, Inc.
SoftSilk Smith & Nephew Andover, MA	 Image courtesy of Smith & Nephew, Inc.

(continued)

Table 11.1 (continued)

BioScrew ConMed Linvatec Largo, FL	 Image courtesy of ConMed Linvatec.
EndoPearl ConMed Linvatec Largo, FL	 Image courtesy of ConMed Linvatec.
Bio TransFix Arthrex Naples, FL	 Image courtesy of Arthrex
Metallic TransFix Arthrex Naples, FL	 Image courtesy of Arthrex

Soft Tissue Graft Fixation

Femoral Fixation

Soft tissue fixation techniques can be divided into two categories: suspensory or compression. Suspensory devices utilize the cortical surface, cancellous surface, or both. A 2006 study of these different types of devices found that cortical-cancellous suspensory fixation had the best biomechanical properties, followed by cortical suspensory fixation and compression devices, which had similar properties, and finally cancellous suspensory fixation with the weakest properties [23] (Table 11.2).

As opposed to suspensory fixation, aperture fixation has theoretical advantages on biologic graft incorporation and can be used in transtibial or anteromedial femoral tunnel preparation. Aperture fixation can be used in the two-incision technique if the outside-in technique is used solely for drilling the tunnel and passing the graft; however, most authors using this technique will fixate the graft on the lateral cortex of the femur. Aperture fixation at the femoral notch side is thought to prevent graft stretching, graft-tunnel motion, and later tunnel widening. Graft-tunnel motion is thought to create a "bungee cord" effect, which may allow an influx of synovial fluid into the tunnel and lead to tunnel widening [37, 38]. In the revision setting, where the tunnel may already be widened, this is of additional concern. Interference screws provide compression of the soft tissue, allowing for direct contact healing with little motion, theoretically improving healing time and preventing a fibrous layer that can be seen with other types of fixation [39]. A recent meta-analysis and systematic review of femoral fixation techniques of soft tissue grafts found a trend toward decreased risk of surgical failure in the interference screw group compared with non-aperture fixation. There was no difference in IKDC values, however [40].

Table 11.2 Available biomechanical data for femoral and tibial fixation devices

Fixation options	Ultimate strength (N)	Stiffness (N/mm)
Metal interference screw with bone patellar tendon [15–17]	416–640	
Knotted loop of Mersilene tape [18]	493	
Knotted loop of No. 5 Ethibond [18]	302	
Hamstring graft: femoral fixation		
Smith and Nephew Endobutton CL [19–22]	Single: 864–1,086	106
	Double: 1,324	
Arthrex Metallic TransFix [20, 21]	1,002–1,235	181
Arthrex Bio TransFix [19, 21, 23, 24]	746–1,392	176
Arthrotek/Biomet Bone Mulch Screw [22, 25]	1,112–1,126	115–225
DePuy/Mitek metallic cross-pin	35 mm pin: 1,003	
	70 mm pin: 1,604	
DePuy/Mitek RigidFix [19, 22]	638–868	77–226
EndoButton with Mersilene Tape [17, 25–27]	352–703	8–98
Arthrex Bioabsorbable screw [19, 28]	327–539	
Linvatec Bioscrew [20, 22, 29]	310–589	26–66
Linvatec Bioscrew with EndoPearl [29]	659	42
6 mm soft tissue washers ×2 [30]	821	29
Sutures tied over 6.5 mm screw post [30]	573	18
20 mm spiked washer with 6.5 mm screw [31]	248	
Hamstring graft: tibial fixation		
Mitek Bio-IntraFix [32]	1,275	
Mitek IntraFix [22, 33]	796–1,332	49–223
Arthrotek WasherLoc plate and screw [22, 34]	903–975	87–273
Tandem AO washers/screws [34]	1,159	259
Evolgate Device [35]	1,237	168
AO washer/screw and sutures around screw post [34]	768	181
Tandem bicortical screws with spiked washers [22]	769	69
Arthrex 35 mm bioabsorbable screw [33]	647	64.5
Suture over screw post [34, 36]	374–442	24–60
Double soft tissue staple [34]	785	118
20 mm spiked washer/screw [34]	724	126
Linvatec SmartScrew ACL [31]	665	115
Linvatec BioScrew [31]	612	91
Smith and Nephew SoftSilk [31]	471	61

In choosing an interference screw, graft type should be considered. While metal screws allow simple fixation of bone plugs, there is concern that metallic interference screws can lacerate the soft-tissue graft, leading to early failure. A previous study has demonstrated that a metal screw cut or partially cut 9 of 10 grafts with a femoral screw, but 0 of 10 with the tibial screw, indicating there may be some effect of the angle of screw insertion on this finding [41]. The RCI screw was designed to combat this by rounding the threads; however, several studies have found the RCI screw to be biomechanically inferior to bioabsorbable screws in terms of ultimate load, stiffness, and graft slippage [42]. Other studies have found no difference between metallic and bioabsorbable screws in the laboratory setting. Also, a recent meta-analysis of bioabsorbable and metallic screws used in both soft tissue and BTB grafts found no difference in infection, KT-1000/2000, pivot shift, or outcomes scores (IKDC and Lysholm) between screw types. This study comprised 790 knees, and there were no differences other than the bioabsorbable screws creating more joint effusions [43], indicating that if used properly, metal screws may not lacerate the graft [41, 44].

The fixation of soft tissue with an interference screw is dependent on several factors, but tunnel diameter and screw size may be most important. Studies have demonstrated that choosing a screw diameter the same as the tunnel width had improved pull-out strength and minimized graft slippage [45]. Other studies have found that longer screws are better for soft tissue fixation, with 35 mm screws having better biomechanical properties than 28 mm screws [46] and 28 mm screws having better biomechanical properties than 20 mm screws [47]. Decreased soft tissue slippage has been reported when a cortical suspensory device is used in combination with the interference screw. This may be the ideal construct in revision situations in which soft tissue grafts are used as there is increased strength and less slippage with the cortical fixation, yet there is aperture fixation to increase stiffness and eliminate the "bungee effect" that can precipitate further tunnel widening. Also, a larger diameter screw can be used to fill an enlarged tunnel, depending on the technique of femoral drilling. The longest screw length should be selected, although 28 or 35 mm screws may not be possible.

Cross-pin fixation is designed to be used with looped ACL soft tissue grafts, typically hamstring autograft or allograft. This fixation method has not been studied in a revision setting with expanded tunnels; however, cadaver studies with somewhat limited bone quality demonstrated similar fixation strength to bone patellar bone with interference screw fixation [48]. A clinical study comparing a cross-pin device to metal interference screw fixation during primary reconstruction with hamstring tendons found no difference in CA-4000 instrumented laxity measurements or in IKDC, Tegner, and Lysholm outcomes scores. The groups had similar tunnel expansion at 2-year follow-up, which indicates the tunnel expansion may be more related to graft type rather than location of fixation [49]. Another clinical study found no differences in ROM, IKDC, KT-2000, and isokinetic peak muscle torque in four different permutations of Rigidfix (Depuy Mitek, Raynham, MA) femoral fixation, Intrafix (Depuy Mitek, Raynham, MA) tibial fixation, and bioscrew; however, there was significant performance bias as several groups had "back up" fixation with either a button or staple. Another type of cortical-cancellous fixation that has been described, the Ligament Plate (Solco Biomechanical, Seoul, Korea), features cortical screw fixation with a loop that enters the femoral tunnel for graft looping. This device has been found to have similar biomechanical properties of graft fixation as compared to the Endobutton and Transfix (Arthrex, Inc Naples, FL).

Endobutton fixation has long been used for suspensory soft tissue graft fixation, and the newer closed loop version, Endobutton CL (Smith and Nephew, Andover, MA), has been shown to have significantly higher failure load than the original Endobutton, Linx HT hamstring fastener, Bone Mulch screw, Transfix, and bio interference screw [50]. However, the bio interference screw has been shown to have greater stiffness than the Endobutton [51], likely due to its aperture fixation. Comparing cortical suspensory fixation to cortical-cancellous suspensory fixation, a recent biomechanical study found that Endobutton direct (Smith and Nephew, Andover, MA) and femoral Intrafix had similar biomechanical properties to the AXL Cross-pin (Biomet, Warsaw, IN) and Biotransfix II (Arthrex, Naples, FL). In a clinical study with a minimum of 4-year follow-up, 105 patients undergoing primary hamstring autograft ACL reconstruction with Endobutton CL (Smith and Nephew, Andover, MA) fixation, the authors reported no failures related to the femoral fixation and no need for back-up fixation using an interference screw [52].

Another study evaluated the biomechanical performance of several different constructs in terms of maximum failure load, slippage, and stiffness. The constructs tested were Endo Button CL-Bio RCI, Swing Bridge-Evolgate, Rigidfix-Intrafix, Bone Mulch-Washer Lock, Transfix-Retroscrew, Transfix-Deltascrew, and Kryptonite bone cement [53]. The Swing Bridge-Evolgate construct had the highest stiffness and ultimate load to failure, while the Transfix-Deltascrew construct and the Kryptonite bone cement had the lowest ultimate load to failure and were the only two below the 500 N threshold for accelerated rehabilitation. This study had multiple confounding variables despite the authors trying to rectify this by reporting the mode of failure.

Tibial Fixation

Tibial fixation can also be divided into compression fixation and suspensory fixation, which is subdivided into cortical-cancellous fixation and cortical fixation. Compressive fixation via interference screws is also a mainstay for soft tissue graft tibial fixation; however, graft slippage may occur and the interference screw may be more frequently "backed up" when used for tibial fixation of soft tissue grafts. This may be because of the risk of slippage or the ease of visualization of this bone tunnel. Regardless of the reason, this additional fixation increases pull-out strength and decreases graft slippage, and multiple different devices can be used for this back-up fixation. A clinical study in primary ACL reconstructions also noted that hamstring grafts in female patients may have improved Lachman and KT-1000 measurements if reinforced with staples in addition to interference screws [54]. Back-up devices that have been reported include: screw and post, Endobutton, a single staple, dual staples, double spike plate, PLLA ball, biotenodesis screw, cortical disc, cortical screw, and button [24, 55–58]. These back-up devices can each be used as the primary tibial fixation as well.

A second type of compressive device is the Intrafix, which consists of a polyethylene screw and sheath placed within the strands of a soft tissue graft. The screw expands the sheath and wedges the graft against the bone tunnel. Studies again differ in their evaluation of the performance of this device. One study found greater slippage in the Intrafix compared to bioabsorbable screw or a screw and washer type device [59]. However, another study found the Intrafix had higher yield load and stiffness than WasherLoc, tandem spiked washers, Bioscrew, SoftSilk screw, and Smart Screw ACL [60].

Cortical suspensory fixation consists of screw and washer constructs, staples, and the Endobutton. Screw and spiked washer techniques are often used for tibial fixation with soft tissue grafts as they can be used to grasp the graft itself or excess suture from the end of the graft. A tandem washer technique has been described where the sutures are tied in tandem with two washers 15 mm apart; however, various permeations of this technique also include using one of these washers to grasp some of the soft tissue graft. The tandem washer technique and Washer Loc device both achieved ultimate strength well above the minimum 500 N value, but had significantly different values in two different studies [34, 60]. Another screw and washer device, CentraLoc (Arthrotek, Inc Warsaw, IN), has also performed well in biomechanical studies [59].

Cortical-cancellous devices have also been advocated for the tibial graft fixation, including similar cross-pin fixation devices as well as specialized screw and washer devices that penetrate the cortex to fixate the graft to the back wall of the tibial tunnel (WasherLoc). Fixation devices that are placed at the aperture of the tunnel require exacting measurement of graft length to achieve adequate tension which may complicate their use.

Bone Fixation

Femoral Fixation

Interference screws are the mainstay of fixation of a bone plug within a bone tunnel; however, other techniques have been described. Most metal interference screws are now created with titanium due to its relatively inert properties. Bioabsorbable screws initially were created with poly-L-lactide (PLL), which takes years to degrade, if at all. Currently most biodegradable screws are made of some formulation of poly-alpha-hydroxy acids. These biodegradable screws have been cited as having several advantages over metal interference screws, including: less chance of graft laceration [61] if used for soft tissue fixation, no interference with CT or MRI if needed for future meniscal injury or graft failure

[62], and the ability to drill through the softer material which negates removal of hardware difficulties in the revision setting [63]. Proponents of metallic screws cite the fact that biodegradable screws are more likely to fracture and have been shown to produce foreign body reactions or persistent sterile effusions within the knee. Recently, biocomposite screws have been introduced. These screws are comprised of varying amounts of tricalcium phosphate and poly-alpha-hydroxy acids, with the claim that there is less soft tissue reaction, faster absorption, and bone ingrowth by 24 months. Another material with increased use is Polyetheretherketone (PEEK), which is thought to be inert and may provide increased strength with similar benefits of being radiolucent and retaining the ability to be drilled [64].

Several studies have found similar results with biointerference screws compared to metal screws [65, 66], with one study finding superior results with metal screws [15]. Clinically, no difference in outcomes was found following fixation with bioabsorbable screws compared to metal screws other than a higher rate of effusions with bioabsorbable screws [43]. The thread height and pitch of the screw are likely the two most important biomechanical properties of the screw itself, and, when used in conjunction with a bone plug, the length of the screw does not improve stability as it does with soft tissue fixation. Most have found that screw lengths greater than 20 mm do not confer any specific advantage over a 20 mm length screw.

Cross-pin fixation has been used with bone plugs, although there is a risk of fracturing the bone plug in bone blocks smaller than 9 mm in diameter [67]. Expansion bolts have also been tested for use with tibial tunnel bone plugs with results similar to bioabsorbable and titanium interferences screws [68]. Staples also have comparable biomechanical properties to interference screws, but similar to the cross-pin fixation, bone plug fracture can occur with one study finding fractured bone plugs in 27 % of specimens [69]. Press-fit fixation has been advocated by some authors in primary ACL reconstruction [70, 71]; however, because of tunnel expansion and decreased bone density, this fixation method is not typically advocated in the revision setting. Using the sutures passed through the bone plug and tying this to a post using a "screw and post" configuration is a good option for additional fixation, but is not likely strong enough for early rehabilitation in isolation [30].

The Endobutton CL is also made for use with bone plugs and can be a reliable method to achieve fixation when a new tunnel converges on an old tunnel or the tunnel is expanded. The Endobutton ultimate failure load is similar to that of a metal interference screw; however, it may have less stiffness and increased displacement of the graft [50]. This finding is less a function of the implant and more a function of the interference screw achieving aperture fixation compared to the suspensory fixation of an Endobutton.

Tibial Tunnel

The interference screw is the most commonly utilized method of fixation of a bone plug within the tibial tunnel. Typically, larger sized screws are used within the tibia because the cancellous bone is less dense than in the femur. Some surgeons will use a 7 mm screw if there is only a 1–2 mm gap between the size of the bone plug and the bone tunnel and a 9 mm screw if there is a 3–4 mm difference in diameter. Others will use a 9 mm screw or larger in the tibia even with a 1–2 mm difference in diameter citing the reduced density of cancellous bone in the tibia. If a cannulated screw system is used, some advocate arthroscopically checking to ensure the guidewire has indeed passed into the joint because there have been reports of the wire and screw being placed into the periosteum of the anteromedial tibia instead of the tunnel. In the revision setting, a larger sized screw can be used or one of the techniques described later in the chapter can be implemented. However, there is a limit to the amount of bone that can be filled with screws as most screws are available in limited diameters between 7 and 12 mm.

Special Techniques

Several fixation techniques have been described to aid fixation in the revision setting. If prior tunnels are in adequate position or if they are close to anatomic position, then divergent tunnels [72, 73] can be created in which the aperture of the tunnels is kept the same, but the remainder of the tunnels are created in normal bone. This can be achieved by several techniques. The tibial aimer can be placed at the intra-articular opening of the prior tibial tunnel and the starting point on the tibia can be moved medial or distal. It is important to recognize that a change in the tibial tunnel orientation will affect the femoral tunnel position if a transtibial technique is utilized for femoral tunnel drilling. Anatomic position may be facilitated by creating a mid-patellar tendon portal as previously described for primary ACL reconstruction [73]. To create divergent femoral tunnels an over-the-top femoral aimer can be placed through the tibial tunnel and rotated externally to lower the tunnel down the lateral femoral wall. Alternatively, commercially available curved anteromedial drilling systems which utilize flexible reamers can be used. This aimer can be inserted through the anteromedial portal and, with the curvature, can be rotated internally or externally to create a divergent tunnel. Alternatively, an anteromedial approach with a straight guide can be used, but requires the knee to be placed in hyperflexion. Finally, a two-incision technique can be used in which the outside-in aimer is placed at the intra-articular entrance of the prior femoral tunnel and a new femoral tunnel is drilled from the lateral cortex of the femur.

In the setting of a large diameter aperture with divergent tunnels, (i.e., “snowman” or “figure eight” tunnels), a stacking screws technique can be used. In this technique, the prior screw is removed and the new tunnel is drilled. Depending on the size of the new tunnel or the amount of the old tunnel that is encroaching on the new tunnel, the graft can either be inserted prior to or after the first screw. If the prior screw is not damaged and is of appropriate size, it can be reused. If there has been tunnel dilation a larger screw can be placed. If the new tunnel encroaches on part of the old tunnel, then a smaller screw can be used in the old tunnel so as to not fill the new tunnel and prevent graft passage. Once the graft has been placed, the second screw is then placed as a normal compression screw and often gets additional purchase from the screw-screw interface. Alternatively, the prior screw can be left in place as a “blocking” screw. This can then be used to ensure the guidewire for the femoral tunnel does not slip into the old tunnel, essentially blocking this path. The screw can then be removed once the guidewire has been passed with good purchase in the remainder of the femoral bone.

Another technique using a biocomposite screw or bone dowel with autograft or allograft can be used to achieve graft fixation in the femur when the prior tunnel will partially encroach on the new femoral tunnel. This technique involves removing the old screw or debriding the soft tissue in the old tunnel and then filling this tunnel with a biocomposite screw or press fit graft. This screw or graft is then partially drilled to create a new tunnel for femoral fixation. The size of the screw used depends on how much the new tunnel will encroach on the old tunnel and the size of the prior tunnel. The biocomposite screw or graft should fill the prior tunnel and should extend the entire length of the tunnel that may invade the new tunnel.

If the majority of the tunnel widening or tunnel convergence is on the femoral side, an excellent technique is the two-incision antegrade outside-in drilling technique. This technique allows the surgeon to place the femoral tunnel in the anatomic ACL location, and at the same time avoid fixation problems in a large tunnel as the graft is fixated at the lateral cortex of the femur. However, this technique does potentially increase the graft motion within the tunnel. This has been a proposed cause of tunnel widening [13, 37], which has been improved with aperture fixation [74]. If the majority of the tunnel widening is on the tibial side, a reversed Achilles tendon allograft can be used. The bone plug can be made as large as needed for the tibial side combined with one of the above femoral fixation techniques.

Interestingly, there have been many biomechanical studies comparing various fixation techniques, yet there is very poor agreement between studies in terms of ultimate load and stiffness. This is likely due to differences in methodology, reconstruction techniques, and cadaveric bone mineral density. Most fixation devices have adequate fixation to allow for early motion and aggressive rehabilitation; however, certain fixation techniques may have certain advantages in the revision setting. Interference screws are available in multiple diameters and lengths, which can be used to fill expanded bone tunnels, can be stacked to fill cavernous tunnels, or can be used to block prior tunnels and allow the graft to follow another path. Combining the versatility of interference screws with cadaveric BTB grafts gives the surgeon even more flexibility with the ability to fill larger tunnels with either larger bone plugs or excess bone in graft format.

Revision ACL reconstruction is challenging. Pre-operative planning is critical and the surgeon must be prepared to deviate from the initial plan if unexpected situations arise. Graft fixation can be accomplished in a number of ways and being facile with different techniques is crucial.

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Single Stage ACL Revision Reconstruction: Indications and Technique

12

Joshua Hamann and Mark D. Miller

Introduction

Newer techniques have complicated ACL reconstruction, including revisions. This chapter will outline some of the factors leading to ACL reconstruction failure, treatment options, and outcomes regarding single staged ACL revision reconstruction.

A multicenter ACL revision study (MARS) group has been established to further evaluate multiple factors regarding ACL revision [1]. In their study, the most common mode of failure found was traumatic (32 %). Technical factors lead to failure in 24 % of the cases, with a combination of factors leading to 37 % of failures. Historically, technical error has been considered the most common cause of ACL reconstruction failure. The most common technical factor is malpositioned tunnels, adding to the difficulty of revision surgery.

Revision ACL surgery can be done in a variety of ways, but should always be tailored to correct the patient's specific mode of failure. An assortment of options must be available to the surgeon at the time of revision surgery as unforeseen obstacles may arise frequently. We refer to this as having Plan A, Plan B, Plan C, etc. The surgeon should be well versed on a variety of options available to him/her prior to revision surgery to facilitate successful outcomes. Single stage revision ACL reconstruction is a viable option in many cases and should be considered for all ACL revisions, as this technique avoids the risks associated with the two-staged approach. These include a second exposure to anesthetic and increased period of time to achieve knee stability which has been shown to lead to increased rates of concomitant intra-articular pathology [2, 3]. Patient satisfaction is much improved with single stage revision reconstruction.

Preoperative Workup

To achieve a successful outcome and avoid repeat failure, a thorough preoperative workup is essential. Determination of the mode of failure begins with a methodical history and physical exam. The first question must be did the knee ever feel stable after the primary reconstruction? Asked another way, did the patient ever "trust" their knee? If the answer is no, then the surgeon should assess for technical error. Was the failure due to trauma? Of course, the surgeon must always guard against the inherent bias of assigning a trivial level of trauma as the mode of failure, when in fact technical error was the critical factor in graft failure. The history should always include

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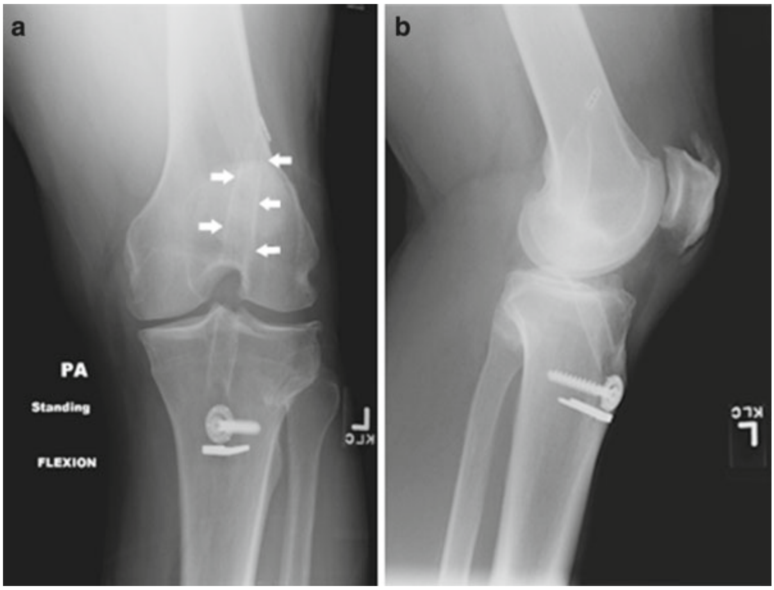

Fig. 12.1 Posteroanterior flexion weightbearing (**a**) and lateral (**b**) X-rays of a left knee 11 years after ACL reconstruction showing vertical placement of the ACL tunnels with proximal positioning of suspensory fixation hardware and slight tunnel widening (*arrows*)

review of previous surgeries, including operative reports with arthroscopic images, hardware used, and prior graft choice.

Physical examination should be comprehensive, looking for signs of additional pathology, including associated ligament injury, meniscal pathology or deficiency, or malalignment. Traumatic rupture of the ACL graft may lead to associated injuries, whereas associated pathology may have been overlooked during the prior workup. The gold standard exam maneuvers for ACL deficiency are the Lachman test and the pivot shift. Quantification of anteroposterior instability may be evaluated with use of a variety of commercially available products. The Dial test should be used to identify posterolateral corner injuries. Knee range of motion and quadriceps muscle tone should also be assessed. It is advised to achieve near full range of motion prior to surgical intervention to prevent post-operative stiffness.

Preoperative imaging should be performed and carefully analyzed. Plain radiographs are essential first steps in the workup of the failed ACL reconstruction. Weightbearing posteroanterior, lateral, and sunrise views are routinely obtained to assess for hardware and tunnel positioning, tunnel widening, patellar congruity, and degenerative changes (Fig. 12.1). Additional studies such as long cassette standing radiographs or PA flexion views may be useful to further assess the joint and extremity alignment. Stress films may also be used to dynamically assess joint stability, particularly the posterolateral corner [4]. Other modalities of imaging should be considered in the workup of the failed ACL reconstruction. Computed tomography (CT) can be used to assess the bone and tunnels and is particularly valuable with osteolysis (Fig. 12.2). It is imperative to identify tunnel expansion prior to revision surgery, as will be discussed below. Magnetic resonance imaging (MRI) can also be used to assess for concomitant injuries, including meniscus tears and cartilage defects, along with confirming the diagnosis of graft rupture.

The patient must be aware of possibilities and appropriately counseled regarding expectations and outcomes. Setting realistic goals and describing the unpredictability of revision ACL surgery is key for the patient to understand. They should be counseled that they will have a more conserva-

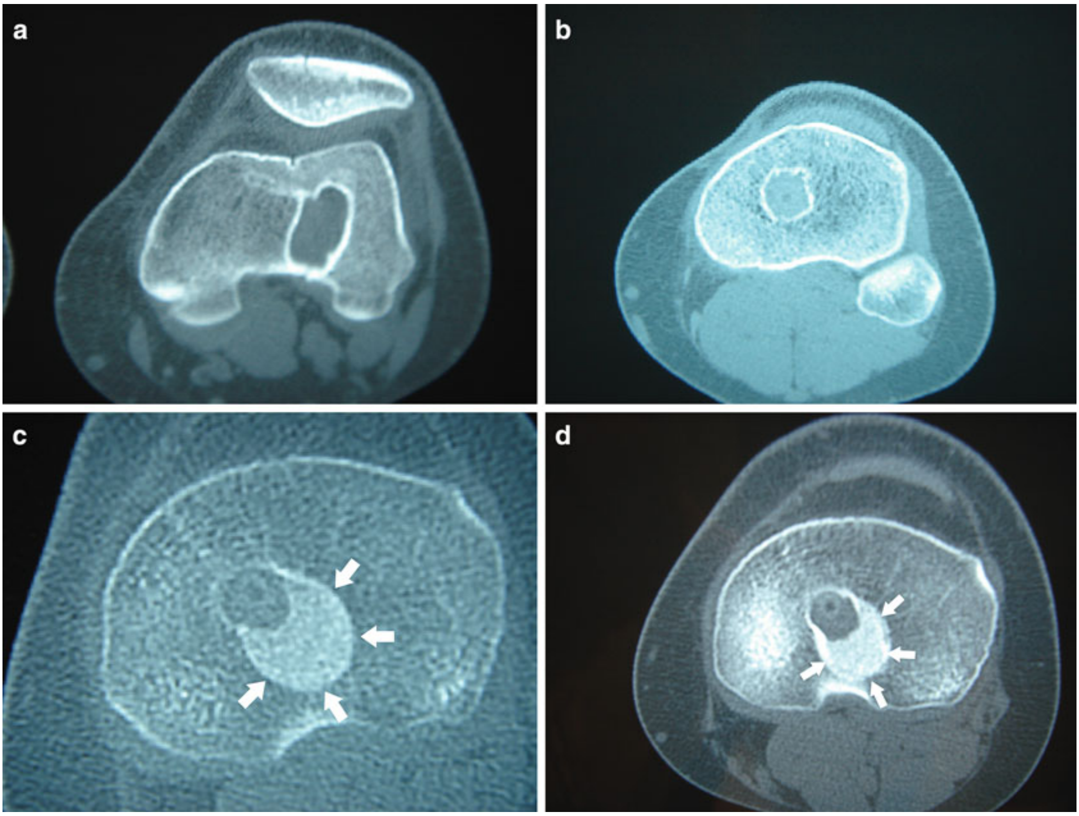

Fig. 12.2 Selected axial computed tomography images showing pre-revision tunnel widening in the femur (**a**) and tibia (**b**), the tibia at 2 months (**c**) and 5 months after revision ACL reconstruction (**d**). *White arrows* show allograft bone dowel incorporation into tibia used during revision reconstruction

tive rehabilitation program following the revision surgery. Patients should be aware that return to their original pre-injury level is variable, if not unlikely. Often times, it is not possible to fully determine if a single stage or multiple stages are necessary for successful revision preoperatively, and the patient should give consent for possible additional surgery if necessary [5].

Preoperative discussions should also include graft choice. A review of previously used graft from the index procedure and a menu of available choices for autograft should be obtained. The patient should understand the morbidities associated with autografts and the risks associated with allografts, including disease transmission and a potentially higher risk of failure.

Timing of revision surgery has also been shown to be a significant factor for the development of radiographic apparent arthritis [3]. It is hypothesized that the continued instability of the knee may lead to further chondral injury and meniscus damage. Thus, avoiding activities that may lead to knee instability is prudent and operating earlier to restore stability is optimal.

Finally, the hospital or surgery center should be stocked with the necessary implants and have access to the necessary equipment for revision surgery. Allograft tissue should be available, even if only as a backup for planned autograft procedures. Custom-sized materials should be ordered in advance, and specific instrumentation for removal of implants should be available. Always have a universal screw removal set available. Fluoroscopy can be an extremely useful tool intra-operatively to assist with hardware removal or the avoidance of prior tunnels.

Treatment Options

The decision for single staged ACL revision surgery should be made on an individualized basis for each patient. The surgeon must have multiple options available to him/her at the time of surgery. Again, a thorough workup is necessary to determine cause of failure and to correct these at the time of revision surgery. The surgeon must be prepared for meniscal work (i.e., repair or partial meniscectomy), cartilage treatment, reconstruction of other ligaments, or the correction of malalignment issues at the time of revision surgery.

Decisions regarding tunnel placement, graft choice, and fixation must be made prior to surgery. The revision surgeon must make the decision both preoperatively and ultimately intraoperatively about previous tunnel placement whether to retain these tunnels or to make new ones. When tunnel expansion has occurred beyond the point at which adequate fixation of the graft is possible, then the two-stage approach must be undertaken. Tunnels that are 16 mm or less can generally be reused in one stage, whereas larger tunnels are generally best treated with bone grafting and a two-stage reconstruction. Backup secondary fixation should be utilized if primary fixation is not optimal.

If the previous tunnels are accurately placed, the surgeon must remove all of the previous graft and be sure to have a healthy base of tissue for the new graft to incorporate (Fig. 12.3a–c). This may require increasing the size of the tunnels with curettes and reamers to remove granulation tissue formed at the periphery of the old tunnel. Larger fixation devices may be necessary to achieve stable fixation of the graft.

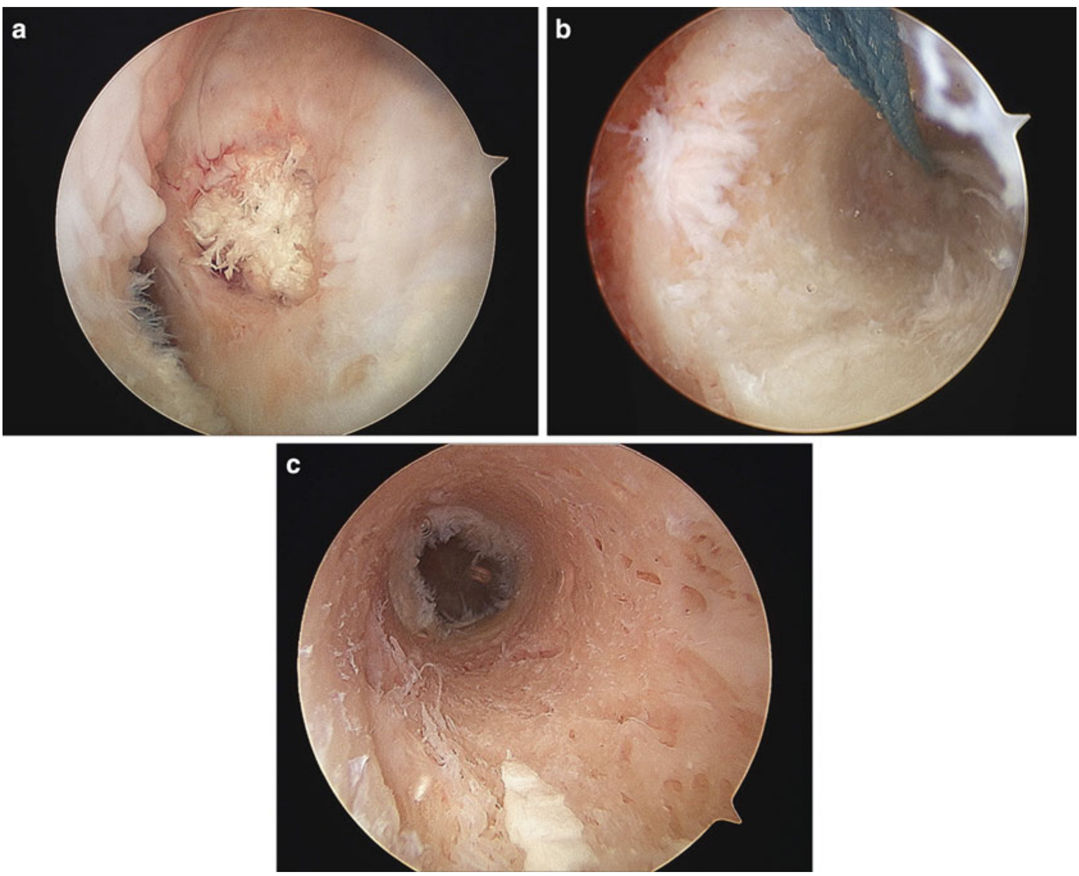

Fig. 12.3 (**a**) Arthroscopic view of ACL femoral tunnel in anatomic position, in which it is possible to re-use tunnel for revision. "Arthroscopic tunnel view" of femoral bone tunnel (**b**) and tibial tunnel (**c**) used to assess for adequate bony walls

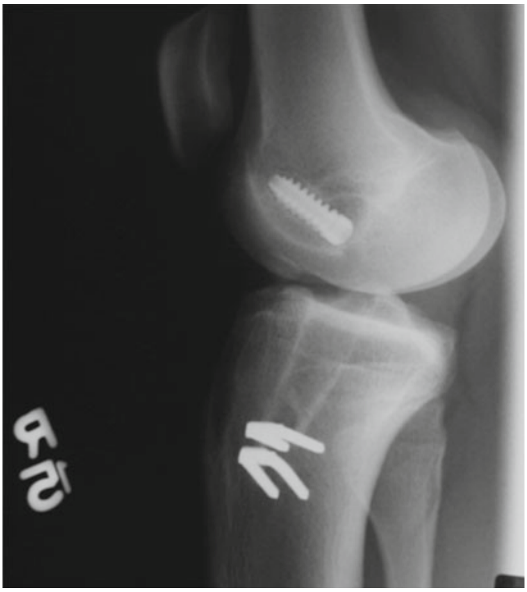

Fig. 12.4 Lateral X-ray showing a malpositioned femoral tunnel placed too anteriorly. If the tunnels are out of anatomic range, hardware may be retained and a new tunnel may be safely placed in an anatomic position

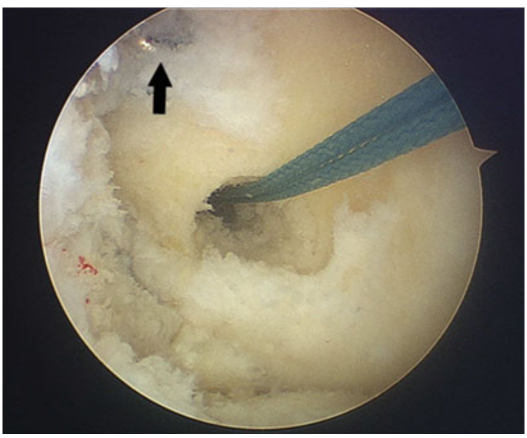

Fig. 12.5 Arthroscopic view of a new femoral tunnel in anatomic position, with previous femoral tunnel fixation in place (*arrow*)

If the tunnels are deemed to be sufficiently inaccurate and out of the range of anatomic insertion (Fig. 12.4), then the options include leaving previous hardware in place and working around the hardware to place the new tunnels in the anatomic position (Fig. 12.5). Removing the previous hardware would be the other option, but this may destabilize the new tunnel wall, leading to inadequate fixation of the new graft.

When the tunnels are malpositioned and interfere with the placement of the new tunnels, the revision surgeon must make a complex decision. Again, the treatment must be individualized to each patient. Each tunnel in the revision setting must be assessed and approached individually. Transtibial ACL reconstruction techniques force the femoral tunnel to be dependent upon the tibial tunnel; therefore the revision surgeon should be prepared to perform independent drilling techniques which allow for more horizontal and anatomic placement of the graft. These include using an accessory medial portal with flexible reamers, placing the knee in hyperflexion during drilling or the two-incision technique with outside-in drilling. This allows for divergent tunnels as described by Bach [6].

As with primary ACL reconstruction, creating a more horizontal graft in the anatomic femoral footprint is imperative for restoring knee rotational stability. Femoral tunnel position should not be compromised in the revision setting. Multiple options exist for creation of an anatomic femoral tunnel. If the patient has had previous fixation with metallic interference screws, they can be replaced with bioabsorbable screws to create a new anatomic tunnel [7]. Removing the old graft and hardware will obviously leave a void of bone. Filling this bone void with autograft bone, allograft bone, or bone filler substances has been described [8, 9]. We prefer the use of allograft dowels in this setting. The key is to have enough structural stability to hold the graft in place to withstand the tensile stress applied to the ACL graft.

Creating divergent tunnels in the tibia is important in the setting of malpositioned tibial tunnel from the primary surgery. Using the variable angle ACL drilling guide will allow for new tunnels to be created for interference fixation. Backup fixation with buttons or posts should be considered if there is any question regarding the adequacy of fixation. Challenges occur when the original tunnel is placed too far posteriorly as can happen with the transtibial technique. Concern exists for the new graft undergoing the windshield wiper effect at the aperture of the tunnel causing graft attrition. A double bundle reconstruction has been postulated as a one-stage solution to this problem, with use of the previous tunnel for the posterolateral bundle and a new tunnel for the anteromedial bundle. Filing the tunnel with bone graft and creating a new tunnel is another option available to the surgeon.

Graft choice in the revision setting is an important consideration for the revision surgeon, and it is especially vital in the single stage revision. Bone to bone fixation in this setting is ideal with autograft BTB being the optimal graft choice. The option of harvesting from the contralateral extremity exists if the primary surgeon used a patellar tendon graft from the ipsilateral leg during the index procedure. Otherwise, allograft (with bone or only soft tissue) or autograft soft tissue can be used. Quadriceps autograft is an additional option for single stage revision.

Fixation of the graft is another important decision in the single stage revision setting. Options include interference fixation with metallic or bioabsorbable screws, suspensory fixation, staples, or tying sutures over a button or post. Again, bone to bone healing with interference screw fixation is ideal, with secondary backup fixation used as needed (Fig. 12.6).

Fig. 12.6 Lateral knee X-ray showing “stacked” interference screws within both the tibia and femoral tunnels, along with “back up fixation” with a tibial post

Authors’ Preferred Technique

The senior author’s preferred technique for revision ACL reconstruction is for single stage revision with allograft bone dowels, if needed [9]. The patient is positioned in the supine position, with use of a lateral post and a bracketed Surgical Knee Holder to aid in hyperflexion of the knee. The contralateral leg is prepped in the surgical field if graft harvest from the contralateral extremity is planned. Standard arthroscopy is performed, with evaluation for any associated injuries. All other injuries are addressed as needed. Hardware from the primary surgery is removed only if necessary. If it is clearly out of the site for the revision tunnel, prior hardware is left in place. Graft tissue from the tunnel is debrided. Aggressive debridement of the previous bone tunnels is undertaken and reamed to fit the allograft bone dowel, which is available in a variety of sizes, 10–18 mm in diameter (Fig. 12.7a). Direct visualization of the tunnel should be performed to ensure that the tunnel is free of unwanted tissue and uncompromised tunnel walls. If single stage reconstruction is appropriate but the prior tunnel compromises the new one, an appropriately sized allograft dowel is selected, the same size as the diameter of the tunnel. Rehydration of the graft is performed with sterile saline. The dowel is then tapped into place with a bone tamp in a retrograde fashion for the tibial tunnel, and with use of a guidewire through the accessory medial portal for the femoral tunnel (Fig. 12.7b). The dowel may be inserted with a cannuated tamp or dilator (Fig. 12.7c–e). Due to the press fit nature of the allograft dowel, new tunnels may then be placed without regard to previous tunnel position. The tunnels should, however, attempt to diverge, keeping the entry point of the tunnel as anatomic as possible to avoid fragmentation of the allograft dowel.

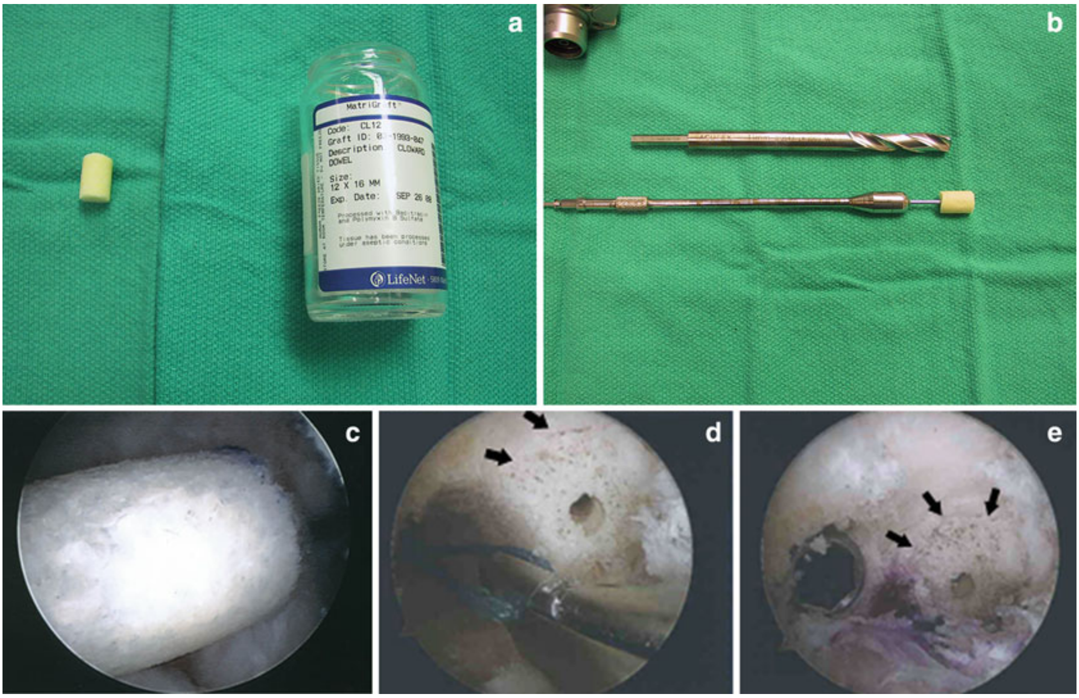

Fig. 12.7 Implant (**a**) and instrumentation (**b**) for use of allograft bone dowels. The allograft bone dowel is placed onto a smooth Kirschner wire, where a cannulated tamp can be used to impact the dowel into position. (**c**) Arthroscopic view of the bone dowel being placed into femoral tunnel. (**d**) Arthroscopic view of new femoral tunnel drilled in an anatomic position with bone dowel in place (*arrows*). (**e**) Arthroscopic view of patellar tendon graft with metallic interference screw fixation with bone dowel allograft in place (*arrows*)

Post-operative Rehabilitation

Rehabilitation after revision ACL reconstruction should be individualized for each patient. In general, rehabilitation programs should be less aggressive than primary ACL reconstructions. Range of motion should be the primary focus in the early stages of rehabilitation, followed by strengthening. We do not routinely use continuous passive motion devices in the post-operative period. As with primary reconstruction, closed chain exercises should be utilized, especially early in the rehabilitation stages.

Single Stage Revision Outcomes

Outcomes of revision reconstruction have not been as well defined as primary surgeries, due to the large number of concomitant injuries (ligamentous, meniscal, or articular) creating an assortment of patient groups and the lack of large series. As previously described, the MARS project has been set up to collect this data [1]. In their first report of 2-year outcome data, SF-36 outcome data was improved, but 15 % of the patients in the study underwent additional procedures within the 2-year follow-up period, including 2 ACL re-revision surgeries. In a systematic review by Wright et al., outcomes of revision ACL reconstruction were poor. An objective failure rate of 13.7 % was found in pooled data, with failure defined as repeat revision surgery, >5 mm side-to-side difference on KT-1000 arthrometer, or grade 2+ to 3+ on pivot shift exam. Subjective outcome measures (i.e., IKDC, Lysholm, and Tegner) of ACL revision are lower than those seen in primary ACL reconstruction, but improved compared to ACL deficient knees. The role of concomitant injuries plays a major role in this finding. Timing of revision surgery correlates with increased intra-articular injury.

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13 Two-Stage ACL Revision: Indications and Technique

Cory M. Edgar, Thomas DeBerardino, and Robert Arciero

Introduction/Indications

Primary ACL reconstruction is a very common orthopedic procedure. Long-term results have been very encouraging with good to excellent results being reported in 75–90 % of cases [1–5]. However, as with all surgical procedures, failures do occur. Recurrent instability after ACL reconstruction is a multifactorial problem that can be simplified by considering the failure in two categories: traumatic and atraumatic failures. Typically, recurrent instability without an associated traumatic event occurs "earlier" in the postoperative period. Modes of failure reported include failure of graft "ligamentization" or biologic failure of the tissue, associated posterior medial or lateral laxity, meniscal deficiency, bone tunnel widening or lysis and "technical error" [6–10]. In a recent review, the mode of failure in 22–75 % of revised ACL reconstructions was most commonly associated with "technical error" [11]. Tunnel malposition is one of the most common technical errors and can have a dramatic impact on the revision surgical procedure.

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Regardless of the cause, the success of a revision procedure is dependent on the ability of the surgeon to place bone tunnels in a proper anatomic position and to provide adequate fixation to maintain graft position and tension. Hence, the two-stage surgery allows for good bone stock for fixation of the ACL graft without compromising the location of the bone tunnels [12]. Only one group has reported results after a series of two-stage procedures in the treatment of the failed ACL reconstruction. In a prospective series of 49 patients in which only the tibia tunnels were bone grafted with iliac crest graft, healing verified by CT scan at 4 months and revised with an outside—in technique for femoral tunnel placement [12]. The outcomes of these patients were reported at a minimum of 3 years after the final procedure with an average of 6 years. This cohort was compared to a matched control group that had primary ACL reconstructions performed by the same surgeon and senior author. The revision group had higher rates of chondral and meniscal lesions and inferior outcomes by IKDC scoring (61.8 vs. 72) compared with the primary reconstruction control group. There was no difference between side-to-side knee laxity measurements compared with the control group at final follow-up. To date there is no data to support or suggest that a two-stage procedure will produce lower rates of graft failure or improved subjective outcomes. However, failure rates in the revision patient approach 25 % and at least in this study, no failures were reported. Optimizing the healing

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Table 13.1 Indications for two-stage revision

Absolute indications	Relative indications
Infection	Concomitant meniscal transplant
Femoral tunnel lysis (>15 mm)	Concomitant osteochondral lesion needing articular resurfacing (OATS; ACI)
Tibia tunnel lysis (>15 mm)	Malalignment requiring osteotomy
Failed double bundle ACL reconstruction with large footprint combined tunnel defect limiting fixation or anatomic graft placement	
Retained hardware requiring bone removal with subsequent tunnel defect that would compromise anatomic tunnel placement	
Arthofibrosis after primary ACL surgery requiring revision of ACL graft following arthroscopic release and manipulation to restore full knee motion	

potential and fixation strength are critical to obtain a stable knee in the revision situation with bone loss or excessive tunnel widening.

There are several indications for staged ACL revision reconstruction (Table 13.1), although infection and bone loss are the primary and most common reasons. The need for bone grafting to treat large tunnels inhibiting anatomic placement of a well-fixed graft in either the femur or the tibia is by far the most common reason. Tunnel diameters of greater than 15 mm in any plane on a CT scan is a strong indication for a two-staged procedure for bone grafting [1, 2, 9, 12]. Often bone tunnel widening with hardware that needs to be removed (such as metal screws) creates the need for a two-stage procedure.

Optimal graft fixation and healing is predicated on healthy, living bone of structural integrity at the aperture of the bone tunnel. Often, removal of hardware, debridement of previous graft back to bleeding bone, and tunnel malposition leading to tunnel overlap during creation can lead to significantly increased tunnel aperture diameters.

Table 13.2 Considerations for two-stage revision

Advantages	Disadvantages
Possible improvement in postoperative Knee ROM—interval rehab following first stage	Concern regarding continued meniscus or cartilage damage with ACL-deficient knee, interval damage between staged procedures
Second procedure should be more similar to primary reconstruction—less operative time	Second procedure—surgical and anesthesia associated risk; more prolonged recovery

Even if suspensory fixation is utilized, the bone must support the graft, and more importantly, have the capacity to promote healing. Therefore, in the absence of adequate bone quantity or quality, a two-staged procedure to optimize the bone should be considered to allow the best chance of graft survival. Ultimately, the decision to expose the patient to the inherent risks of two surgeries is patient-specific and the risks and benefits must be weighed (Table 13.2).

Technique

Patient Evaluation and Initial Work-up

The importance of the patient history, examination, radiographic assessment and, if possible, review of prior operative notes cannot be overemphasized. Laxity in the posterior–lateral structures is an important, commonly unrecognized concomitant problem associated with revision ACL patients. Concurrent deficiency has been reported as high as 10–15 % [13] and therefore must be ruled out in the evaluation. Infection with or without ACL deficiency or knee instability always necessitates a staged procedure. However, concomitant ligament laxity or meniscal deficiency, mainly medial, that can affect the long-term survival of the revision ACL construct may be addressed in a single or staged procedure.

Diameters of bone tunnels should be determined by measuring in two planes—AP and lateral (Fig. 13.1). It is not uncommon that with double bundle ACL reconstructions (Fig. 13.2) or

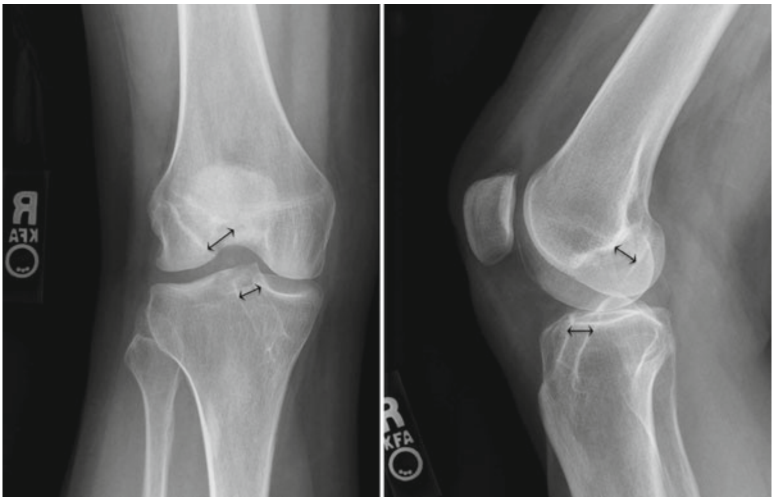

Fig. 13.1 Quantification of bone tunnel size, diameter in two planes using AP and lateral radiographs

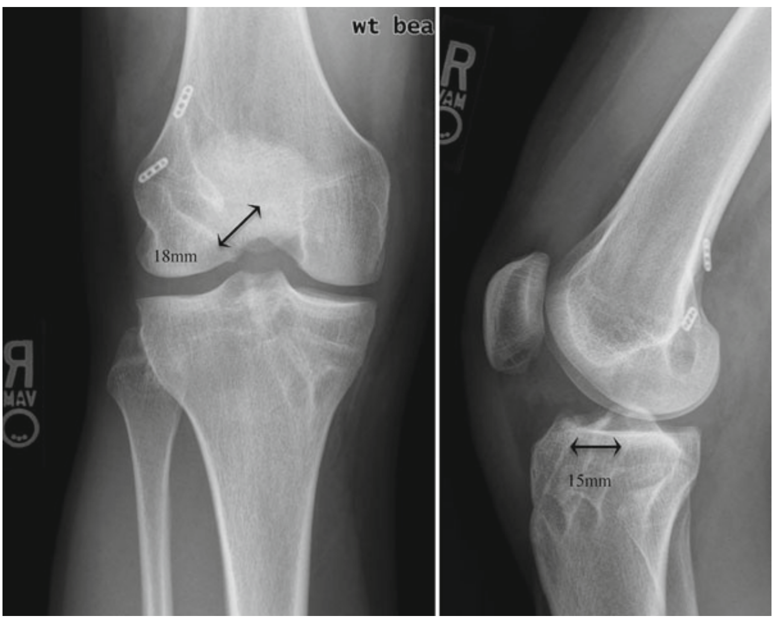

Fig. 13.2 A radiographic case example of a patient with combined tunnel enlargement following a double bundle ACL reconstruction technique

in the case of a prior revision procedure utilizing divergent tunnels, the combined tunnel bone loss at the femoral aperture can be significant enough to warrant staged procedure to facilitate bone grafting. Improper tunnel placement is commonly reported as a reason for ACL graft failure and can be assessed by radiographs [7, 9, 14]. Genu varum or valgum may be present and standing full-length hip to ankle films should be obtained to determine the mechanical axis. High tibial osteotomy (HTO) or distal femoral osteotomy to correct the alignment can be done as part of an initial procedure during which hardware is removed and tunnels grafted to optimize the revision procedure.

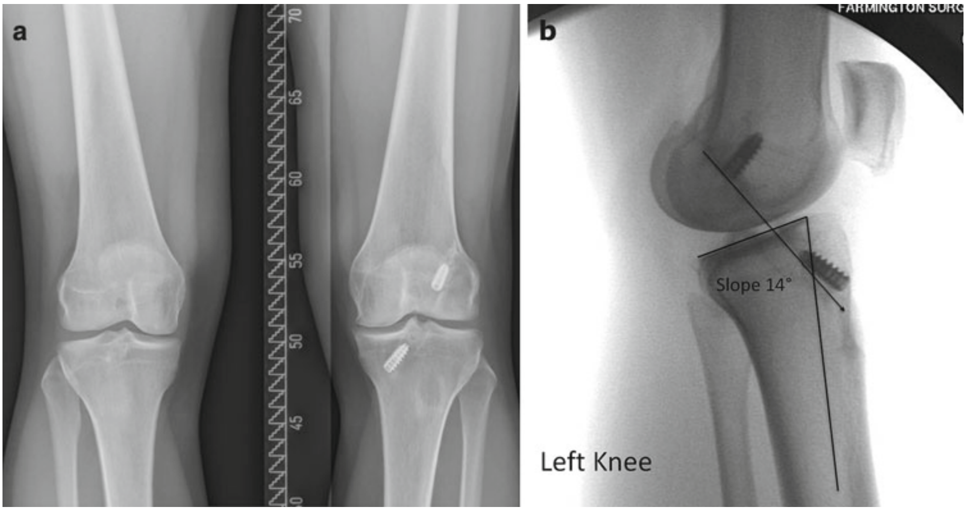

Fig. 13.3 Initial radiographs, standing, of case example #3. (**a**) Failed revision ACL of the left knee in a 20 y/o female soccer player. (**b**) Posterior tibia tunnel placement noted on lateral, increased sagittal plane slope and aperture bone tunnel measurements of 14–16 mm

Case Examples Illustrating Situations in Which a Two-Staged Technique Was Utilized

Case 1: Two-Stage with Femoral and Tibia Tunnel Grafting with HTO with Decreased Posterior Slope

Patient in case example 1 is a 20 y/o college female who was seen as a referral for chronic ACL deficiency, medial meniscal deficiency, and clinical complaint of knee instability limiting activity. A soccer player in high school, who had a primary ACL rupture and reconstruction with autogenous bone-tendon-bone at the age of 16, within 1 year of the surgery the reconstruction failed traumatically during a jump while participating in sport. Within 6 months of the re-rupture she underwent a single-staged revision ACL reconstruction with allograft tendon. Less than 1 year after revision surgery she reinjured the knee and arthroscopic partial medial meniscectomy was performed. She still is very active in many recreational sports but progressive instability and "shifting" of the knee is limiting her ability to be active. During periods of increased activity, she reports mild swelling in the knee and a dull ache localized to the medial aspect of the knee.

Physical examination demonstrates mild quadriceps atrophy (1.5 cm compared to contralateral), no thrust with ambulation and no increased laxity to the medial or lateral complex with varus and valgus stress at 0 and 30°. Prone dial test negative for increased external rotation. Lachman test is 3+ with no end point, pivot shift present in clinic exam, and markedly positive flexion-rotation drawer. Mild joint line tenderness is present medially and laterally. Posterior drawer demonstrates no laxity and firm endpoint. Radiographs demonstrate mild medial joint space narrowing, enlarged bone tunnels, and a vertical femoral tunnel with a posteriorly placed tibia tunnel (Fig. 13.3). Standing hip to knee radiographs demonstrate genu varum alignment while the MRI confirms ACL deficiency and bone loss at the femoral tunnel aperture that would limit fixation and bone tendon contact for healing (Fig. 13.4a, b).

Patient positioning is critical to ensure complete circumferential exposure. We use a circumferential padded knee holder in which the top can be removed to allow for high knee flexion when drilling the femoral tunnel through the low accessory anterior–medial portal (Fig. 13.5). The superior pad on the circumferential leg holder is removed during the case to allow for hyperflexion during femoral tunnel work.

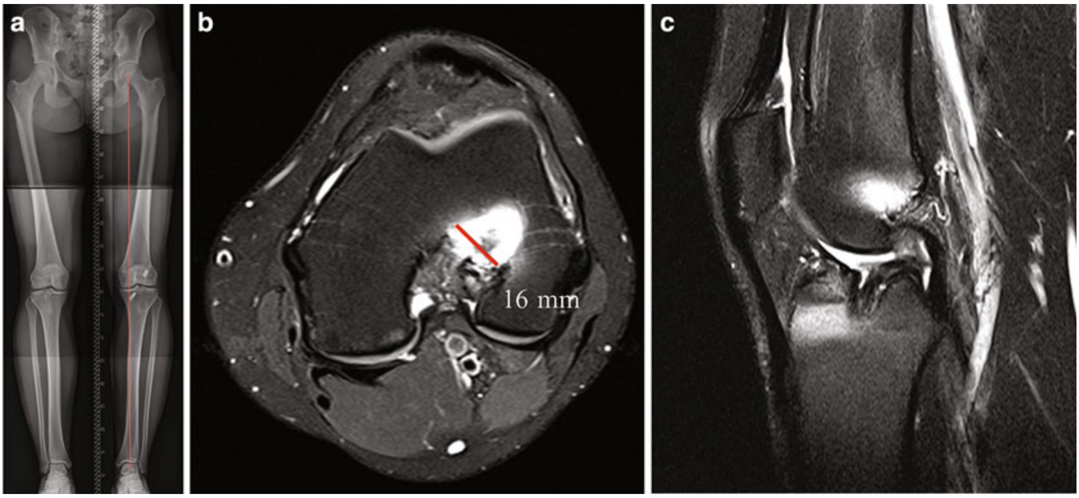

Fig. 13.4 Preoperative imaging. (**a**) Standing mechanical axis hip to ankle X-rays demonstrating genu valgus alignment with weight bearing axis in the medial compartment. (**b**) MRI demonstrating tunnel widening at the femoral tunnel footprint. (**c**) Lateral MRI demonstrating posterior-positioned tibia tunnel and aperture widening

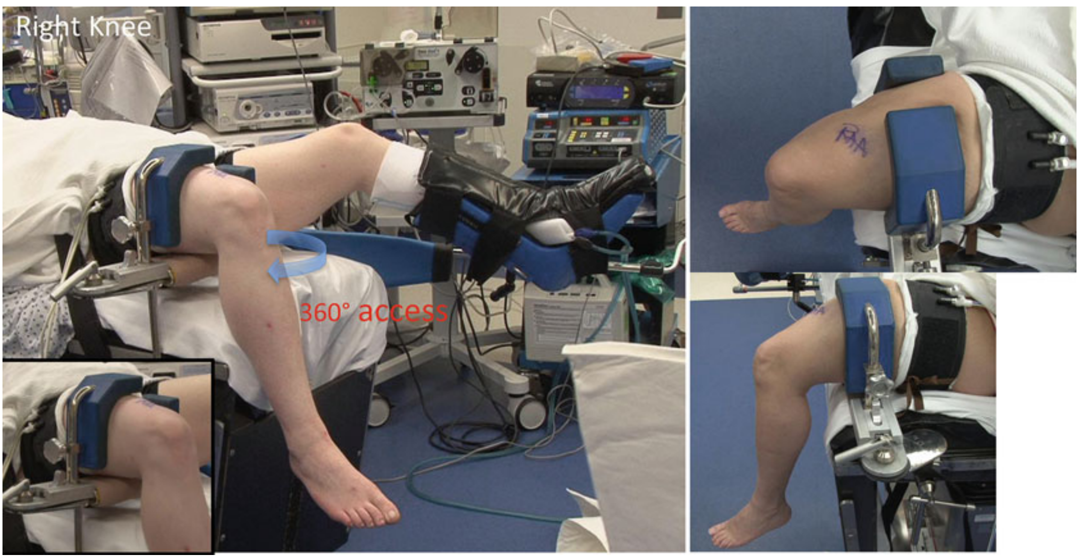

Fig. 13.5 Patient positioning in padded leg holder elevated off the bed. Proximal tourniquet used during the case to facilitate maximal visualization. During hyperflexion of the knee, for femoral tunnel work, the superior–lateral pad is removed by circulating nurse from under the drapes

Radiographic and MRI observed bone loss was found arthroscopically and accentuated on the femoral side after the removal of the metal fixation screw through the accessory anterior medial portal. After debridement of remnant ACL graft, both screws were removed and the tunnels reamed free of residual graft. This was done using a guide pin free hand in the femoral tunnel and with an ACL guide on the tibia to centrally place the pin. The tunnels were reamed with 14 mm reamer to remove all residual graft tissues. Bone tunnels were grafted with allograft dowel cores made from femoral head allograft bone. Core dowels measured 15 × 10 mm to allow

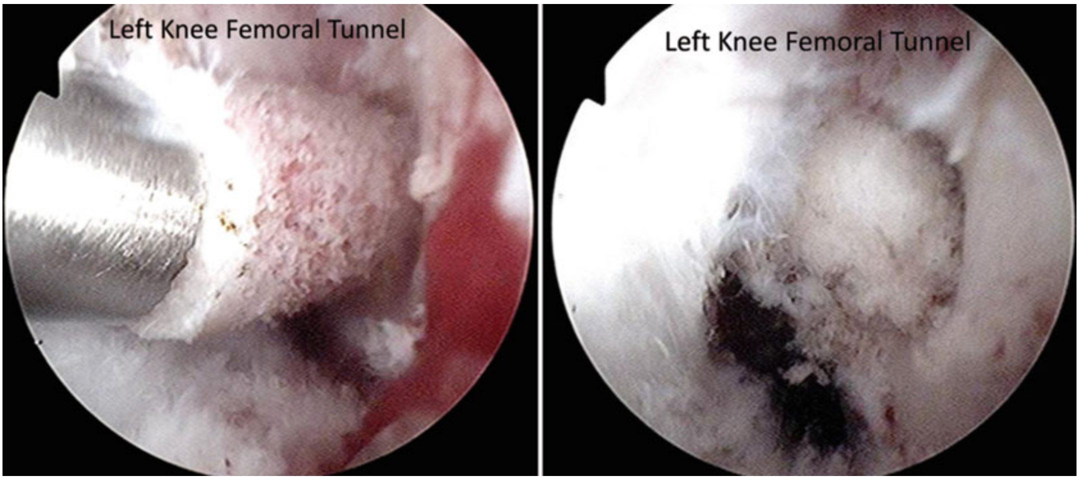

Fig. 13.6 Allograft bone dowel grafting obtained from femoral head allograft. 15 mm plugs are press fit into over reamed femoral tunnels to 14 mm. Graft is packed into the defect to a depth of 10 mm minimum. Accessory anterior–medial portal is used to introduce the dowel graft into the femoral tunnel and inserted with bone tamp under direct visualization

for press-fit fixation within the grafted tunnel that had been reamed to 14 mm (Fig. 13.6).

Medial compartment demonstrated moderate articular wear and a medial meniscal remnant of approximately peripheral 40–50 %. Preoperative mechanical access films demonstrate medial compartment loading with the axis approximately 50 % into the medial plateau (Fig. 13.4a). It is important to consider the sagittal plane angle or posterior tibia slope when considering a patient for HTO; in this patient it was measured to be approximately 14° (Fig. 13.3), slightly above a normal range of (8–10°). In this situation, an HTO is indicated to normalize the mechanical axis and allow for a reduction in her sagittal plane slope to protect the revision ACL following the second-stage reconstruction (Fig. 13.7). Adjustment to the slope is achieved by placing the puddu plate as posterior on the medial tibia cortex as possible and utilizing a sloped metal wedge for the contralateral side (use a left implant for right knee) to allow the posterior slope to be decreased. Healing of the bone grafts and HTO are monitored by serial radiographs and CT scan performed prior to definitive ACL reconstruction. The medial puddu plate and screws are removed at the time of revision reconstruction. Defect in the medial tibia cortex from puddu plate is grafted with bone obtained during tibia tunnel creation with cylindrical reamer.

Currently our patient is 6 months out from first stage and reports improved stability and no pain, despite no ACL present. She is awaiting her school schedule to accommodate the second stage that will be the removal of her puddu plate hardware and autograft hamstring tendon ACL reconstruction (Table 13.3) with suspensory fixation on both sides.

Case 2

Case example number 2 is a 21 y/o female who originally ruptured her ACL at the age of 17 during a non-contact injury while playing high school sports. Her initial reconstruction was performed within 3 months of the injury with autograft hamstring tendons, femoral endobutton fixation and tibial interference screw fixation. The reconstruction failed within 1 year secondary to a reported traumatic event producing an acutely swollen and unstable knee. At the age of 19 y/o she underwent a single-staged revision ACL reconstruction with central 1/3 of the quadriceps tendon with bone from the patella. The tunnels for the revision were made “around the

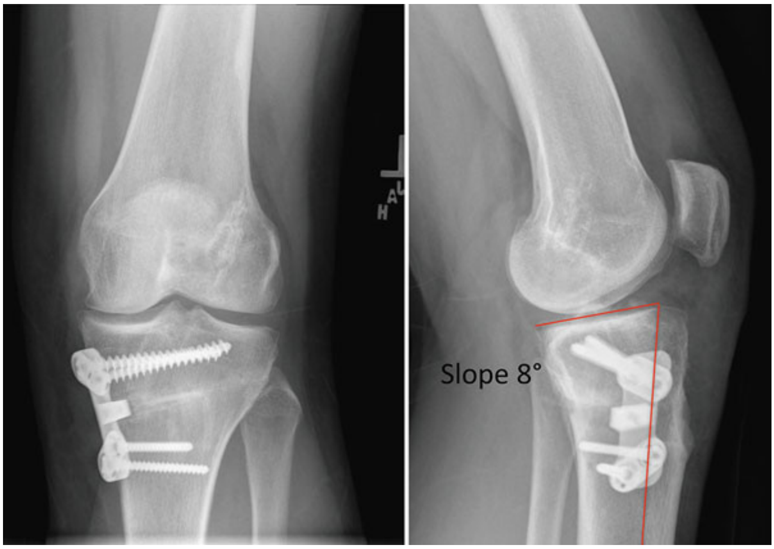

Fig. 13.7 Follow-up radiographs of the left knee after completion of first stage of two-stage ACL reconstruction, note the healed tibia and femoral bone tunnels and reduced posterior tibia slope to a new angle of 8°. Prior to ACL reconstruction as the second stage the Puddu plate is removed and the defect is bone grafted with reamings from the tibia tunnel

Table 13.3 Options for bone graft

Autograft	Allograft/bone graft substitutes
Illiac crest: plugs or free graft	Allograft chips (osteoconductive)
Local bone graft—proximal tibia or distal femur	Allograft demineralized bone matrix, DBx© putty (osteoinductive)
	Allograft bone—dowel plugs from fresh frozen bone: femoral head
	Synthetic bone substitutes: OsFerion© wedges (Arthrex)

prior tunnels" according to the operative note. The patient states the knee has never really been stable since revision surgery and it has limited her from almost any athletic activity. Pain is not a problem unless she has a "shift" in the knee, which occurs approximately once a month. Initial radiographs demonstrate large bone tunnels with significant lysis and bone loss, specifically on the tibia with a "combined" tibia tunnel loss of almost the anterior 1/3 of the tibia plateau (Fig. 13.8). MRI demonstrates stacked interference screws from her two prior surgeries and an attenuated graft that is present but clinically not functional (Fig. 13.9). CT scan was obtained to quantify the amount of bone loss, tibia tunnel measures 24 mm in the anterior–posterior plane and 15 mm in the sagittal plane and represents a substantial bone defect that necessitates a staged procedure for bone grafting (Fig. 13.10).

During stage one of the procedure, it is important to remove all retained hardware that will affect fixation or healing of the new graft. In this case, the bio-composite interference screws were removed. The scar formed on the side and within the bone tunnel is demonstrated in (Fig. 13.11). Note, it is very important to fully debride this tissue back to bleeding bone with shaver, burr, or curette to facilitate healing after bone grafting (Fig. 13.11). On the femoral side, a guide pin is inserted into the tunnel, through the far cortex and used as a guide to ream the tunnel to remove unhealed graft or nonviable bone. Bone tunnels can then be filled with cancellous bone autograft, or as in this case, bone graft substitute can be used (Fig. 13.12). The graft material is impacted into the defects with bone tamps to get compression and complete fill of the tunnel defects. In this case, the large tibia defect required a large amount of graft therefore the synthetic graft was chosen because the quantity is unlimited

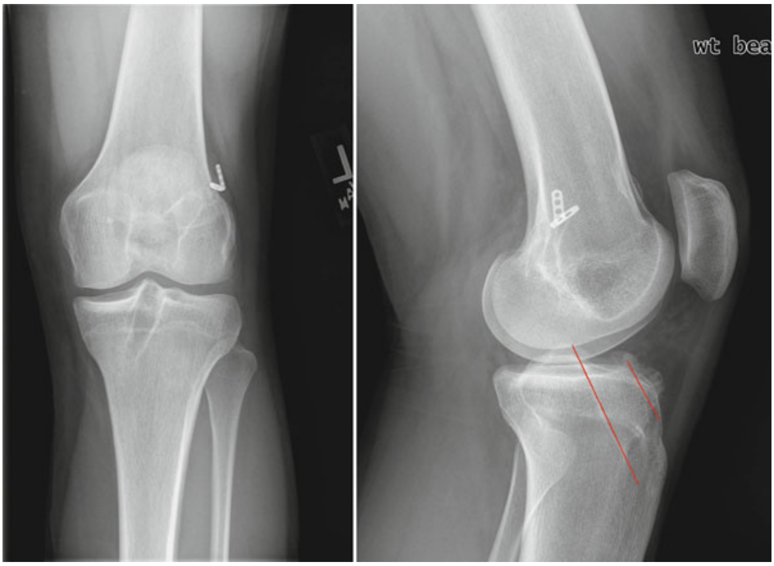

Fig. 13.8 AP and lateral radiographs taken on initial clinic evaluation demonstrating large amount of bone loss particularly on the tibia following revision surgery "around" prior bone tunnel creating a "combined" large >15 mm tibia bone tunnel

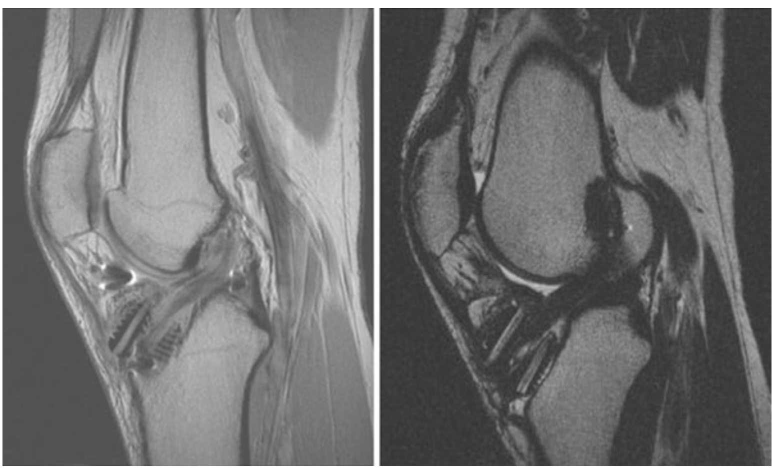

Fig. 13.9 Lateral MRI demonstrating intact graft but attenuated, stacked tibia interference screws from the prior two ACL reconstructions, and no healing or bone formation within the tibia plateau

(Fig. 13.12). Postoperative radiographs are taken serially to monitor bone graft incorporation, with a minimum of 4–6 months for reconstitution of the bone prior to second stage and final revision of the ACL (Fig. 13.13). During the time between the first- and second stages, patients do physical therapy for quadriceps strengthening and knee range of motion. Significant knee instability is usually not reported, but we recommend a brace to prevent recurrent subluxations which can cause meniscal damage.

One benefit of the two-stage technique is that the definitive reconstruction is made much easier and can be performed using primary ACL

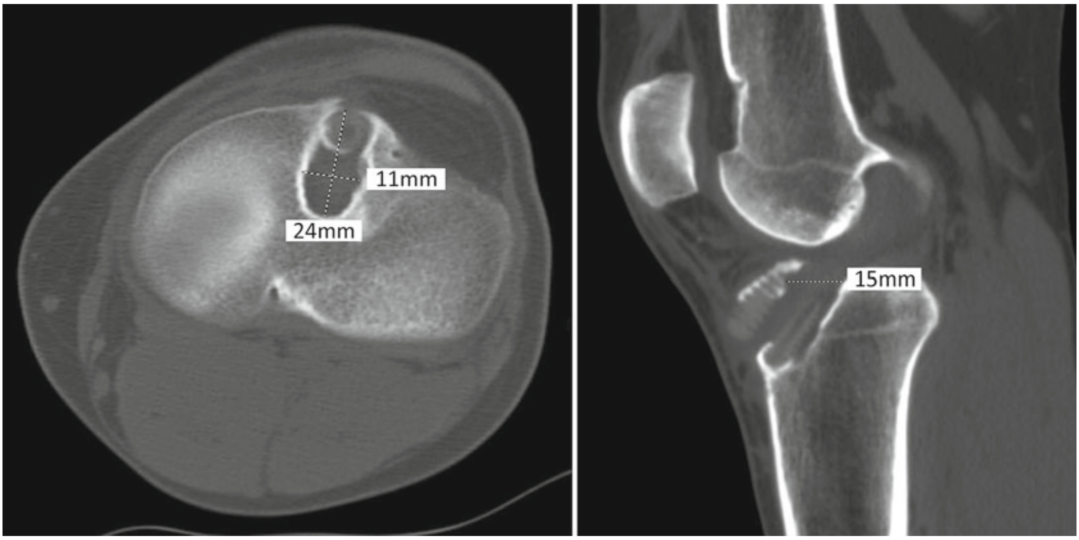

Fig. 13.10 Axial and sagittal CT images demonstrating significant tibia tunnel diameter: 24 mm A-P on axial cut and 15 mm on sagittal cut

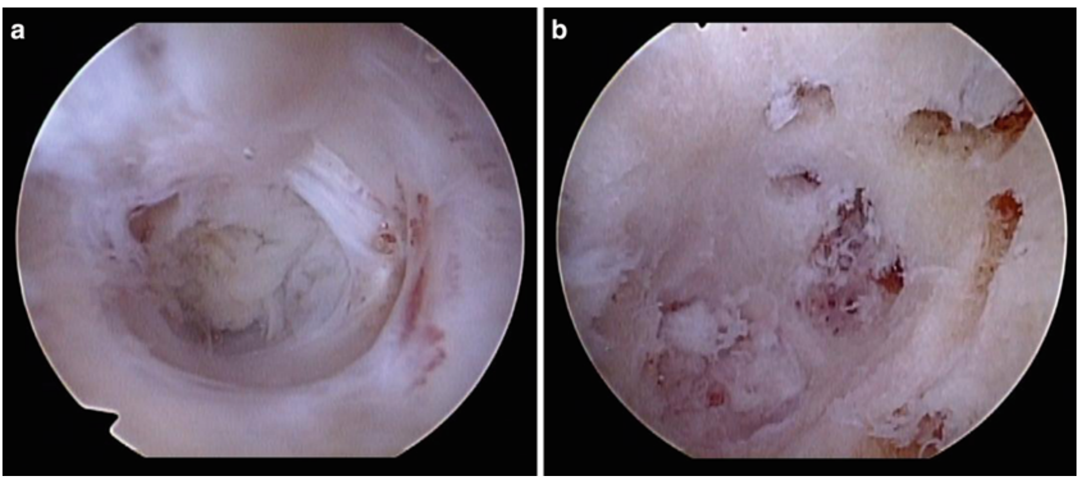

Fig. 13.11 Intra-operative image looking down the tibia tunnel (**a**) before reaming tunnel: note the fibrous tissue and residual graft material. (**b**) After the same tunnel was "over" reamed to prepare the tunnel for bone grafting, creation of bleeding cancellous bone for graft packing and facilitate incorporation. This should be debrided down to bleeding bone to allow maximum healing of the bone graft

reconstruction technique. Femoral and tibia bone stock is reconstituted and allows for healthy bleeding bone for tendon to bone incorporation while facilitating fixation (Fig. 13.14). In this case, an allograft was used simply because of the patient's history of prior autograft hamstring and quadriceps tendon with bone use during primary and revision surgery (Table 13.3). Construct was a quadrupled peroneus longus tendon, quadrupled into a Y-construct with cortical button suspensory fixation on the femur with double bundle tunnels—8 mm each and a single tibia tunnel

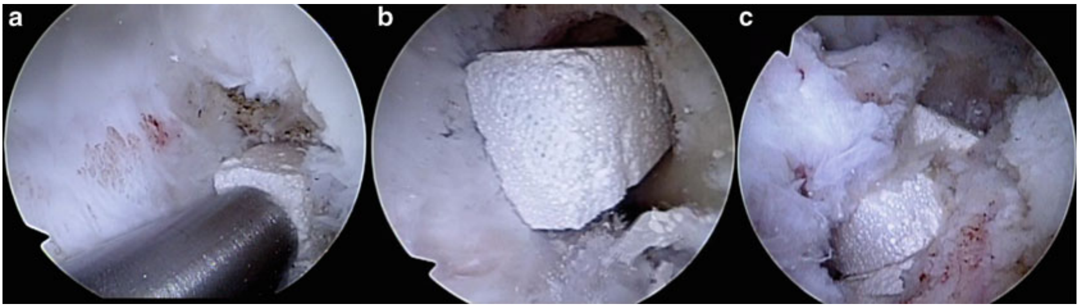

Fig. 13.12 Arthroscopic images taken during bone grafting of femoral tunnel (**a**, **b, c**) with Osferion © wedges (Arthrex, Inc.). The synthetic osteoconductive graft is impacted into the tunnel for complete fill. The size of the tibia defect required multiple wedges for complete fill. Tamp is used to impact graft material to fill tunnel *Note*: Regardless of graft material used to fill the defect, the tunnel debridement down to bleeding bone is essential

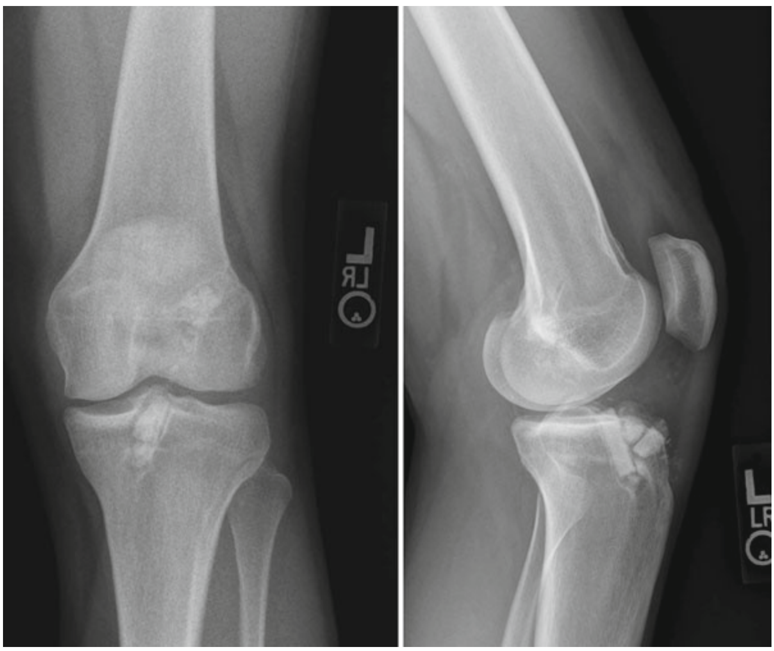

Fig. 13.13 Postoperative radiographs, AP and lateral of bone grafted defects. Complete fill of the tibia defect required multiple Osferion © wedges (Arthrex, Inc.). The wedges are composed of Beta tri-calcium phosphate (β-TCP) and therefore easily visualized on radiographs

12 mm in diameter (Fig. 13.14). Radiographs demonstrate cortical button position and healed bone tunnels in anatomic position (Fig. 13.15). An aggressive postoperative rehabilitation was initiated and the patient remains happy and stable 1 year from stage two.

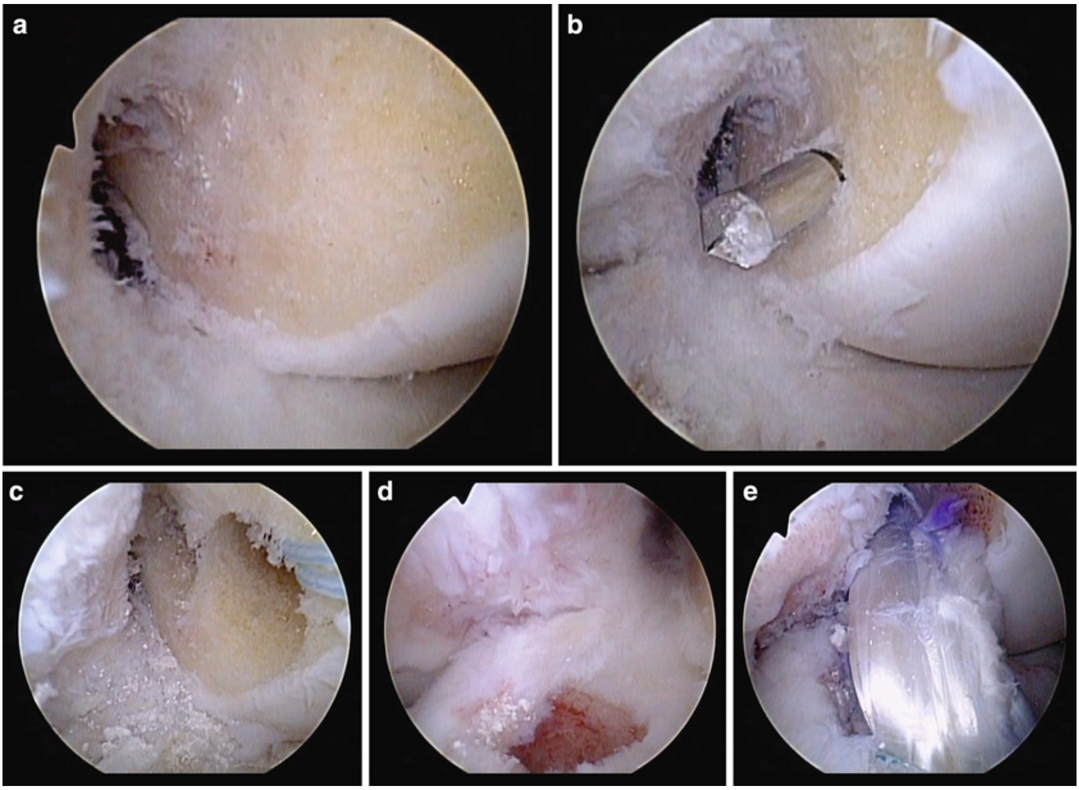

Fig. 13.14 Arthroscopic images of the left knee during staged procedure 6 months after bone grafting during revision ACL reconstruction. (**a**) Femoral footprint demonstrating complete healing and reconstitution of the lateral wall, some residual calcium phosphate crystals are still obvious. (**b**) The first (posterior–lateral) tunnel of femoral double bundle reconstruction being drilled retrograde with FlipCutter® (Arthrex, Inc.). (**c**) Both tunnels on lateral wall of femur. (**d**) Single tibia tunnel with good reconstituted bone stock. (**e**) Final ACL construct, Allograft double bundle peroneus longous tendon in quadrupled into a Y-construct with two femoral tunnels and suspensory fixation

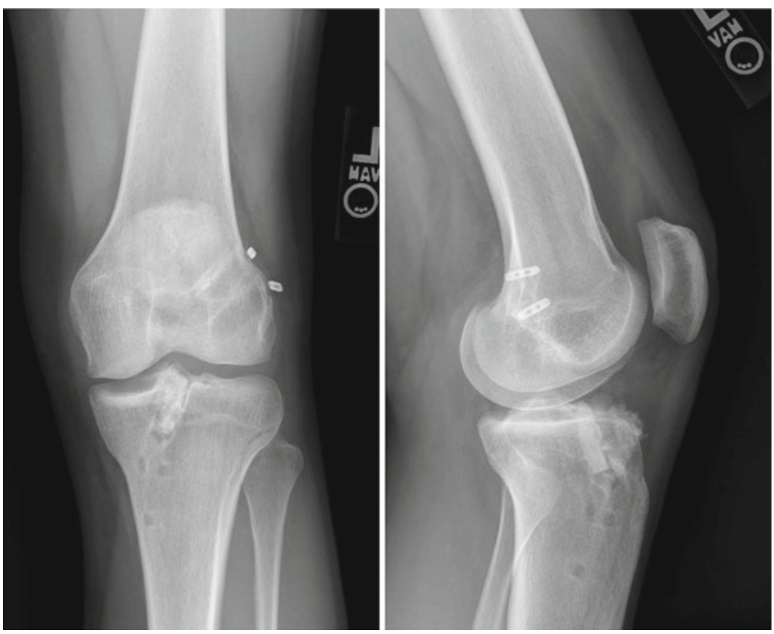

Fig. 13.15 Postoperative radiographs after second stage and final ACL revision. Two cortical button suspensory fixation and aperture interference screw fixation on the tibia

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Revising Failed Double Bundle ACL Reconstruction

14

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Introduction

The anatomic double bundle (DB) anterior cruciate ligament (ACL) reconstruction was developed to more functionally restore the native ACL dimensions, collagen orientation, and insertion sites through the individual reconstruction of a separate anteromedial (AM) and posterolateral (PL) bundle. The fundamental principles involved in this procedure include appreciation of the native ACL anatomy, individualization of surgical technique to each patient's specific anatomy, restoration of the ACL footprint, and recreation of the native ligament functionality by applying appropriate tension to mimic the pre-injury state as closely as possible [1]. Biomechanical studies have clearly demonstrated improved restoration of rotational and translational stability following double bundle ACL reconstruction vs. single bundle (SB) reconstruction [2, 3]. Clinical studies have demonstrated favorable outcomes including objective and subjective restoration of knee stability and return to activity [4–6].

Nevertheless, a subset of patients will continue to complain of instability following ACL reconstruction [7, 8]. When analyzing the failure rates according to the technique van Eck et al. found no statistical difference in failure rates after single (11 %) or double bundle (13 %) ACL reconstruction with allografts in young patients [9]. In a recent study, Suomalainen et al. demonstrated superiority of the DB reconstruction over the SB when comparing failure rates, 4 % and 15 %, respectively, however in this chapter, the definition of failure was based only in magnetic resonance imaging (MRI) findings [10].

Many factors influence the success or failure following surgery including surgical technique, integrity of the secondary ligamentous stabilizers and preoperative knee laxity, status of the articular and meniscal cartilage, graft selection, postoperative rehabilitation, and patient expectations [8]. Double bundle reconstructions have additional factors that need to be considered in the setting of failure and subsequent revision surgery including the presence of multiple tunnels, previously placed surgical hardware, and isolated one bundle vs. two bundles graft ruptures [11]. The goals of revision ACL reconstruction are identical to the goals of primary reconstruction, although a careful evaluation is required to identify contributing causes to graft failure that may require additional surgical consideration or management. This chapter will present our current evaluation and surgical techniques employed to manage the double bundle (DB) ACL reconstruction failure.

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Failures

Primary double bundle ACL reconstruction is subject to the same causes of failure as single bundle reconstruction. The risk of failure for technical reasons is higher due to the presence of multiple tunnels, fixation devices, and graft tensioning. Overconstraint of the knee has been demonstrated to occur with tension imbalance within the anteromedial (AM) and posterolateral (PL) grafts and can lead to flexion contracture or graft elongation postoperatively [12, 13]. Variability in tunnel positioning can also alter the biomechanical function of the knee and may affect the forces within the grafts during knee motion. The most common pattern of graft failure is a midsubstance rupture of both the AM and PL bundles, although isolated rupture of the AM graft with either an intact or an elongated PL graft may also be encountered [11]. Figure 14.1 synthesizes the most important mechanisms of ACL reconstruction failure.

Many factors must be considered while formulating a treatment plan for the management of a failed ACL including the type and etiology of graft failure, patient symptoms and complaints, and timing and possible staging of procedures in the case of surgical revision.

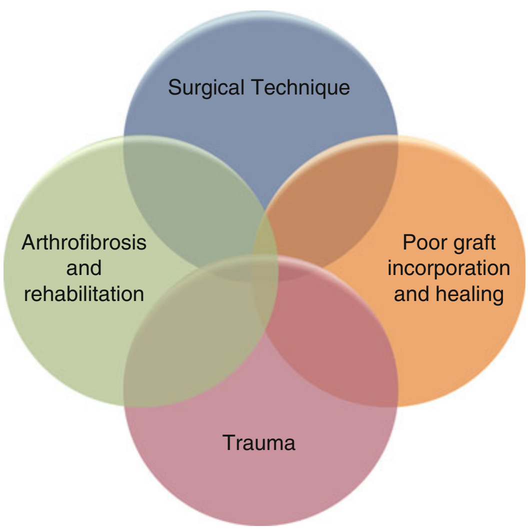

Fig. 14.1 Diagram showing possible causes for anterior cruciate ligament (ACL) failure. An overlapped area represents greater chance of failure

Physical Examination

Specific tests for ACL laxity should be performed. It is noteworthy that in DB reconstruction, an isolated bundle graft failure can occur. Therefore, the Lachman test, anterior drawer test, and pivot shift test results should be jointly analyzed. A positive Lachman and anterior drawer with a negative or a slightly positive pivot shift may indicate an isolated AM bundle tear, while a positive pivot shift with a negative Lachman and anterior drawer test point to an isolated PL bundle tear.

The specific tests for ACL laxity described above address antero-posterior (AP) or rotational laxity, however they are subjective in nature. The KT-1000 (Medmetrics, San Diego, USA) provides an objective measurement in millimeters on the antero-posterior translation. On the other hand, portable and simple methods to reliably quantify the pivot shift phenomenon are still being developed.

Imaging

Radiographs

A complete radiographic series including Merchant view for patellar evaluation, weight-bearing antero-posterior (AP) view in 45° of flexion, lateral radiographs in 45° of knee flexion, and full extension AP radiographs are appropriate in the initial imaging analysis of a reinjured knee. These films allow evaluation of hardware position, degenerative changes, previous deformities, and associated fractures or avulsions. In addition, femoral and tibial tunnel widening, angle, and position can be assessed. Illingworth et al. showed that in AP radiographs a femoral tunnel angle less than 30° is non-anatomic and more than 30° is most probably located in the anatomic position [14] (Fig. 14.2).

In cases of valgus or varus extremity malalignment, a weight-bearing long-cassette radiograph is obtained for objective quantification of the lower limb axes.

Fig. 14.2 Femoral tunnel angles of an anatomic double bundle ACL reconstruction

Magnetic Resonance Imaging

MRI has been used as the gold standard exam to confirm ACL graft tear and identify concomitant intraarticular pathology. In addition to the regular MRI views (sagittal, coronal, and axial), special sequences such as oblique coronal and oblique sagittal, with sections at the same anatomic alignment of the ACL, should be obtained to allow a complete visualization of the ligament [15]. In addition to the diagnosis of graft rupture, MRI also allows for additional data on the previous surgery such as associated injuries, tunnel positioning, and graft orientation. Tibial insertion site size, ACL length, ACL inclination angle, and quadriceps and patellar tendon thickness on sagittal views are routinely obtained to assist in ACL revision technique and graft source decision. These measurements are even more meaningful if the primary injury MRI is available, allowing a direct comparison of the native insertion sizes, estimation of ACL length, and inclination angle (Fig. 14.3). This evaluation provides information on the initial restoration of native ACL anatomy, which is of fundamental importance for the preoperative planning of revision ACL reconstruction.

3D-CT Scan

We routinely utilize a CT scan with three-dimensional reconstruction for evaluation of failed ACL reconstruction to identify previous tunnel placement and bony deficiencies irrespective of prior technique (Fig. 14.4). After a primary DB reconstruction, this exam is even more important as numerous tunnels are present and single-stage or two-stage revision procedures must be meticulously planned.

Indications and Contraindications

Overall, the indications and contraindications for a revision after double bundle ACL reconstruction follow the same principles as the primary surgery. Patients with recurrent instability after double bundle ACL reconstruction are better treated with revision reconstruction. Patients who participate in cutting, jumping, and pivoting sports are also appropriate candidates for surgical treatment.

On the other hand, asymptomatic, low demand, or elderly patients should have nonoperative treatment. Similarly, patients that have had multiple ACL reconstruction failures must be analyzed carefully before indicating another surgery. Individual anatomic, biomechanical, and behavioral factors that may have contributed to the previous failures must be addressed to increase the likelihood of a successful outcome.

Preoperative Planning

In order to develop an adequate preoperative plan for a revision ACL reconstruction, the primary cause of failure should be known. History, physical examination, and imaging should provide the necessary elements. The first decision to be made is if the revision surgery is going to be performed in only one or two stages.

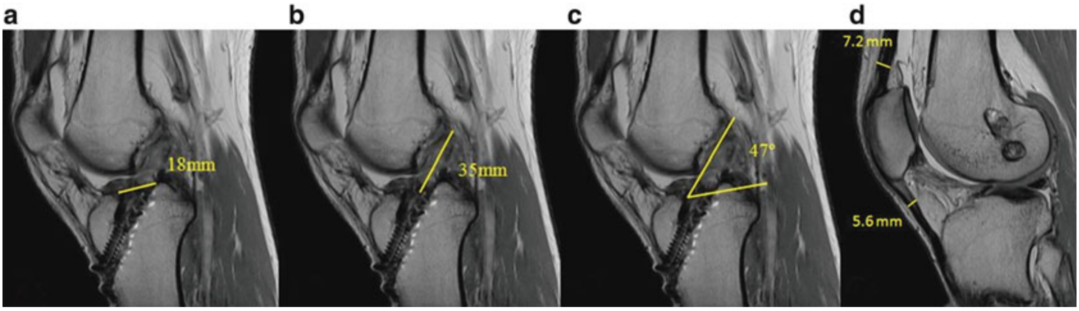

Fig. 14.3 Magnetic resonance imaging (MRI) preoperative measurements

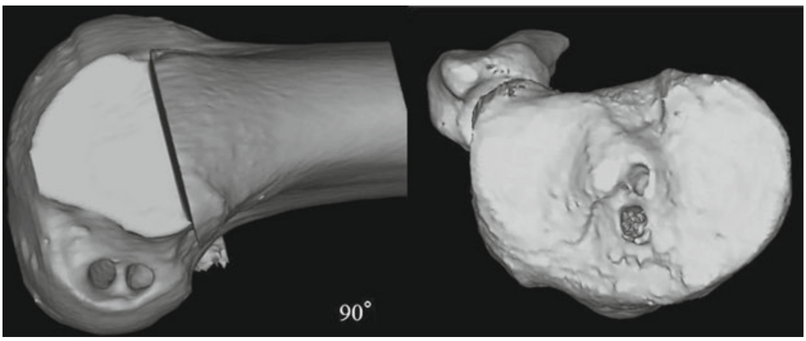

Fig. 14.4 Three-dimensional reconstructed CT scan of an anatomic double bundle ACL reconstruction

A single-staged procedure is preferred when the previous tunnels are anatomically placed with no evidence of widening. In this case, tunnels may be reused and a DB revision is performed (Fig. 14.5). Another option for previous anatomically placed tunnels is converting the two tunnels' entrances into one and performing SB revision ACL reconstruction by creating a single tunnel between the two. This is a particularly good option when one of the tunnels has evidence of widening with the other one remaining well preserved (Fig. 14.6).

For a previous non-anatomic primary DB reconstruction there are several alternatives to perform a single-staged surgical intervention.

1. Non-anatomic placement of both the tibial and femoral tunnels: A complete non-anatomic DB is rare. However, in this scenario an anatomic SB revision procedure is our preferred technique. A DB reconstruction, even if possible, may increase the risk of condylar fracture due to the presence of multiple tunnels; although, a safe DB reconstruction can still be performed with the AM bundle placed in the over-the-top position (Fig. 14.7). In the tibial side, the PL and AM are usually anatomic or very close to the anatomic position and can be reused. If a SB procedure is planned, the closest tunnel to the tibial anatomic position should be prepared.
2. If one tunnel is anatomically placed and the other is completely non-anatomic and:
   (a) The anatomic tunnel is placed in the central portion of the insertion site: This tunnel may be prepared and reused for a SB revision reconstruction (Fig. 14.8). The tunnel edges may need to be freshened or dilated to allow for graft passage. This preserves condylar bone stock and simplifies the revision procedure.

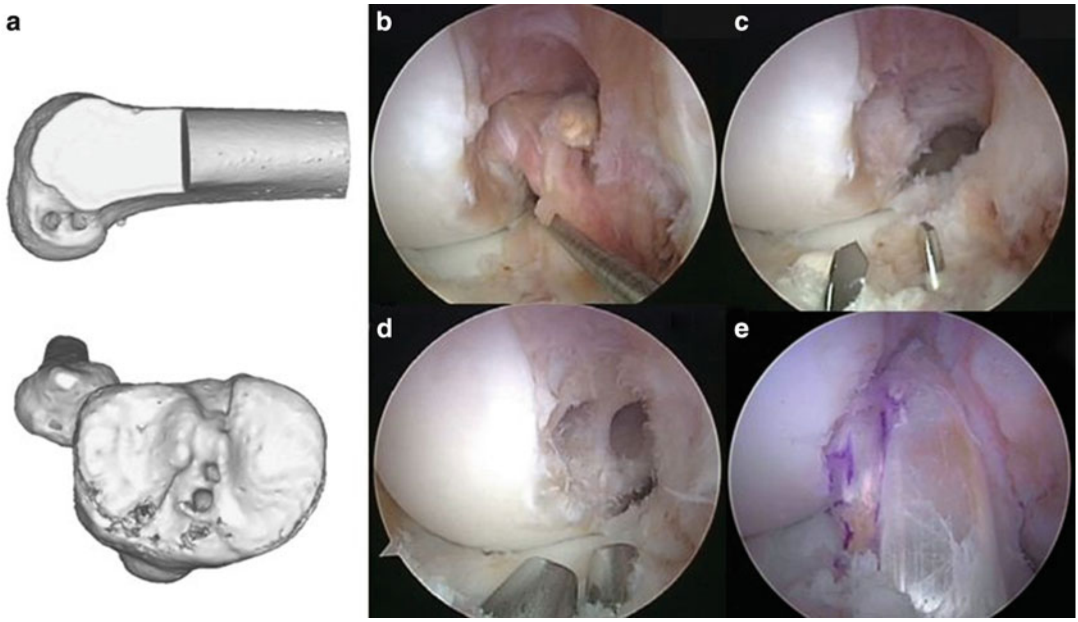

Fig. 14.5 Anatomic double bundle revision surgery after a primary anatomic ACL double bundle reconstruction. (**a**) 3D-CT scan showing double bundle anatomic placement. (**b**) Central portal visualization of the injured graft. (**c**) AM and PL tibial tunnel drilling. (**d**) All tunnels (two femoral and two tibial) prepared for graft passage. (**e**) Final aspect

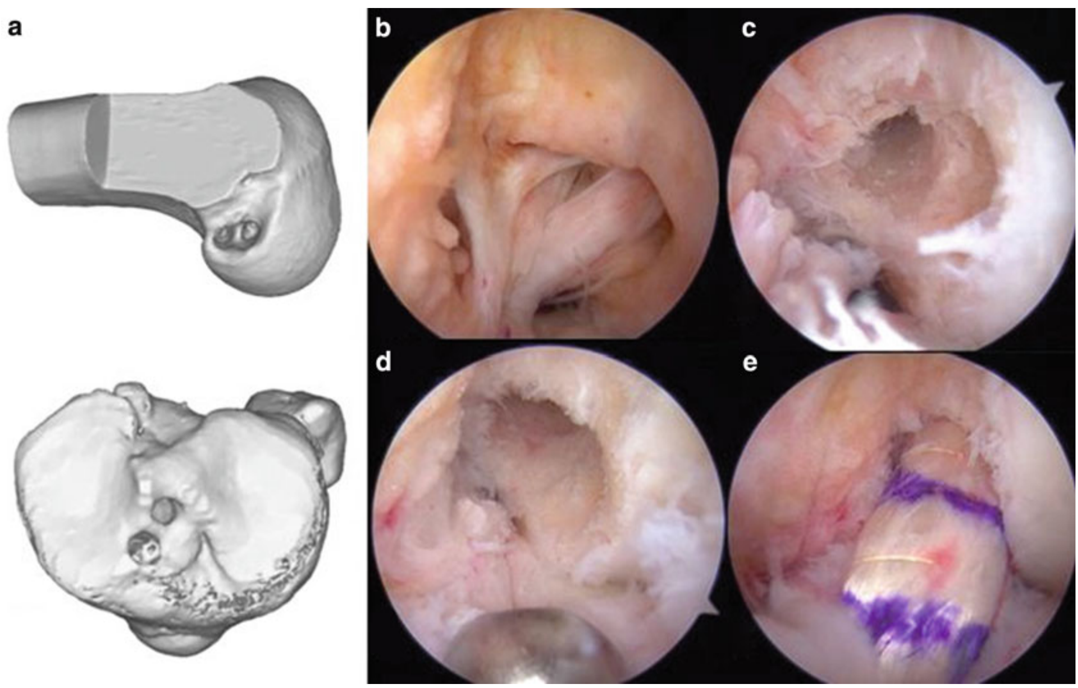

Fig. 14.6 Anatomic single bundle revision surgery after a primary anatomic ACL double bundle reconstruction. Both tunnels in each insertion site were converted into one. (**a**) 3D-CT scan showing double bundle anatomic placement. (**b**) Central portal visualization of the injured graft. (**c**) Femoral AM and PL tunnels separated. (**d**) AM and PL femoral tunnels converted into one tunnel. (**e**) Final aspect

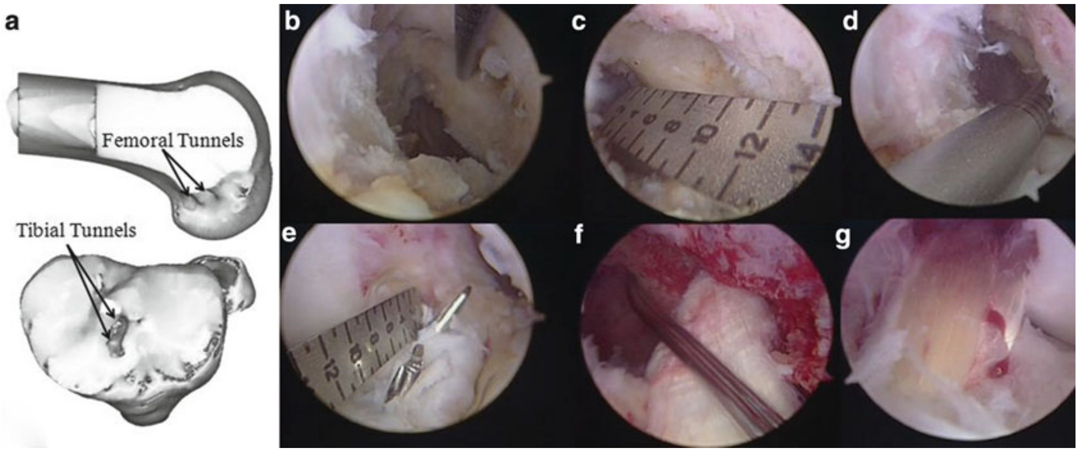

Fig. 14.7 Double bundle revision surgery after a non-anatomic primary double bundle ACL reconstruction. (**a**) 3D-CT scan showing femoral non-anatomic tunnels and anatomic tibial tunnels. (**b**) Old femoral tunnel probing. (**c**) Femoral insertion site measurement. (**d**) New PL femoral tunnel drilling. (**e**) Tibial tunnels drilling and measurement to confirm necessary space between them. (**f**) Femoral PL graft and "over-the-top" AM graft passage preparation. (**g**) Both AM and PL grafts final aspect

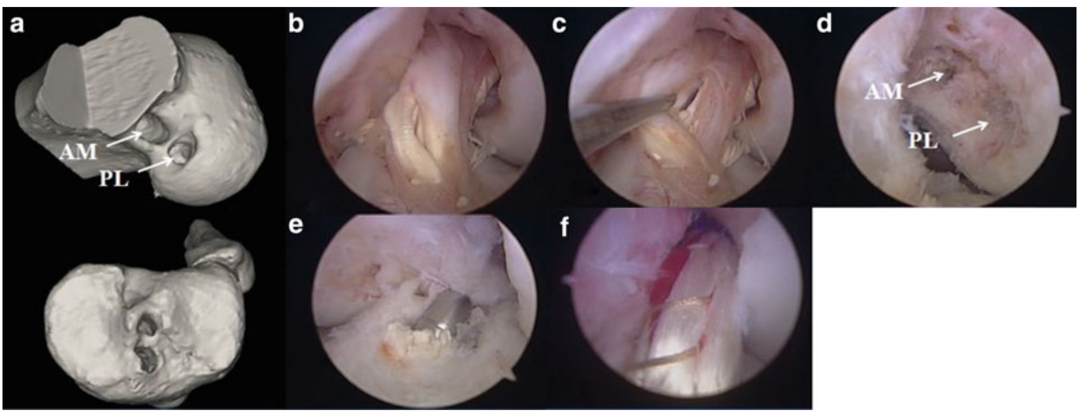

Fig. 14.8 ACL single bundle revision surgery after a non-anatomic primary double bundle ACL reconstruction. (**a**) 3D-CT scan showing PL tunnel within the ACL insertion site and a high AM tunnel in the femur. Tibial tunnels adequately positioned. (**b**, **c**) Central portal arthroscopic view of the stretched grafts. (**d**) Lateral intercondylar wall showing the aperture of both AM and PL tunnels. (**e**) Tibial tunnel dilation. (**f**) Final aspect

(b) The anatomic tunnel is placed in either the PL or AM position (Fig. 14.9): In this case, either a DB or a SB revision may be performed. If a DB technique is chosen, the anatomic tunnel should be preserved and the missing tunnel should be freshly drilled and prepared. If a SB technique is planned, the anatomic tunnel may be eccentrically dilated towards the central position of the insertion site and converted into a standard anatomic single tunnel.

3. When one or both tunnels partially occupy the anatomic insertion site but are not appropriately placed to allow a single-stage revision reconstruction, a two-staged revision should be performed. In this situation, attempting to create a new tunnel in the anatomic position will increase the risk of tunnel convergence, or osseous deficiency and possible condylar fracture.

Finally, if the lateral wall of the femoral intercondylar notch is too damaged to permit the use of a previously placed tunnel or creation of a new

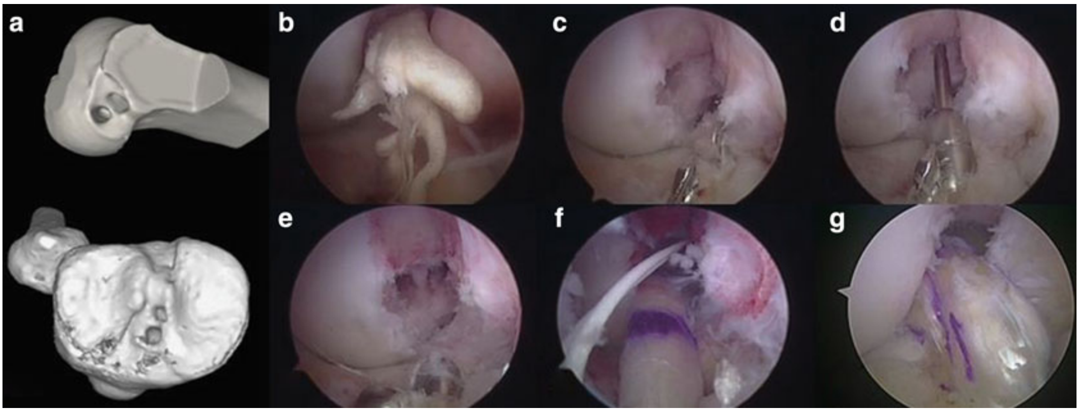

Fig. 14.9 ACL double bundle revision surgery after a non-anatomic primary double bundle ACL reconstruction. (**a**) 3D-CT scan showing an anatomic femoral PL placement and non-anatomic AM femoral tunnel. (**b**) Central portal arthroscopic view of the injured grafts. (**c**) Tibial tunnel drilling. (**d**) Preparation for anatomic femoral AM tunnel drilling through tibial PL tunnel. (**e**) All tunnels ready for graft passage. (**f**) PL tunnel graft and suture through AM tunnels for graft passage. (**g**) Final aspect

tunnel, an "over-the-top" technique is indicated. A similar technique may also be employed during a double bundle revision technique with the AM graft placed in an over-the-top fashion and the PL graft placed through a standard femoral tunnel (Fig. 14.7).

Graft Choices

Graft choice should be matched to the patient's needs, and ideally allow restoration of 80–90 % of the native insertion site of the ACL. Options are based on the availability of grafts, preoperative MRI measurements, and the amount of graft needed for the revision surgery. There are three options for grafts, synthetic, autograft, and allograft [16]. The authors' first choice is autograft, but if not available allografts may be utilized.

Autografts such as hamstring, quadriceps–patella, iliotibial band, and BTB grafts are often used in both primary and revision surgery. The use of one autograft in primary surgery precludes its use in revision surgery. Most primary ACL reconstruction utilizes hamstring autograft, BTB autograft, or one of the various allograft options. Quadriceps tendon is often a viable option in revision ACL [17]. The size of the tendon is usually sufficient to provide a stout graft and the patellar bone plug can allow for significant tunnel fill. Other autografts can be used, if they were not harvested in the primary reconstruction. For example, hamstrings may be used if BTB was used in the primary reconstruction and vice versa. The contralateral knee can also be an autograft source in revision reconstruction.

Allograft tissue can also be used in revision surgery. Calcaneus-Achilles, BTB, soft tissue allografts (iliotibial band, tibialis anterior or posterior, hamstrings, or peroneus longus) have all been used for revision ACL reconstruction. They allow for shorter operative times, less morbidity, and larger graft size. Allograft is especially helpful in revision cases where larger allograft bone plugs can fill larger tunnel diameters. The disadvantage of allograft tissue remains immunologic reaction, risk of disease transmission, and delayed incorporation [17–19].

General Considerations and Portal Placement

A three-portal technique is our preference for arthroscopic visualization [20]. For a single-stage reconstruction, a diagnostic arthroscopy is initially performed through the high anterolateral portal. The anteromedial portal (central portal) is used to view the femoral insertion sites of the

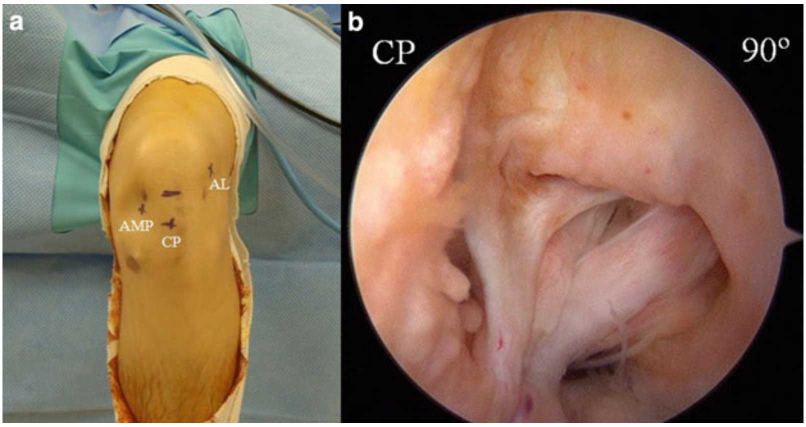

Fig. 14.10 (**a**) Three-portal technique. (**b**) Central portal arthroscopic view allowing for a straightforward evaluation of the lateral wall and graft remnants

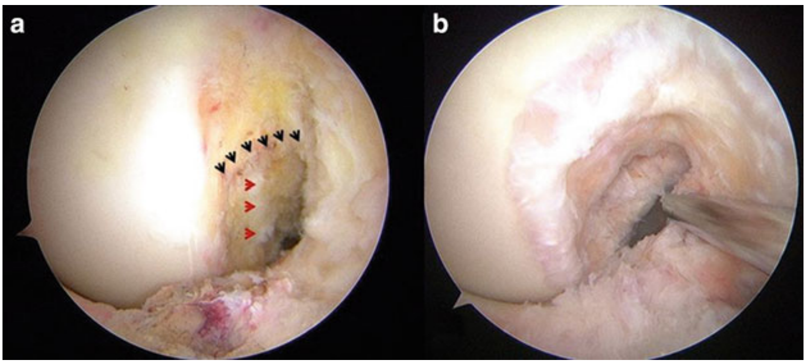

Fig. 14.11 Central portal view of the lateral wall of a primary injured knee (**a**) and a reinjured knee after a double bundle ACL reconstruction (**b**). (**a**) Intercondylar ridge in *black* and bifurcate ridge in *red*. (**b**) Ridges no longer visible after primary double bundle reconstruction

anteromedial and posterolateral bundles (Fig. 14.10) and the accessory medial portal is mainly used as a working portal. The standard high anterolateral portal is used to visualize the tibial insertion sites. First, the injury pattern of the torn graft is identified. The anatomic insertion sites of the tibia are isolated and marked using osseous landmarks as ligament remnants of the two bundles may be obscured by the previous reconstruction. The femoral insertion sites are also identified and marked. With the knee in 90° of flexion, the femoral insertion sites of the AM and PL bundles are horizontally aligned. The lateral intercondylar ridge lies at the superior border of the femoral insertion site of the ACL [21]. The lateral bifurcate ridge separates the anteromedial and posterolateral insertion sites [21]. The marked insertion sites are measured with regard to length and width. If the combined lengths of the insertion sites of the anteromedial and posterolateral bundles are between 14 and 18 mm either SB or DB revision reconstruction can be performed. If greater than 18 mm, we prefer anatomic double bundle revision reconstruction if otherwise possible. If the combined lengths of the insertion sites of the anteromedial and posterolateral bundles are <14 mm, then anatomic single bundle ACL reconstruction is indicated.

Many times in revision cases bony landmarks are no longer available for visualization (Fig. 14.11). In such cases, the lower 1/3 of the lateral wall of the intercondylar notch can be roughly used as a reference for anatomical placement of the femoral tunnel(s) [1]. Fluoroscopic assistance using the quadrant method described by Bernard and Hertel may be also helpful when bony landmarks are not available [22].

Operative Techniques

Double bundle ACL reconstruction can be performed with several different techniques: two tunnels in the femoral and two tunnels in the tibial side, which is the most common procedure; two tunnels in the tibial side and one tunnel in the femoral side or vice versa, for example, when the DB is performed with quadriceps tendon with a bone block. Therefore, the techniques described below should fit any of the possible primary DB reconstruction procedures.

Anatomic Primary Double Bundle Reconstruction

Both the femoral and tibial side must be assessed for placement of previous screws in both the AM and PL tunnels. If hardware is present, it should be removed. A guidepin is placed in the anteromedial tunnel and reamed to the appropriate size (Fig. 14.12). From the accessory medial portal, a guidepin is placed in the posterolateral tunnel and reamed to the appropriate size. On the tibial side, tip-to-tip drill guides are used to redrill both the AM and PL tunnels. Once positions are confirmed, passing sutures are placed and the grafts are passed into their respective tunnels. The PL graft is passed first, then the graft for the AM tunnel (Fig. 14.5).

Non-anatomic Primary Double Bundle Reconstruction

It is often possible to reuse one of the previous tunnels for either the AM or PL grafts on the femoral or tibial side. One must also remember to measure the sizes of the tibial and femoral footprints in these instances to make sure that the footprints are greater than 14 mm and can accommodate a double bundle revision reconstruction. If not, single bundle reconstruction should be performed (Fig. 14.13).

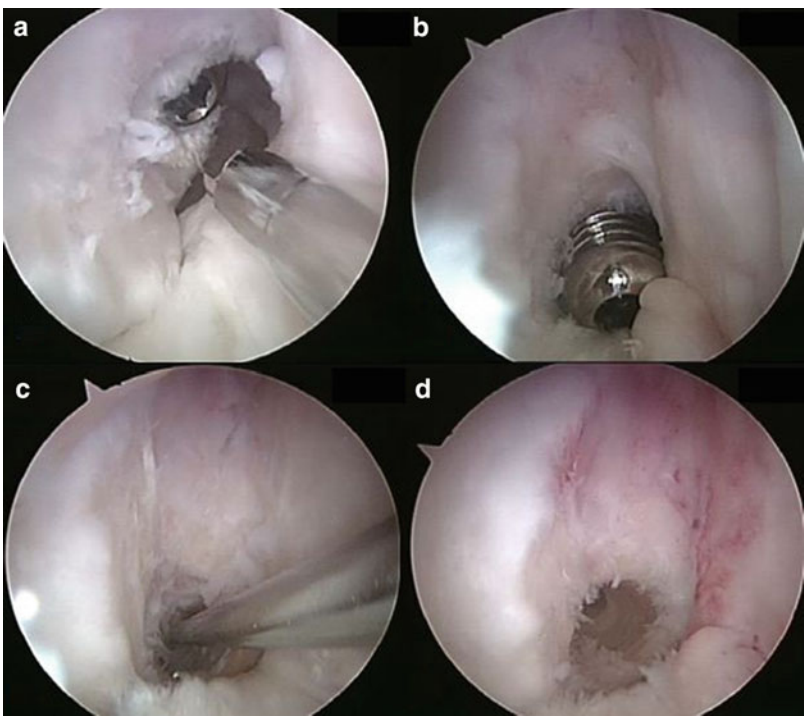

Fig. 14.12 Surgical assessment for a reinjured knee. (**a**, **b**) Interference screw removal. (**c**, **d**) Tunnel preparation for revision surgery

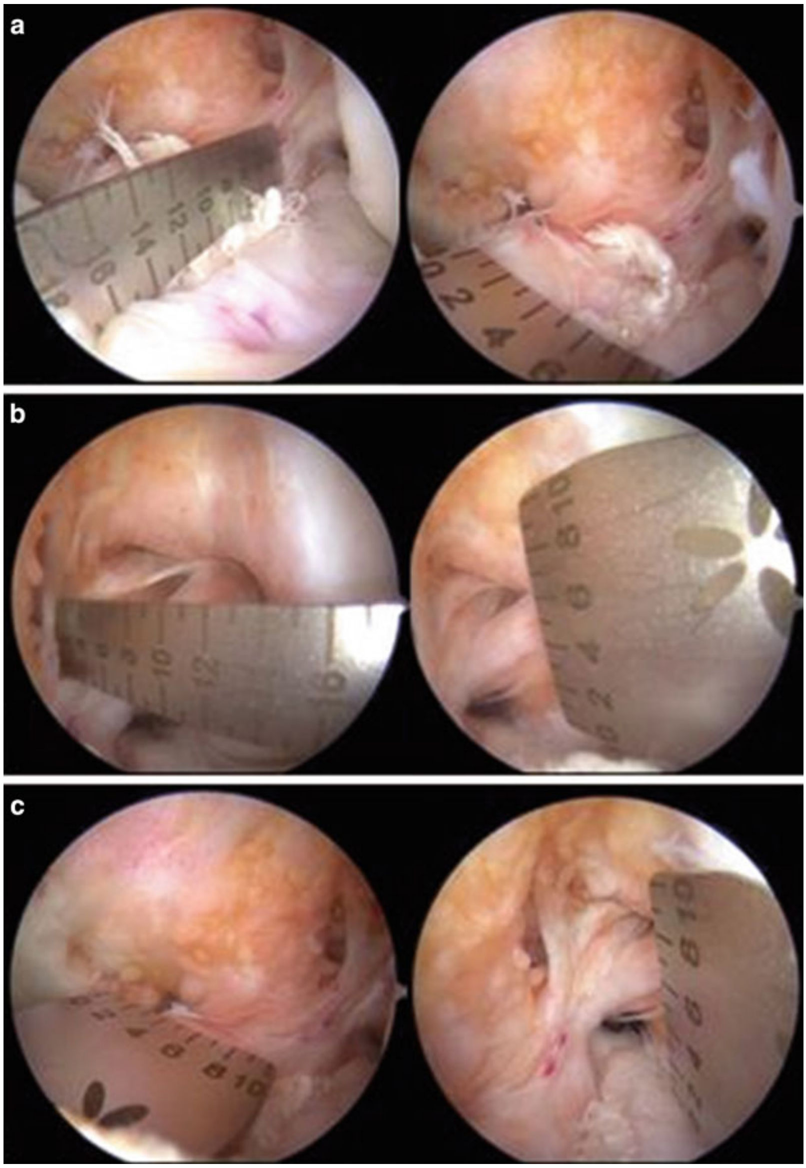

Fig. 14.13 Intra-operative measurements. (**a**) Tibial insertion site measurements. (**b**) Femoral insertion site measurements. (**c**) Notch width and height measurements

If the previous tunnels on the tibial side show an anatomically placed PL tunnel, but non-anatomic AM tunnel, a new anteromedial tunnel is created. If there is not enough room to create a new AM tunnel, the two tunnels can be coalesced to a diameter of 10–11 mm to contain both the anteromedial and posterolateral grafts. This also holds true for a non-anatomically placed PL tunnel, but anatomically placed AM tunnel. If enough room is present to create a new PL tunnel, a new tunnel is created. However, if there is insufficient room to create a new PL tunnel, the tunnels can be coalesced to a diameter of 10–11 mm to contain both the anteromedial and posterolateral grafts. If there is significant osteolysis, a two-staged procedure with placement of bone graft should be considered and two new tunnels drilled based on previously described anatomic landmarks at a later date.

On the femoral side, one of the tunnels can often be employed. If the PL tunnel is non-anatomic and the AM tunnel is anatomic, there is often enough room to drill a new PL tunnel. If the AM tunnel is non-anatomic and the PL tunnel is anatomic, then one can either place a new AM tunnel in its anatomic position or use the over-the-top position if there are blockages from hardware or thin bone bridges are present (Fig. 14.7). It is our experience that it is rare to find both tunnels to be non-anatomic, but close to the native insertion site. If this is the case, a two-staged procedure can be performed with bone graft and placement of two new tunnels at a later date. If both the tunnels are far from the native insertion site, a single-staged single bundle technique is our preference for the revision reconstruction to reduce the risk of condylar fracture.

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15 The Role of Lateral Extra-articular Augmentation in Revision ACL Reconstruction

Robert A. Magnussen, Sebastien Lustig, Matthias Jacobi, Ahmed Elguindy, and Philippe Neyret

Introduction

The anterior cruciate ligament (ACL) is the most frequently reconstructed ligament in the knee. While current reconstructive and rehabilitation techniques generally succeed in restoring sufficient knee stability for a return to most desired activities, treatment failures continue to be a problem. The most frequent cause of such failures is persistent or recurrent knee instability [1–3]. Identifying and addressing the reasons for failure of the primary ACL reconstruction is the key to successful revision ACL reconstruction [1, 4, 5]. While technical errors certainly contribute to a significant percentage of failures of primary ACL reconstruction [2–4], failures are often seen in the absence of obvious technical mistakes [6]. These failures are frequently associated with a traumatic reinjury and can be quite frustrating to patients as well as surgeons. Such patients may benefit from lateral extra-articular augmentation in association with revision ACL reconstruction.

The goal of this chapter is to explore the role of lateral extra-articular augmentation in improving outcome of revision ACL reconstruction. We will address the rationale, indications, technique, and outcomes of this procedure.

Rationale

The ACL is the primary restraint to anterior tibial translation, but also plays a key role in controlling internal tibial rotation relative to the femur. Rupture of the ACL thus results in increased anterior tibial translation as well as anterolateral rotatory instability during running and cutting activities [7]. Recent years have seen an increased emphasis on the importance of controlling not just anterior tibial translation, but also rotation through the placement of more anatomical ACL grafts and the emergence of double-bundle techniques [8–12].

Augmentation of an intra-articular ACL reconstruction with a lateral extra-articular

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reconstruction is an alternative method of restoring rotational stability in these patients [13–15]. Such an approach has several inherent advantages. Primarily, the extra-articular position of the graft provides it a longer lever arm than intra-articular grafts have, improving its ability to provide rotational control. Further, the addition of a lateral extra-articular graft has been shown to decrease forces on intra-articular reconstructions [15, 16].

Both characteristics of lateral extra-articular augmentation (improved rotational control and protection of the intra-articular graft) are particularly desirable in cases of revision ACL reconstruction. It has long been noted that objective control of knee laxity is worse in revision cases than primary ACL reconstructions [1, 17, 18], especially in cases with associated meniscal loss. Control of laxity in revision cases may also suffer due to small compromises in tunnel position due to previous tunnel location and bone loss. In such situations, lateral augmentation may help improve rotational control. A large multicenter study has demonstrated improved rotational control in revision cases when lateral extra-articular augmentation is utilized [19]. In cases in which the failure of the primary reconstruction is related to a traumatic injury, the capacity of the extra-articular augmentation to diminish the load borne by the revised intra-articular graft may diminish the risk of further traumatic graft ruptures.

Indications

We have identified several situations in which lateral extra-articular augmentation is a useful adjunct to revision intra-articular ACL reconstruction. The most common situation involves patients with an explosive pivot-shift characterized by significantly increased anterior tibial translation in the lateral compartment that may be poorly controlled by an intra-articular graft alone [14]. In our experience, augmentation in these patients leads to decreased subjective instability postoperatively. We also consider extra-articular augmentation in patients in whom a return to collision sports such as rugby or American football following ACL reconstruction is anticipated. As noted above, the additional constraint provided by augmentation may protect the intra-articular ACL graft when it is exposed to excessive loads during these activities [15, 16]. These situations are both relatively common among patients undergoing revision ACL reconstruction.

An additional situation unique to revision surgery in which lateral augmentation may be useful is revision of a torn graft that was only slightly malpositioned, particularly on the femoral side. This situation, which we have termed as type II femoral tunnel [20], can be difficult to address with a revision reconstruction because the ideal tunnel position overlaps the previous tunnel. In such a case (particularly when the malposition is slightly vertical), reconstruction using existing tunnels along with lateral extra-articular augmentation may improve rotational control and help avoid a two-stage procedure (with bone grafting of the prior tunnel) that may be necessary to alter the position of the intra-articular graft.

Another frequently encountered situation involves the presence of residual laxity following an ACL reconstruction without a clear reinjury. These patients may in fact have intact intra-articular grafts that fail to completely restore stability. We find that our patients with residual anterior laxity following ACL reconstruction (demonstrated by an increased Lachman without a grossly positive pivot-shift test) are much less symptomatic and less likely to undergo revision than those suffering from residual anterolateral rotatory laxity (demonstrated by a large pivot-shift). Those displaying residual rotatory laxity with an intact vertical graft may see improvement with revision to a more anatomically placed graft; however, those displaying rotational laxity in spite of the presence of an intact, anatomically positioned graft may benefit from a lateral extra-articular reconstruction to supplement their intact intra-articular graft.

The surgeon must be aware of several situations in which lateral extra-articular augmentation is contraindicated. Primary among these are patients with ACL deficiency and an associated posterolateral rotatory instability due to a posterolateral corner injury. Lateral extra-articular augmentation in such patients may actually fix the tibia in a posterolaterally subluxated position. Even following reconstruction of the posterolateral knee structures, we do not recommend lateral extra-articular augmentation due to this risk. The procedure also offers little advantage in patients in whom the primary laxity is in the anteroposterior direction. Laxity in this direction is most efficiently controlled with an intra-articular graft. Lateral extra-articular augmentation using the technique described below is also contraindicated in skeletally immature patients due to the high risk of injury to the distal femoral physis [21]. In such patients a physeal-sparing technique can be used [10].

One must also bear in mind that throughout this chapter we are discussing lateral extra-articular *augmentation*. An isolated extra-articular ACL reconstruction is generally not sufficient to control the multidirectional laxity caused by ACL deficiency and we do not recommend it [22]. The exception to this rule is the situation described above in which a patient exhibits persistent rotational knee laxity in spite of the presence of an intact, appropriately positioned intra-articular graft. In such carefully selected cases, an isolated lateral extra-articular reconstruction can work in concert with the existing intra-articular graft to provide knee stability while minimizing trauma to the joint by avoiding additional intra-articular procedures.

Technique

Examination under anesthesia should precede all ACL reconstructions and is especially important in cases of revision surgery. With the patient relaxed, the surgeon can gain valuable insight into the degree of rotatory instability that is present in the patient and confirm the need for lateral extra-articular augmentation.

Our preferred technique for intra-articular ACL reconstruction with lateral extra-articular augmentation utilizes both a BTB and gracilis autograft [23]. Modification of the technique may be required in cases of revision surgery due to prior graft harvest. One could consider the use of allograft tissue or graft harvest from the contralateral knee depending on patient and surgeon preference and allograft availability. The patellar tendon graft includes a patellar bone block shaped to approximately 9 mm in width and 20 mm in length, the central 10 mm of the patellar tendon, and a semi-trapezoidal tibial bone block to facilitate press-fitting into the femur. The tibial block is cut to approximately 10 mm in width at its superior border and over the first 10–15 mm of length. It should then flare out to 12–13 mm in width distally. The total length of the block should be about 25 mm. After determining the shape of the tibial bone block but prior to harvest, a 3.2 mm drill hole is created in the center of the bone block and then enlarged to 4.5 mm by over-drilling. Graft harvest is then completed in the surgeon's preferred manner. The gracilis graft (at least 18 cm in length) is then harvested using standard techniques (or allograft is utilized).

Both grafts are carefully transferred to the back table and prepared. The gracilis is stripped of all muscle tissue and whip-stitched on both ends with number 2 FiberWire. The patellar tendon graft is then carefully shaped so the patellar bone block easily passes through a 9 mm graft sizer. The semi-trapezoidal shape of the tibial bone block is maintained and trimmed such that the first 10–15 mm easily passes through a 10 mm graft sizer and the distal flare is left to facilitate the press-fit fixation technique. The gracilis graft is then passed through the hole in the tibial bone block, completing the graft (Fig. 15.1).

While the graft is being prepared, preparation of the knee continues. Prior to arthroscopy, an incision is created on the anterolateral knee extending from just proximal to the lateral epicondyle to the level of Gerdy's tubercle (GT). One then divides the iliotibial band (ITB) in line with its fibers from the level of Gerdy's tubercle proximally to the end of the incision, taking care not to damage the underlying lateral collateral ligament (LCL) (Fig. 15.2). The LCL is identified by palpation with the knee in Fig. 15.4 position. Soft tissue is cleared to provide good visualization of the ligament, but dissection under the ligament is avoided prior to arthroscopy to prevent extravasation of arthroscopic fluid.

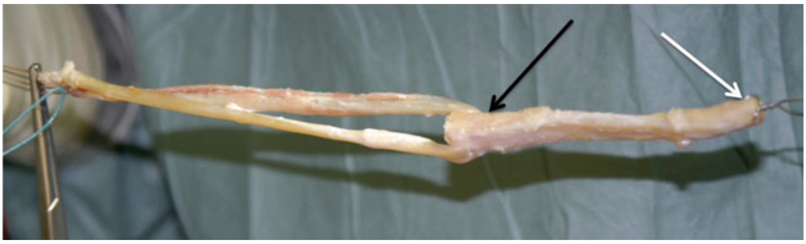

Fig. 15.1 Completed graft for intra-articular anterior cruciate ligament (ACL) reconstruction with lateral extra-articular augmentation. A gracilis autograft has been passed through a 4.5 mm hole (*black arrow*) drilled in the semi-trapezoidal tibial bone block of a patellar tendon autograft. The smaller patellar bone block has been shaped to easily fit in a 9 mm tibial tunnel (*white arrow*)

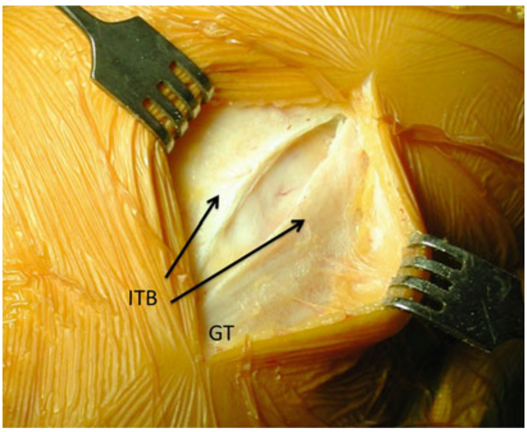

Fig. 15.2 An anterolateral incision extending proximal from Gerdy's tubercle (GT) has been carried down through the iliotibial band (ITB)

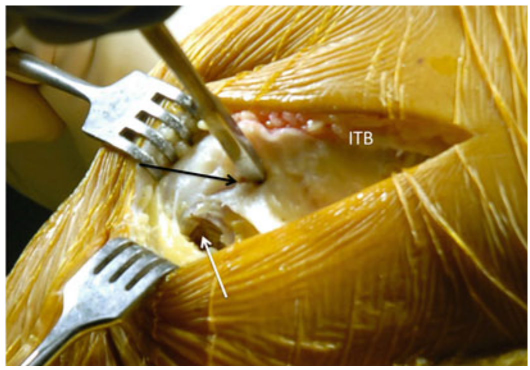

Fig. 15.3 View through the anterolateral incision and divided ITB. The bone tunnel through Gerdy's tubercle (GT) has been created inferolaterally with an awl (*white arrow*) after elevating some of the origin of the tibialis anterior. The superomedial end of the bone tunnel is being created with an awl (*black arrow*)

Gerdy's tubercle is then identified in the distal portion of the incision and a small amount of the origin of the tibialis anterior is elevated to improve visualization. A bone tunnel from superomedial to inferolateral is created with an awl and dilated sufficiently to allow passage of a doubled gracilis graft (Fig. 15.3).

At this point the arthroscope is placed into the knee and notch preparation proceeds as with an isolated intra-articular reconstruction. Tunnel placement may be complicated in revision cases. Decisions must be made regarding tunnel reuse vs. the creation of new tunnels. The femoral tunnel is generally drilled to 10 mm and the tibial tunnel to 9 mm. If significant bone loss is present from a prior femoral tunnel, the tibial bone block size can be increased at harvest to fill this defect and still obtain a good press fit.

The graft is passed in an antegrade direction (from femur to tibia) and the patellar bone block is directed into the tibial tunnel. Femoral fixation is achieved with a press-fit technique, simultaneously fixing the lateral extra-articular graft into the femur (Fig. 15.4). Tibial fixation of the intra-articular graft is then performed with an interference screw.

The two free ends of the gracilis graft are then passed toward the tibia for fixation into Gerdy's tubercle. The more posterior limb is passed under the LCL, superficial to the popliteus tendon, and through the tunnel in Gerdy's tubercle in a superomedial to inferolateral direction. The other limb is passed under the LCL, superficial to the popliteus tendon, under the posterior portion of the ITB, and through the same tunnel in Gerdy's tubercle in an inferolateral to superomedial direction. The graft

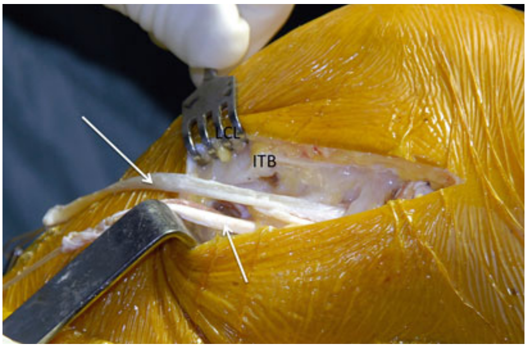

Fig. 15.4 View through the anterolateral incision and divided ITB. The intra-articular portion of the graft has been passed into the knee in an antegrade direction. The two limbs of the gracilis graft (*arrows*) that have been looped through the bone block prior to press-fitting the graft into the femur can be seen

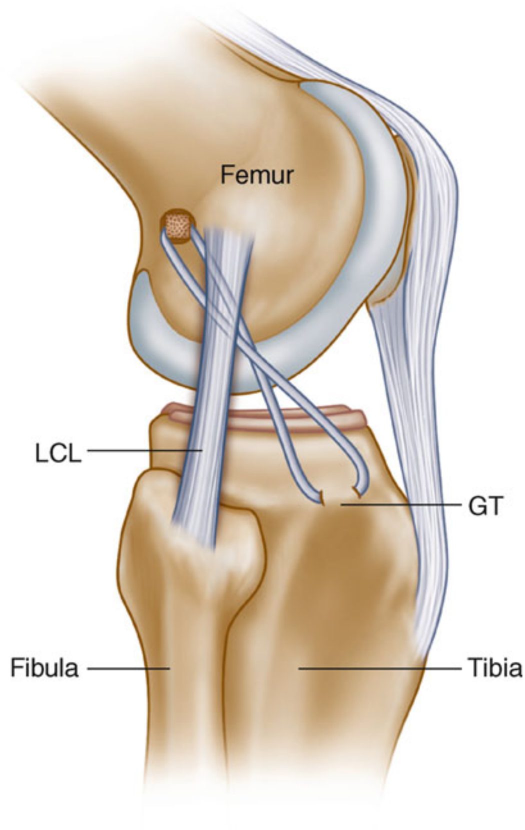

Fig. 15.5 Line drawing demonstrating the completed graft position. Note that the graft passes deep to the lateral collateral ligament (LCL) as it passes toward Gerdy's tubercle (GT) from its femoral attachment site proximal to the LCL origin

is tensioned with the knee in approximately 30° of flexion and neutral rotation and the two limbs of the graft are sutured to each other in a side-to-side manner, completing the reconstruction (Fig. 15.5).

In the rare case of well-placed and intact intra-articular graft that fails to adequately control rotation, one can consider the addition of a lateral extra-articular reconstruction. We prefer to utilize the central third of the ITB for such reconstructions as described by Lemaire [24, 25].

Outcomes

The role of lateral extra-articular augmentation of intra-articular ACL reconstruction procedures remains unclear due to a lack of high-level evidence. Published comparative studies of patients with and without lateral extra-articular augmentation have reported inconsistent results. Several authors have reported no difference in stability with lateral augmentation [26, 27], while others have demonstrated increased stability with augmentation, generally in specific populations such as female athletes reconstructed with soft tissue grafts [28] and those with significant lateral compartment translation preoperatively [13–15].

Specific to the revision ACL population, Trojani et al. recently noted an improvement in the pivot-shift in patients in whom a lateral extra-articular augmentation was added to an intra-articular reconstruction [19]. They noted a persistent pivot-shift in 35 % of patients treated with intra-articular reconstruction along vs. 19 % in those in whom the intra-articular reconstruction was augmented. However, they noted no difference in the overall IKDC scores between patients in the two groups.

Conclusions

Lateral extra-articular augmentation of intra-articular reconstructions of the ACL is an effective method of controlling the pivot-shift phenomenon that has potential to decrease the stress on intra-articular ACL grafts. The technique has utility in carefully selected cases of revision ACL reconstruction.

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16 Managing the Infected ACL Reconstruction

Daniel Burke Whelan, Howard E. Rosenberg, and Nicholas J. Yardley

Introduction

Infection after anterior cruciate ligament reconstruction (ACLR) is fortunately relatively uncommon; however, it remains a potentially devastating complication. The majority of retrospective reviews estimate the prevalence of postoperative deep knee infection, namely septic arthritis, after ACLR to be less than 1 % [1–15]. Infection not only places the ACL graft at risk, but more importantly subjects the knee cartilage to a significant insult, thereby jeopardizing its viability and risking post-infectious osteoarthritis. This chapter attempts to address some of the clinically relevant challenges of diagnosing and managing postoperative septic arthritis after ACLR.

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The Literature

Despite an increasing incidence of ACLR and associated research, relatively little information exists regarding postoperative ACLR infection. What literature does exist consists mostly of fairly small, heterogeneous, retrospective case series. High quality research is challenged by the difficulty in accurate surveillance and case detection, as well as the inability to identify sufficient cases to generate adequate statistical power to allow useful inferences. To date, the total number of cases reported in the literature is under 200. The two largest case series published in the literature involved 4,068 patients over an 11-year study period, of which only 21 were complicated by septic arthritis [14] and 5,364 patients over 26 years with only 13 infections [1]. A similar but slightly lower rate (0.1–0.5) has been seen in the larger case series of knee arthroscopies [16–18]. The largest case series of post-op ACLR infections is 24 patients; however, an alarming 19/24 had their initial ACLR at a different institution than the treating surgeons [10]. Similarly, in another study, 6/15 post-ACLR septic arthritis patients were from another institution [12]. The fact that a significant proportion of infected patients did not return to their treating surgeons highlights the potential risk of missing postoperative complications (i.e. "loss to follow up") during single-centre retrospective case reviews, thereby potentially underestimating the incidence. As a result, the prevalence and severity of

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postoperative septic arthritis may be higher than previously suggested by the current retrospective reviews available. In the end, there is a paucity of literature investigating postoperative septic arthritis after arthroscopy and arthroscopically assisted ACLR. From what literature exists, there is a poor consensus regarding the exact method of diagnosis, treatment, and surgical management.

Prevention and Risk Factors

Although the specifics are beyond the scope of this text, it would be remiss not to include a brief, yet important, comment on the prevention of post-ACLR septic arthritis. An understanding of the modifiable risk factors influencing the risk of postoperative infection is clearly important. Although a compromised host is rarely a problem in the relatively young and healthy ACLR population, medical optimization prior to elective surgical intervention is a crucial first step in avoiding postoperative infection. A recent review outlines some specifics regarding the modifiable risk factors for postoperative infection in orthopaedic surgery [19]. For example, on the day of surgery, any patient who has a recent history and evidence of ongoing infectious symptoms (fever, chills, cough etc.) is at risk for transient bacteremia and surgical intervention should be delayed until all clinical symptoms have resolved. Similarly, if an open wound or rash exists at the surgical site, surgery should be delayed until it has resolved. Additionally, patients who have modifiable risk factors for infection such as diabetes or smoking are encouraged to maintain tight glycaemic control during the perioperative period and are counselled on smoking cessation, respectively. Despite this, no link has been made between medical comorbidities and postoperative infection in ACLR. This likely is a result of the poorly powered clinical studies in combination with the relatively healthy patient population. In practice, any patient undergoing ACLR who is admitted to hospital (because of the complexity of their surgery or significant comorbidities) should likely receive 24 h of intravenous antibiotics postoperatively as prophylaxis. Interestingly, a recent study reviewing 1957 ACLR patients, of which 88 were professional athletes, found an infection rate of 5.7 % in the athletes relative to 0.37 % in the remaining cohort [11]. Whether this is an aberrant finding or not is difficult to know, but does suggest some specific populations may be at greater risk and therefore warrant closer monitoring.

There has been some evidence to suggest a trend toward increased risk for postoperative septic arthritis after arthroscopic interventions that involve multiple procedures (e.g. meniscectomy or meniscal repair) and/or are longer in duration [3, 15, 16, 20]. Additionally, one investigator has suggested a potential increased risk for post-ACLR septic arthritis after having undergone previous surgical procedures on the operative knee [8]. The clinical significance of these findings is difficult to determine, but underlines the importance of minimizing the complexity and duration of surgical time whenever possible.

Intra-articular steroid at the time of surgery has been linked to increased rates of infection [16, 21]. Armstrong showed an odds ratio of 27.4 for postoperative infection with the use of intra-articular intraoperative steroids. A good summary article by Gosal et al. provides a strong argument against the use of intra-articular steroids perioperatively [22]. The time interval a surgeon should wait between knee joint steroid injections prior to ACLR is debateable and lacks good evidence; however, we recommend avoiding ACLR until at least 3 months after a previous knee joint steroid injection. Additionally, steroids should not be used intraoperatively nor postoperatively in the first 3 months.

Preoperative razor shaving has been linked to higher rates of surgical site infection [23–25]. Because of this, when hair removal is necessary to facilitate a surgical procedure and subsequent wound closure, it has been suggested to use hair clippers immediately preoperatively. This is likely an appropriate practice prior to ACLR also.

Graft type has not been conclusively shown to influence the risk of postoperative infection. The rate of allograft contamination is admittedly higher in some reported series vs. autograft tissue. Culture positive rates of intraoperative samples sent during the use of allograft have been estimated at 2.6–13.3 % [26–29]. However, the clinical significance of this is not clear. That is, even though allografts have a theoretical risk of increased rates of postoperative infection (given the associated higher incidence of culture positive status) the only study specifically investigating this showed no difference [4]. However, during this investigation no deep infections were discovered in any of their study patients. Additionally, no differences in superficial wound infection rates were found between the use of auto and allograft. Counter intuitively one paper has shown a lower rate with allografts use versus autografts [30]. This is clearly an area in which more dedicated research would be helpful.

In the orthopaedic ACLR literature, the use of preoperative antibiotics is now nearly unanimous. We recommend using a first generation cephalosporin or an antibiotic with similar gram positive potency, administered intravenously within 1 h prior to the case. Despite this, the use of postoperative antibiotics is more controversial. No evidence exists either way regarding their use. In our hands, patients who are admitted into hospital because of the complexity of their reconstruction are given an additional 24 h of intravenous antibiotics.

Lastly, although monitoring of all post-ACLR complications is important, the monitoring of deep infections is particularly crucial because of the significant risk to the health of the patient and their knee cartilage. Any increase in postoperative infection rates should be investigated for a possible cause and should involve the entire medical team including administration. For example, sterilization techniques and sources of potential contamination should be investigated closely in order to minimize the risk to future surgical patients. During an investigation into a dramatic rise in post-op infections in one institution, the long cannulas used for knee arthroscopy were found to have positive cultures after sterilization and were theorized to be the potential source of infection [13]. Wang et al. showed a trend, but not statistical difference, towards increased risk of infection with the use of flash sterilization of the instruments over a standard technique [14]. Babcock et al. also found higher rates of infection with the use of flash sterilization [23]. The value of intermittent surveillance of perioperative sterilization techniques should not be underestimated.

Diagnosis

- Clinical evaluation

The diagnosis of postoperative septic arthritis can be surprisingly challenging. First, because of its relatively low prevalence, detection based on pattern recognition from previous cases is less useful. Even high volume surgeons are often exposed to less than one case per year and only a handful in their career [7]. Additionally, the classic symptoms of septic arthritis—namely, swelling, pain, fever, severe restriction in motion, and wound discharge are often subtle, absent, or misconstrued as normal postoperative findings [9, 16, 31, 32]. The majority of authors, who appear to have the greatest experience with postoperative ACLR septic arthritis, warn against misinterpretation of the often relatively benign appearance of the infectious process. In addition, the diagnostic dilemma is clouded by a crossover in symptoms from other, more common, complications such as DVT, superficial cellulitis, or adverse suture reaction. A high index of suspicion is absolutely critical for a timely diagnosis and treatment.

The literature suggests the average time from surgery to onset of clinical symptoms is most often between 1 and 3 weeks postoperatively [3, 5, 8, 9, 13, 16]. The onset of symptoms is often insidious. Late infections are much less common and infrequently reported in the literature [1, 10, 12, 15]. It is difficult to know how many cases of infection are in fact missed on initial presentation, but it is likely undesirably high. Scholling-borg reported 6/10 patients being missed on initial presentation [9]. Of these 6, 4 were misdiagnosed as having superficial skin infections, given oral antibiotics, and sent home.

An aggressive philosophy of "a superficial infection is deep until proven otherwise" is prudent in the early postoperative setting. A mildly warm and erythematous wound which is thought to be a possible superficial wound infection should be recognized as a potential harbinger of a more significant process. Therefore, all superficial wound infections should be considered at high risk of deeper infection and evaluated as such. Early knee aspiration through a non-contaminated site can be useful to help rule out a deep postoperative septic arthritis.

The positive and negative predictive value of increased pain or elevated temperature in the diagnosis of postoperative infection is likely quite low. However, the typical acute pain associated with the procedure should only last for a few days. Therefore, pain persisting beyond this or an acute exacerbation of postsurgical pain should be scrutinized closely. An elevated temperature is commonly absent or only mildly elevated [3, 8, 16]. Even when an elevated temperature is present, it clearly is not very specific, and has a vast differential diagnosis, including more common infectious origins such as respiratory or urogenital causes.

In summary, clinical suspicion for postoperative infection needs to be high. The threshold for further investigation should be quite low, particularly in the early postoperative period. Patients should be educated on the symptoms suggestive of infection and should be encouraged to see their surgeon, without delay.

- Laboratory findings

In the situation where the clinical picture is obvious, prompt intervention is essential. That is, treatment should not be delayed while waiting for confirmation from laboratory data. In the more indolent situation where clinical suspicion of postoperative infection exists, further evaluation with routine screening blood work should occur—including a white blood cell (WBC) count, erythrocyte sedimentation rate (ESR), and C-reactive protein (CRP). However, WBC is nonspecific and commonly within the normal range or just slightly elevated with postoperative septic arthritis [8, 9, 12, 14, 15]. In patients with spontaneous septic arthritis of the knee without surgery, a WBC count >11,000 and ESR >20 have a sensitivity of 75 % and specificity of 55 and 11 % [33]. The relevance of this literature, however, to the post-ACLR scenario is difficult to know. CRP and ESR may be more valuable in helping guide the evaluation, particularly after the first postoperative week. Both ESR and CRP have high sensitivities and negative predictive values—that is, normal tests all but rule out the possibility of septic arthritis [8, 31]. Little guidance exists on what threshold values should be used after ACLR. The literature ranges greatly in ESR and CRP values detected for the infected ACLR. A postoperative CRP >6 and ESR >50, beyond the first week, should greatly increase the suspicion of septic arthritis, particularly when clinical correlation exists. Because CRP rises and falls more quickly in the postoperative period, many believe an elevated CRP is perhaps a more useful indicator of postoperative septic arthritis. For example, the CRP should normalize in the uncomplicated ACLR by 2 weeks postoperatively [14, 34]. In one study comparing infected patients to controls 5 days post-op, the highest ESR in the normal group was lower than the lowest rate in the infected group [13]. In addition to this blood work, we recommend routinely obtaining blood cultures. Although blood cultures often take several days to indicate a positive result and may be negative [16] in the setting of an infected joint, when positive, they can help guide antibiotic treatment. When the clinical picture becomes clouded by infectious symptoms such as cough or dysuria, a low threshold to evaluate these with urine cultures and chest X-rays is likely prudent. First, other infectious etiologies present a significant risk of seeding the postoperative knee and second, they can coexist on initial presentation. Therefore, a simple cough or routine UTI in the postoperative period should be scrutinized closely.

- Knee aspiration/microbiology

Knee aspiration should be used when any clinical suspicion and/or laboratory data suggests the possibility of infection. The potential diagnostic and therapeutic benefits of an aspiration however, should be weighed against the possibility of inoculating a previously sterile joint. This is especially important to consider in the setting of an associated peri-articular cellulitis or prepatellar bursitis. Moreover, the unlikely but possible false positive result can further complicate the clinical picture. When clinically indicated, aspirates should be sent for cell count, gram stain, as well as aerobic and anaerobic culture and sensitivity. Mycobacterium and fungal testing should also be performed [35–37]. Although crystalline arthropathies are relatively rare in the young, athletic population undergoing ACLR, they should be considered in the differential diagnosis. However, even when present they don't necessarily rule out concurrent infection [38].

Ideally a knee aspirate should be taken prior to the administration of antibiotics; however, it is critical that a knee aspirate not significantly delay their administration. If there is clinical suspicion of septic arthritis, a relatively low threshold of 10,000 cells/μL should be used when necessary to help confirm the diagnosis. Knee aspirate cultures are often, but not always positive. Within the larger series, positive aspirates range from 60 to 100 % [2, 5, 9, 14]. The differential count of polymorphonuclear (PMN) cells can be particularly useful in the borderline case. A value of >85 % PMNs is highly suggestive of infection. Lastly, there are likely other biochemical markers with greater sensitivity and specificity that have yet to gain popularity in general orthopaedics. For example, there has been recent interest in using a neutrophil secreted enzyme, leukocyte esterase, as a marker of joint infection [39].

Isolates most commonly reported in the literature are consistently coagulase-negative staphylococcus (often *Staphylococcus epidermidis*) and *Staphylococcus aureus*. Rare cases of unusual pathogens such as *Enterobacter cloacae*, *Klebsiella pneumonia*, and proprionibacteriaceae have however been reported [9, 16, 23]. These cases, because of their added complexity, warrant additional evaluation and input from infectious disease experts. Unfortunately, isolates of coagulase-negative staphylococci are occasionally dismissed as contaminants when an underlying indolent infection lurks. All isolates should be taken seriously since the risks of missed diagnosis are potentially devastating. Aspirates should be used to help tailor future antibiotic treatment and their results should not delay antibiotic treatment and definitive surgical management of postoperative septic arthritis.

- Imaging studies

Routine radiographs are recommended but are unlikely to be helpful in the early postoperative period. Late changes, including peri-articular osteopenia and joint space narrowing suggest that the likelihood of irreversible cartilage damage is high. Also hardware loosening may be evident during prolonged infection and may help guide surgical management. The use of MRI or WBC bone scan is of little utility in the acute setting, but may have some value in recalcitrant or delayed diagnosis cases—particularly when there is a concern for potential osteomyelitis.

Management (See Fig. 16.1)

Once the diagnosis of postoperative septic arthritis has been made, prompt surgical management is critical in minimizing the deleterious effects on the articular proteoglycans and collagen by the bacterial production of degrading enzymes and toxins [40]. Second, in theory, any delay in treatment increases the risk of more complicated graft involvement and potential biofilm formation. For example, several authors have described debriding a "fibrinous coating" off of the graft [3, 12]. Also, with pathologic sectioning, bacteria have been found in the mid substance of the graft [15]. As a result, prompt administration of antibiotics and surgical irrigation and debridement remain the hallmarks of management in all cases. All suspected postoperative joint infections should be considered a surgical emergency and should be dealt with in an expedited fashion. A wait-and-see strategy has essentially no role in the treatment algorithm.

- Antibiotics

Once cultures have been obtained, intravenous antibiotics should be administered as soon as

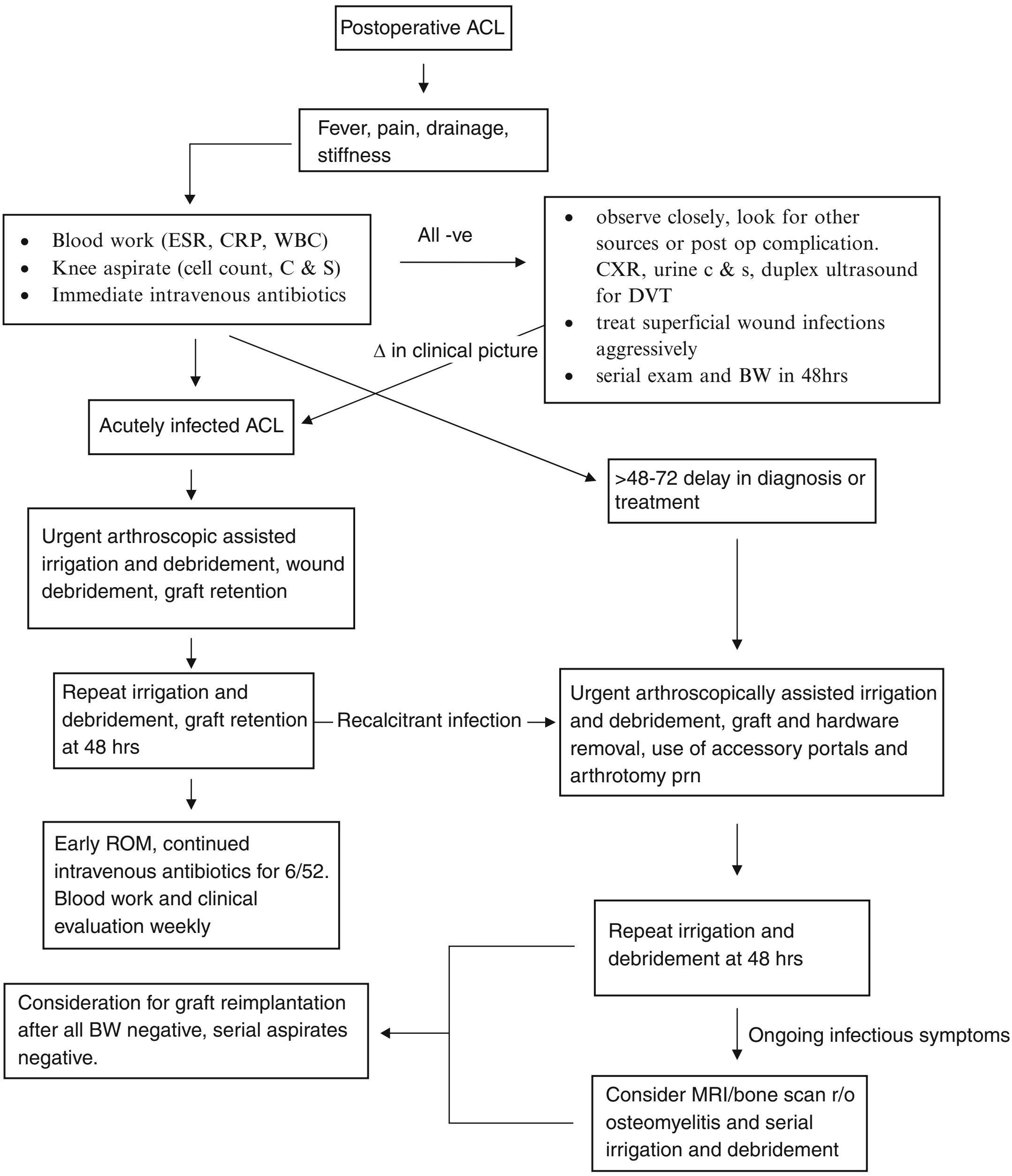

Fig. 16.1 ACL infection; suggested management flow diagram

possible. Empiric coverage should target the most likely organisms and later be tailored based on particular isolates and antibiotic sensitivities. Due to an increasing amount of antibiotic resistant gram positive bacteria including methicillin-resistant *Staphylococcus aureus* (MRSA) [41, 42] the use of broad spectrum, intravenous antibiotic as the initial treatment is likely prudent. While waiting for culture results, we recommend broad spectrum coverage with an agent effective against MRSA (e.g. Vancomycin) as well as gram negative coverage (e.g. third generation

Cephalosporin). Once definitive cultures are obtained, the antibiotic regimen is tailored accordingly. In culture negative cases, empiric regimen covering *Staphylococcus* and *Streptococcus* species as well as anaerobes is indicated (e.g. Ceftriaxone and Metronidazole). Early involvement of an infectious disease specialist is often helpful.

Even in the nonsurgical septic arthritis literature, no consensus or randomized control trials exist concerning the duration of antibiotic treatment [43]. As a result, the duration of antibiotics is tailored to the individual. Intravenous antibiotics are continued for 6 weeks. Patients with intra-articular sepsis after ACL reconstruction are considered to have contiguous osteomyelitis, hence the 6 week duration. Some authors have advocated the routine use of high dose intra-articular antibiotics after irrigation and debridement [10]. As there is no good evidence to suggest its efficacy and because of the potential, but unproven, deleterious effects on intra-articular structures, its routine use in practice is not recommended, but may be considered in the most recalcitrant cases.

- Surgical management

  Surgical intervention plays a critical role in controlling and eradicating postoperative septic arthritis. Some literature, particularly dated research from the nonsurgical literature, has suggested antibiotics alone or repeat aspirations may be as sufficient as surgery in controlling septic arthritis [44]. We would advocate, in general, that a more aggressive approach utilizing both surgical and medical interventions likely affords the joint cartilage the greatest chance of survival and is the safest and most prudent approach in the young, otherwise healthy population of patients with suspected joint infection after ACLR.

  – Superficial wound infection

    In the situation where an isolated superficial wound infection is diagnosed and there is no evidence of deep infection, we recommend oral antibiotics and serial examinations. However, the diagnosis should be absolutely clear and no doubt should exist that an insidious deeper infection lurks. If the wound infection worsens or fails to improve quickly, early wound debridement should be considered. An extremely low threshold for knee irrigation and debridement exists at all times. Only one research paper has discussed superficial wound infections after ACLR in detail [4]. In their experience, oral antibiotics and wound care were successful in 100 % of cases. However, there are relatively frequent reports in the literature of post-ACLR septic arthritis that were preceded by a prior diagnosis of a superficial infection [9].

  – Acutely infected ACLR

    The infected ACLR knee should be brought to the operative theatre as soon as possible—ideally within hours of the diagnosis. Either an open, arthroscopic, or combined approach should be used to perform a thorough synovectomy, debridement, and washout of the knee. All surgical wounds including the graft harvest site should be surgically opened, regardless of their appearance, in order to ensure as few potential sources of recalcitrant infection are left behind. There have been reports of as high as 86 % of patients having secondary extra-articular sites of infection concurrent with the septic arthritis [15]. Although a formal arthrotomy is rarely necessary, the use of postero-medial and/or postero-lateral accessory portals can be valuable in ensuring an adequate debridement and synovectomy is performed.

    Regarding graft removal or retention, most investigators recommend retention whenever possible [7]. The knee should be examined under anaesthetic intraoperatively. If the knee is grossly unstable to Lachman and pivot shift testing, the graft is incompetent and it should be removed along with all hardware. Similarly, if there is a significant delay (>48 h) between the clinical picture of septic arthritis and surgical management, there should be a consideration of graft removal. In the more likely scenario where the knee remains stable and the diagnosis and subsequent treatment is reasonably prompt, graft retention during the first surgical intervention is an acceptable option. Careful inspection of the graft followed by debridement of any fibrinous exudates is necessary to avoid ongoing and recalcitrant infection. Some authors have suggested the decision of graft retention or removal be based on the visual appearance of the graft intraoperatively [5]. This is a potentially dangerous practice, given the low case exposure and the subjective nature of visual graft inspection.

Copious amounts of normal saline (>9 L) should be used to irrigate the knee and soft tissue wounds. The value of antibiotic impregnated solutions or impregnated solutions such as soap, alcohol, or betadine are not conclusively known to have any particular value. In fact, although impregnated solutions may have a greater bacterial kill rate in vivo, their effects on soft tissue viability are of particular concern. Similarly, although occasionally utilized, the addition of a postoperative drain or continuous irrigation device lacks evidence. In fact, postoperative intra-articular drains may undesirably serve as a conduit for further infection. Therefore, in the acutely infected ACLR, after thorough debridement and irrigation with normal saline, the wounds should be closed primarily without a drain. The use of intra-articular deposition of high dose antibiotic beads has been described [10]. This approach has several potential draw-backs and should be avoided: the sterile exudate created may serve as a potential source of ongoing drainage from wounds thereby complicating the clinical picture, effluent from the bead's dissolution is often of a gritty consistency and may lead to a "third-body" mechanism of cartilage erosion, and the effect of high concentrations of antibiotic on articular cartilage, although unknown, may be deleterious. Its use may play a more important role in recalcitrant setting, particularly with osteomyelitis.

– Postoperative management

All patients who undergo an initial irrigation and debridement and are suspected of having a deep infection should be admitted to hospital. Admission helps facilitate intravenous administration of antibiotics, allows for guided physiotherapy, and most importantly allows the best opportunity for close monitoring for clinical regression. A protocol of protected weight bearing with a knee immobilizer when ambulatory until quadriceps function and proprioception return should be instituted. Early, physiotherapist-guided range of motion of the knee is encouraged in an attempt to avoid postoperative stiffness. Liberal use of intermittent ice packs or cooling sleeve is encouraged to reduce postoperative swelling and to aid in pain control. Because of the added surgical insult, it may be prudent to add thromboprophylaxis and place patients on subcutaneous heparin on the first day postoperatively, and continue until the patient is fully mobile or for a minimum of 21 days. Reports of DVT and PE after post-arthroscopic infection exist [16]. Laboratory monitoring with WBC, ESR, and CRP is performed regularly during the initial postoperative period. Clinical monitoring should be frequent and the threshold for repeat irrigation and debridement should be extremely low. To give the articular cartilage its best chance at survival, and avoid recalcitrant cases, patients should be taken back to the operative theatre at approximately 48 h for an additional irrigation and debridement in order to avoid ongoing infection. In cases where the clinical picture is particularly benign, one trip to the operating room may suffice. However, this is an area of controversy for which there is limited evidence in the literature for either approach.

– Missed or delayed diagnosis

The distinction between a missed infection or delayed diagnosis and an acute infection can be challenging to make. In the circumstance where it is obvious a deep infection has been ongoing for more than several days untreated, a more aggressive surgical approach is required. In this unfortunate circumstance, urgent surgical debridement including early graft and hardware removal likely gives the best chance at eradicating the established infective process. Particular attention should be made to the tunnels ensuring an adequate debridement in order to avoid the risk of ongoing osteomyelitis. The threshold for employing accessory posterior medial and/or posterior lateral portals to facilitate a complete synovectomy under these circumstances is low. The additional use of a formal arthrotomy should be considered if it increases the adequacy of the debridement. All patients should undergo an additional irrigation and debridement at approximately 48 h for delayed cases and sequential debridements may well be necessary to eradicate the infection.

– Recalcitrant infections

Despite the best efforts to quickly diagnose and treat postoperative septic arthritis, the risk of continued infection remains real. For this reason, repeat irrigation and debridement is likely of significant benefit in most cases. Even though an expedient repeat surgical intervention may occur, clinical signs suggestive of ongoing infection can persist. In the case of ongoing infectious symptoms despite two consecutive irrigation and debridements, the most prudent intervention is graft and hardware removal and an aggressive complete synovectomy. The concern being that the graft, hardware, or synovium remain an untreated nidus of infection. Graft tunnels should be thoroughly debrided, removing all residual graft and debris—reamers may be particularly helpful in this regard. In one study, where removed grafts were sent to pathology, inflammatory infiltrates were found within the substance of the graft the majority of the time—creating concern it may serve to harbour infection and provide a culture media of sorts [15]. The primary goal is eradication of the infection and protection of the articular cartilage. This philosophy has led some authors to suggest graft removal during the initial intervention. This is likely overly aggressive as a majority of investigations have shown successful elimination of infection with graft preservation. However, if infection persists after two consecutive irrigation and debridements, sacrificing the knee stability in order to successfully eradicate the infection is prudent.

In the resistant infection, consideration must be made for the possibility of less common pathogens or polymicrobial infections. In these situations incorrect or insufficient antibiotics may be being administered. Zalavras' investigation of recalcitrant cases demonstrated 3/5 (60 %) of cases were polymicrobial [45]. They advocated aggressive arthrotomy, synovectomy, and graft removal in these cases. Additionally, repeat aspirations and broader spectrum antibiotics may play a more significant role in these settings.

In the rare but unfortunate situation, where despite repeated washouts and graft/hardware removal infection persists, ruling out osteomyelitis with bone abscess as the cause is important. In these rare situations, MRI scan can be valuable. If osteomyelitis (involucrum or sequestrum) is diagnosed, an urgent and aggressive debridement of the bone is recommended. Severe osteomyelitis requiring additional surgery and bone grafting has been reported very infrequently [2].

– Revision ACL reconstruction

If the graft is incompetent and removed during the first surgical intervention, or removed during a subsequent debridement, revision reconstruction should be approached judiciously. This unfortunate circumstance mandates a lengthy discussion with the patient regarding the possibility of repeat infection (and potential sepsis) as well as the pros and cons of a significant revision surgical intervention with its own inherent risks. In the case where revision surgery is desired to address ongoing symptomatic knee instability, a minimum of 6 weeks off of antibiotics is recommended. Inflammatory markers including ESR and CRP must be normalized, and at least two serial knee aspirates must be negative. In most instances, this likely means a minimum of 3–6 months after the initial surgical intervention for septic arthritis. The traumatic experience to the patient having to deal with multiple surgeries should not be understated. For this reason, further surgical interventions should be personalized to accommodate the best interest of the individual. In one series where seven grafts were removed for infection on the initial surgical intervention, 3/7 patients decided against subsequent ACL reconstruction [3]. Additionally, the value of ACL reconstruction in a post-septic arthritic knee may be of less value and depending on the symptomatology of the individual. That is, if a patient's symptoms and decreased quality of life are focused more on post-arthritic pain and not instability, treatment should be focused on the arthritis and not revision ACL reconstruction.

- Intraoperative contamination

Intraoperative contamination of the graft, poses a relatively unique challenge. In the unfortunate event that the graft comes into contact with unsterile conditions (e.g. the dropped graft) a predetermined plan of action should be in place. The dilemma of washing the graft, harvesting an alternative autograft, or using an allograft is troubling, each with its own inherent risks and benefits. Our practice is to have a backup allograft available for these situations. In the event that an allograft back up is not available, determined to be unsuitable, or not anticipated (e.g. preoperative consent not obtained), several regimens for decontamination have been suggested. From what little research on this topic exists, evidence for washing the graft and implantation exists [46, 47].

A simple and effective method of graft decontamination was described and tested by Parker et al. [48]. Their technique of "mechanical agitation and serial dilution" included ten serial washes in 100 cc of polymyxin B antibiotic solution (166 u/cc), each time agitated with 15 s of gentle shaking. This method proved superior to both antibiotic soak alone and pulsatile lavage. What solution to use to wash the graft is clearly debatable, but antibiotic impregnated or chlorohexidine gluconate-based solutions may be superior to providine-iodine solutions [49].

When allografts are used for ACL reconstruction, a sample is often sent for culture and sensitivity. Although the results of these cultures are frequently positive (5.7–13.25 %), no evidence of detrimental effects on the ACL reconstructed knee exist [26, 27, 29]. In these situations full disclosure to the patient is mandatory as is administration of 2 weeks of prophylactic antibiotics. Close clinical follow up is crucial to ensure expedient diagnosis and treatment of potential postoperative septic arthritis.

Complications

Postoperative stiffness, particularly after multiple surgical interventions, is always of significant concern. Early, but not overly aggressive, range of motion exercises are encouraged after each operation. Despite this, surgical patients complicated by postoperative infection are at a significantly increased risk of postoperative arthrofibrosis and/or stiffness [8]. If an adequate physical therapy regimen fails to meet a satisfactory range of motion by 3–6 months, lysis of adhesions and/or manipulation under anaesthesia should be considered. Few guidelines exist in this regard and we recommend that evaluation and institution of specific rehabilitative protocols be done on a case by case basis.

Outcomes

Several investigators have shown decreased satisfaction after the complication of post-reconstruction septic arthritis. For example, Fig. 16.2 demonstrates X-rays of advanced post-septic arthritis in a 22-year-old male who had his primary ACLR 3 years prior, complicated by early infection in the early postoperative period. He subsequently went on to have a series of irrigation and debridements and a subsequent revision reconstruction. He currently has a draining wound, negligible range of motion, and a positive knee aspirate suggestive of ongoing infection. His reconstructive options are limited and knee fusion is likely.

Lower modified Lysholm scores have been noted compared to uncomplicated cases [2, 8, 9]. Schollin-borg et al. showed Tegner scores nearly 2 levels lower for the infected ACLs at long-term

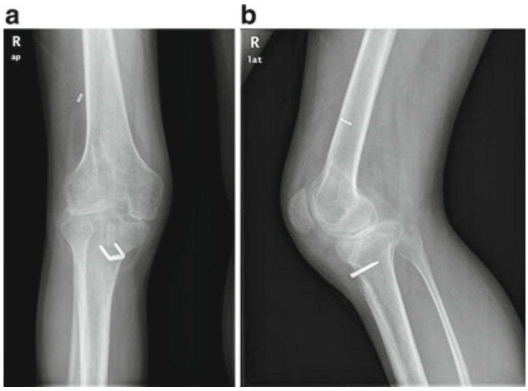

Fig. 16.2 (**a**, **b**) ACL infection; late sequelae of recalcitrant infection. AP and lateral knee radiographs of a 22-year-old male that underwent primary ACL reconstruction (hamstring autograft) 2-year prior. MRSA infection was diagnosed at 3 weeks postoperative. Serial irrigation and debridement was unsuccessful as were two course of IV vancomycin. Graft and hardware removal was delayed 6 months. Aspirates were not taken and graft subsequently revised with allograft at 18 months. Patient presented to another surgeon (author) at 4 months post-revision with a draining sinus (tibial incision), and severe stiffness (20 degree ROM). Gross arthritic changes and joint subluxation are seen on X-ray. Reconstruction options are limited

follow-up compared to their matched controls [9]. This decreased satisfaction may in part be due to permanent cartilage damage. Several investigators reported joint space narrowing in several of their patients in follow up [8, 9, 12]. Increased crepitus, particularly in the patellofemoral joint has been noted also [9]. Others, however, have reported surprisingly good results despite having postoperative septic arthritis [3, 50]. What determines a good or poor outcome after post-ACLR septic arthritis is difficult to elucidate from the relatively heterogeneous group of small case reports in the literature.

Summary

Post-ACLR septic arthritis remains a challenging and potentially devastating complication. As the incidence of ACL reconstruction increases, the importance of early diagnosis and the potential significance of this complication will only become increasingly more important. Like many aspects of clinical research, particularly for those which investigate outcomes with a low frequency of occurrence, larger, prospective, multi centred studies are likely necessary to create enough power and be sufficiently free of bias to make clinically relevant inferences. One way to facilitate this is to create a nationally or at least regionally based ACL registry—similar to the arthroplasty registries that have been created in Scandinavia and now with increasing frequency in North America and other areas of the world. The value of such a database would be considerable and would, in theory, be the next step in properly understanding ACL reconstruction outcomes, including infection.

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17 Meniscus Allograft Transplantation in Revision ACL Reconstruction

Travis G. Maak, Venu Nemani, Thomas L. Wickiewicz, and Scott A. Rodeo

Introduction

The typical indication for meniscus transplantation is for symptoms of early arthrosis following meniscectomy, in an attempt to restore the "chondroprotective" function of the meniscus. In this chapter we will consider the role of the meniscus in knee stability, and discuss how meniscus transplantation in the setting of anterior cruciate ligament (ACL) reconstruction may function more to protect the ACL graft during the early period of ACL graft incorporation rather than have a long-term "chondroprotective" effect.

Background

Zukor et al. [1] reported the first meniscal allograft transplants in the early 1970s. MAT was initially performed in patients with knee osteoarthritis and prior total meniscectomy. The goal of this procedure in that setting was to prevent and possibly reverse the arthritic degeneration that may follow meniscectomy [2]. The clinical indications for the MAT have been continually refined. MAT has become more frequently utilized with the development of improved allograft harvest and preservation techniques and with data demonstrating potential chondroprotective effects [3, 4].

The medial and lateral menisci serve several critical functions in the knee including stability, load transmission, shock-absorption, lubrication, and proprioception [5]. The menisci act as important secondary stabilizers of the knee joint, especially in an ACL-deficient knee. Previous data have demonstrated that meniscectomy increases the risk of arthrosis progression [6]. This risk may be accelerated in ACL-deficient knees [7, 8]. ACL reconstruction surgery attempts to recreate knee ligamentous stability and reduce the potential for meniscal injury. Meniscal protection may aid to reduce the risk and delay the onset of knee osteoarthritis.

The menisci have an important role in knee stability via load-sharing with the ACL. ACL reconstruction outcomes are improved with an intact medial meniscus, as compared to reconstructions performed in knees with a deficient medial meniscus [9]. Unfortunately, the translational and rotatory subluxation that occurs with ACL rupture is associated with concurrent meniscal injury. This injury may occur during both primary ACL rupture and failure of previously performed ACL reconstructions. The menisci and ACL serve

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complementary and intertwined roles in knee stability and chondroprotection, and thus performing a meniscus transplant concomitantly with revision ACL reconstruction may enhance the stability of the knee by providing a secondary restraint against anterior-posterior translation and lead to improved outcomes. This chapter will discuss the biomechanics, indications, patient evaluation, preoperative considerations, surgical technique pearls, and outcomes pertaining to MAT in the setting of revision ACL reconstruction.

Biomechanics

The ACL, medial, and lateral menisci are vital structures in the knee that play complementary roles in providing knee stability and chondroprotection. The chondroprotective role of the menisci occurs through shock-absorption and reduction in the joint contact pressure on the tibiofemoral articular cartilage.

Meniscus deficiency has been associated with early progression of degenerative joint disease. In 1948, Fairbank documented the association between total meniscectomy and significant arthritic changes in the knee [6]. Subsequent studies have also demonstrated an accelerated progression of osteoarthritis (OA) in meniscus-deficient knees [10, 11]. These data highlight the importance of meniscal preservation for knee stability and chondral protection.

The importance of the menisci in normal knee kinematics has been well documented. The U-shaped medial meniscus and C-shaped lateral meniscus function to deepen the tibiofemoral socket. This function produces an increased area for pressure distribution and also improves biomechanical stability. A recent biomechanical study by Lee et al. highlighted this function by documenting increased contact stress with incrementally increasing meniscectomy in a dose–response fashion [12]. These data demonstrate the stabilizing role of the medial and lateral meniscus; however, the mechanism by which the menisci contribute to joint stability differs between the medial and lateral menisci.

The secondary stabilizing effect is primarily due to the posterior horn of the medial meniscus in resisting anterior tibial translation as demonstrated during a Lachman maneuver [13, 14]. Prior data have demonstrated that deficiency of the posterior horn of the medial meniscus in the setting of primary ACL reconstruction is associated with graft elongation and recurrent joint laxity [9]. Papageorgiou et al. [15] documented 33–50 % higher forces in ACL reconstruction grafts in the absence of a medial meniscus. Prior data regarding the etiology for ACL failure documented a 70 % rate of prior meniscectomy in patients undergoing revision ACL reconstruction [16]. In addition, significantly increased function was documented following revision ACL reconstruction in patients with intact menisci. Recent biomechanical data have demonstrated the importance of the medial meniscus in controlling anterior tibial translation during a Lachman maneuver [17]. Spang et al. [18] also documented the association between meniscectomy and significant increases in anterior tibial translation at all knee flexion angles. Moreover, significant increases in ACL strain at 60 and 90° of knee flexion were identified. MAT restored these values to those of the intact knee. Medial MAT is most commonly performed concomitantly with ACL reconstruction due to the stabilizing effect of the posterior horn of the medial meniscus. Garrett [19] reported significantly improved KT-1000 arthrometer results for ACL reconstructions with concomitant medial meniscal transplantation, as compared to patients with medial meniscal deficiency who underwent isolated ACL reconstruction. For this reason, revision ACL reconstruction in the setting of concomitant anteromedial instability should include meniscal evaluation and, if indicated, MAT.

The biomechanical stabilizing effect of the lateral meniscus has also been well documented. The lateral meniscus carries 70 % of the lateral compartment load, compared with just 40 % by the medial meniscus [20]. Lateral meniscal deficiency may significantly reduce knee stability, specifically with tibial internal rotation (and subsequent pivot shift) [21]. Musahl et al. [17] utilized computer-assisted navigation in a cadaveric model to document a significant 6 mm increase in anterior tibial translation following lateral meniscectomy in ACL-deficient knees during the pivot shift but not Lachman maneuvers. These data demonstrate the importance of the lateral meniscus as a stabilizer during axial, rotatory loading of the knee.

Optimal MAT requires ligamentous stability including an intact ACL to control abnormal tibiofemoral translation and rotation that could produce meniscal damage and graft failure. Ligamentous instability has been previously identified as a contraindication to meniscus transplantation [3]. Conversely, ACL reconstruction outcome is closely dependent upon an intact medial meniscus to share anterior-posterior and rotational stresses and to limit potential ACL graft rupture [3]. These studies demonstrate the synergistic effect between the ACL and menisci for both knee stability and chondroprotection.

Indications for Meniscal Transplant

MAT in the setting of revision ACL reconstruction is primarily indicated for young, non-obese patients with stable, well-aligned knees and minimal to no arthritis. The associated symptoms include pain in the affected compartment due to compartment overload as well as recurrent instability due to a failed ACL reconstruction. While age per se is not a contraindication for meniscus transplantation, it is uncommonly recommended in patients over age 50 due to concomitant degenerative changes in that setting. Skeletal maturity should also be confirmed to minimize the risk of intraoperative physeal injury, asymmetric physeal arrest, and progressive angular deformity. Obesity is also a relative contraindication for MAT due to the suboptimal mechanical environment for the allograft and increased risk for early failure. As described previously, knee instability also places abnormal stresses on the meniscus and ACL reconstruction. This laxity can be a cause of early failure for both procedures and thus must be identified and addressed prior to or during MAT and revision ACL reconstruction.

Significant controversy exists regarding the acceptable degree of degenerative changes for MAT. The most common contraindication to MAT is the presence of osteoarthritis with grade III to IV Fairbank's changes. However, many surgeons believe that MAT may be contraindicated in the setting of Outerbridge cartilage changes of grade I or II. Nevertheless, focal areas of grade III or IV degeneration might not preclude a positive outcome, especially if these can be addressed with a concomitant cartilage restoration procedure. Knee arthrosis due to lower extremity malalignment is also a contraindication to MAT. In the young patient without arthritis, angular malalignment may need to be addressed, and the surgeon should have a low threshold to perform a concurrent osteotomy during MAT to optimize the mechanical environment of the knee and reduce the risk of meniscus allograft failure.

Most surgeons now agree that there is a minimal role for meniscal transplant in knees that have already developed moderate to severe degenerative joint disease, since the likelihood of symptom improvement in this mechanical environment is quite low. Currently, no clinical evidence exists supporting the use of MAT for treatment of advanced knee osteoarthritis. In addition, meniscal transplants are contraindicated in patients with active inflammatory arthropathies, as this inflammatory environment increases the risk of early graft failure. Finally, any history of an infectious, immunological, or metabolic condition affecting the knee is a relative contraindication to MAT given the high risk for potential complications and early graft failure.

Patient Evaluation

A complete patient history, physical examination, and radiographic assessment are crucial for the evaluation of the patient when considering meniscus transplantation in conjunction with revision ACL reconstruction. Thorough evaluation is particularly important in this setting, as patient selection can be difficult given the complexity of the associated pathology. A detailed description of the patient's symptoms prior and subsequent to the index surgery should be obtained. Complaints of instability with increased joint line tenderness localized to the involved compartment are common. Intermittent swelling may also be present, specifically with increased level of activity. Emphasis should be placed on complaints of increasing pain in a particular compartment, as this may be associated with increased compartment loading and chondral damage.

Operative documentation of the index ACL reconstruction and subsequent surgical procedures should be obtained. Prior operative reports, clinic records, and imaging studies should be obtained. Focus should be placed on meniscal injury identified at the index arthroscopy and any intervention including meniscectomy or meniscal repair. Articular injury or repair, and varus, valgus, or rotational laxity identified during the index or subsequent surgeries should also be noted.

The patient history can then serve to guide a focused physical examination. Limb alignment and gait should be visualized, as malalignment may require concomitant surgical correction in the setting of meniscal transplant and revision ACL reconstruction. Range of motion should be evaluated and restricted motion should be carefully documented, since meniscal transplantation should not be performed if motion is restricted. Ligamentous instability and signs of chondral damage should also be identified. A painless effusion may be a sign of early chondral damage. Concomitant, unrecognized ligamentous laxity can increase the risk of ACL reconstruction failure and thus should be recognized and addressed during revision ACL reconstruction, especially in the setting of meniscal transplantation. Joint line tenderness is commonly identified and may be localized to the meniscal-deficient compartment. Pain during palpation of the medial or lateral femoral condyles can also suggest compartment overload and chondral damage.

Careful imaging evaluation should be performed following the history and physical examination. Several modalities are available including plain radiographs, magnetic resonance imaging (MRI), triple-phase bone scan, and three-dimensional gait analysis. Initial evaluation with routine plain radiographs should include weight-bearing anteroposterior (AP) extension views of both knees, a weight-bearing 40° flexion postero-anterior (PA) view, a 45° flexion non-weight-bearing lateral view, and axial (Merchant) views of both patellofemoral joints (Fig. 17.1). The 40° flexion PA view allows improved assessment of posterior tibiofemoral chondral damage [22]. (Fig. 17.2) Additionally, a standing full-length

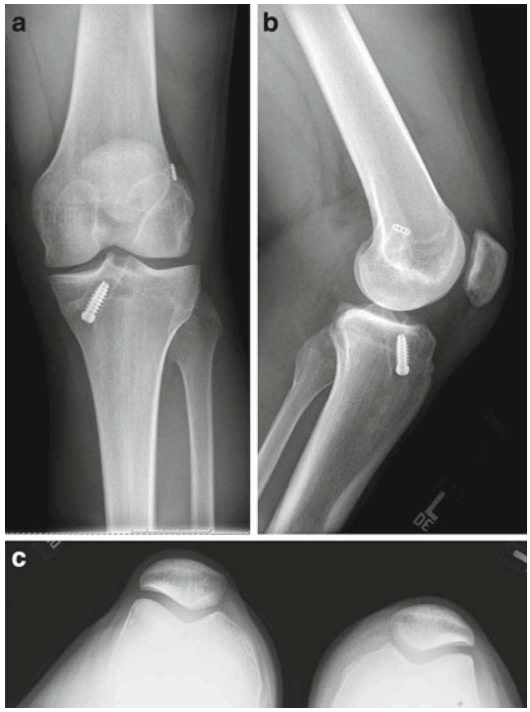

Fig. 17.1 (**a**) AP, (**b**) lateral, and (**c**) merchant plain radiographic views demonstrating the location of the tibial and femoral tunnels and hardware fixation including a tibial metallic interference screw and a lateral cortical button fixation. Care should be taken to evaluate the degree of tunnel widening on these images

Fig. 17.2 Weight bearing 45° PA view plain radiograph demonstrating preservation of posterior joint space

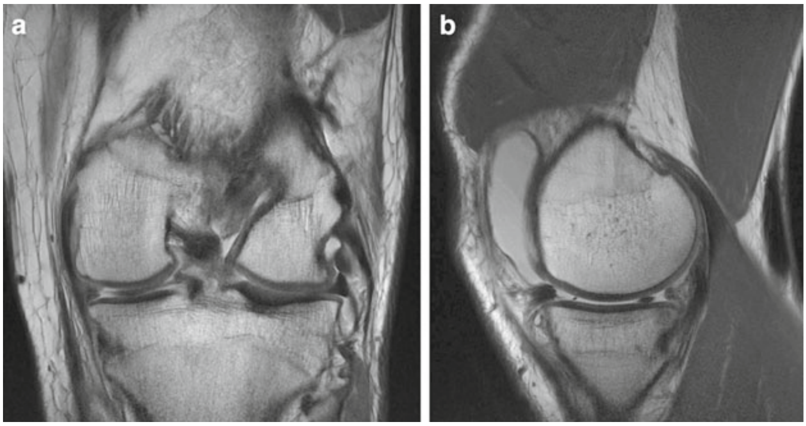

Fig. 17.3 MRI (**a**) coronal and (**b**) sagittal views demonstrating preserved cartilage with absent medial meniscus

lower extremity AP radiograph of both limbs should be obtained to evaluate limb alignment.

MRI should be obtained to evaluate the status of the menisci, ligaments, cartilage, and subchondral bone. Additional cartilage-specific MRI sequences including three-dimensional fat suppression, proton density, and two-dimensional fast spin-echo can be used to fully assess patellofemoral and tibiofemoral hyaline cartilage and subchondral bone [23]. Cartilage signal intensity and morphology should be noted. Increased signal within the chondral layer, chondral fissuring, and subchondral sclerosis or edema may be identified and are suggestive of chondral damage (Fig. 17.3). Advanced, quantitative MR imaging protocols including measurement of T2 relaxation time (measure of collagen organization) and T1 rho (measure of proteoglycan content) are more sensitive for early degenerative changes in articular cartilage. Computed tomographic (CT) scan may be used to evaluate the bony architecture and facilitate preoperative planning including ACL graft tunnel placement. This planning is particularly important if the revising surgeon uses a bone plug technique for meniscal transplant, since multiple tibial tunnels will be required for fixation. While triple-phase bone scan is not routinely obtained in the setting of meniscal transplant in revision ACL reconstruction, increased uptake may suggest compartment overload and impending chondral damage, thus increasing the importance of attempting to restore the compartment load-sharing through MAT. Gait analysis is also rarely required but has been previously used to evaluate compartment overload in the setting of meniscal injury and concomitant malalignment [7]. Malalignment should be considered during preoperative planning, as correction of malalignment with a high tibial osteotomy (HTO) or distal femoral osteotomy (DFO) may be required with or without a meniscal transplant. The patient's response to a trial in an unloader brace provides helpful information about relative compartment overload.

Preoperative Considerations

Allograft Procurement and Processing

Meniscal allograft selection for MAT in revision ACL reconstruction requires consideration of graft procurement, processing, and storage, graft sizing, and timing for donor matching and implantation. Various meniscal allograft preservation options exist including fresh, fresh-frozen, cryopreserved, and lyophilized. Cellular viability is preserved in fresh and cryopreserved grafts. However, fresh allograft implantation is required within days of procurement to maintain cellular viability, which presents difficult logistics. In an effort to preserve cell viability while allowing increased storage time, cryopreservation techniques have been developed. These techniques use controlled-rate freezing with cryoprotectants such as glycerol to protect cell viability. However, only cells on the meniscus surface are protected, with little preservation of cells deep in the meniscus substance. Fresh-frozen tissue does not contain any viable cells, as the freezing process kills all cells. These tissues require cellular repopulation after transplantation, which occurs from synovial cell ingrowth. Fresh-frozen tissue can be stored indefinitely, allowing for elective surgical scheduling. Fresh-frozen tissue is the most commonly used allograft type [2, 24]. Lyophilized grafts are acellular and thus can be stored for prolonged periods, but have been associated with graft shrinkage. The current authors do not suggest using lyophilized grafts for this reason [25, 26].

The risk of disease transmission and immunogenicity has been considered for fresh and fresh-frozen allografts and allograft rejection has been documented [27]. Sterilization methods including gamma irradiation and ethylene oxide have previously been employed in an attempt to reduce the risk of disease transmission. Gamma irradiation will reduce or eliminate allograft viral DNA; however, a minimum radiation strength of 3.0 mrad is required for sterilization and this magnitude of irradiation has been associated with impaired meniscal tissue properties [28]. Ethylene oxide sterilization is effective in reducing disease transmission for lyophilized grafts but has been associated with synovitis due to the pro-inflammatory ethylene chlorohydrin byproduct [29].

Careful donor screening rather than graft processing procedures, however, most effectively decreases the risk of disease transmission. Meniscal allograft immunogenicity is also a consideration and is primarily associated with the cellular elements of the attached bone plugs or block. However, no animal studies have substantiated this concern [30–33]. Moreover, data from massive osteochondral allograft transplantation have documented a minimal rate of immunogenicity [27]. It is our opinion that the sterilization risks and minimal concern for immunogenicity outweigh the potential benefits and therefore the preferred option is the fresh-frozen, nonirradiated meniscal allograft.

Allograft Sizing

Meniscal allograft size matching represents a crucial component of preoperative planning and significant limiting factor in graft availability. Meticulous preoperative graft size matching helps optimize ease of implantation and meniscal allograft mechanical function [34]. Intraoperative and radiographic measurement methods may be used to ensure donor-recipient size matching. Radiographic measurements of the meniscus or tibial plateau are most commonly used. Plain radiograph, CT scan, and MRI may be used to calculate donor graft dimensions [35]. Significant controversy exists regarding the measurement accuracy among these modalities [35–37]. As a result, the most accurate, relevant anatomical landmarks for meniscal allograft measurement remain unclear. Previous authors have suggested MRI measurement of the contralateral, intact meniscus; however, significant intrasubject variability between contralateral menisci has been observed [35, 38]. Direct or radiographic measurement of the injured, ipsilateral meniscus is often impossible secondary to prior meniscectomy, especially in the revision setting.

Given the variability among soft tissue landmarks, the authors' prefer to match size based on tibial dimensions. There is a reliable relationship between bony, radiographic landmarks and meniscus size [39, 40]. Nevertheless, this technique has also been associated with significant variability up to 8.4 % or 3.8 mm in meniscal length and width relative to the respective tibial plateau dimensions [39]. MRI matching data have documented improved correlation rates, but 65 % of the images differed by more than 2 mm of actual measured plateau dimensions [35]. While an exact donor-recipient size match is considered optimal, limited data exists regarding tolerance for size mismatch or the effects of meniscal allograft size mismatch [41]. The current authors' use both plain

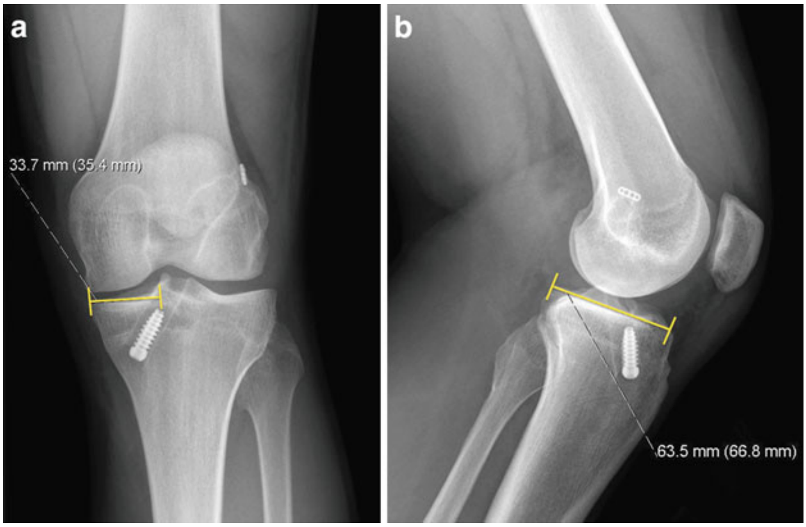

Fig. 17.4 (**a**) AP and (**b**) lateral plain radiographs demonstrating medial meniscal allograft sizing technique using the medial tibial plateau osseous dimensions

radiographs with a size magnification marker and MRI to determine tibial plateau osseous measurements. These measurements allow donor matching for a fresh-frozen tibial plateau or hemiplateau with attached meniscal allograft(s).

Pollard et al. [39] described the technique used by the current authors for allograft donor size matching using plain radiographs. Lateral and anteroposterior radiographs corrected for magnification determine the meniscal length and width. The lengths of the lateral and medial menisci are calculated by multiplying the sagittal length of the tibial plateau on the lateral radiograph by 0.7 and 0.8, respectively. Correct use of this technique will provide a graft size mismatch risk of less than 5 % (Fig. 17.4).

When submitting the aforementioned measurements, the surgeon should be familiar with the providing tissue bank, associated procurement techniques, and sizing restrictions. In some circumstances, the tibial plateau-meniscus graft may not be available. Rather, isolated meniscal allograft tissue may be the only available option. In this setting, a measurement formula specific to the meniscal soft tissue is required for size matching. Moreover, the graft should be checked prior to induction of anesthesia, due to the rare incidence of an unacceptable graft due to a tear or compromise of the bone.

Tunnel Placement

Tunnel placement is particularly important in the setting of MAT in revision ACL reconstruction. Prior tibial ACL tunnels with or without tunnel widening may require ACL tunnel repositioning, which can further reduce the space remaining for meniscal tunnel placement. Additional tunnels with a bone plug meniscal transplant technique may be difficult, especially with medial meniscal transplant due to the medial approach commonly used for ACL tibial tunnel placement. Careful preoperative evaluation with CT scan and MRI should be used to plan for tunnel placement or changing to a slot or "keyhole" technique (Fig. 17.5). The tunnel and keyhole positions should be considered not only at the level of the plateau but also within the tibial metaphysis. Nevertheless, tunnel compromise can occur even with the keyhole technique. In either technique, the surgeon must ensure that both the anterior and posterior meniscal horns are securely fixed [42–44]. If there are excessively enlarged tunnels, a two-stage approach might be considered, with bone grafting of the tunnels, followed by graft implantation after tunnel healing. Another option to consider in the setting of enlarged bone tunnels is a blind-ended tunnel in the tibia using a reverse cutting drill (Retrodrill, Arthrex™) (Fig. 17.6).

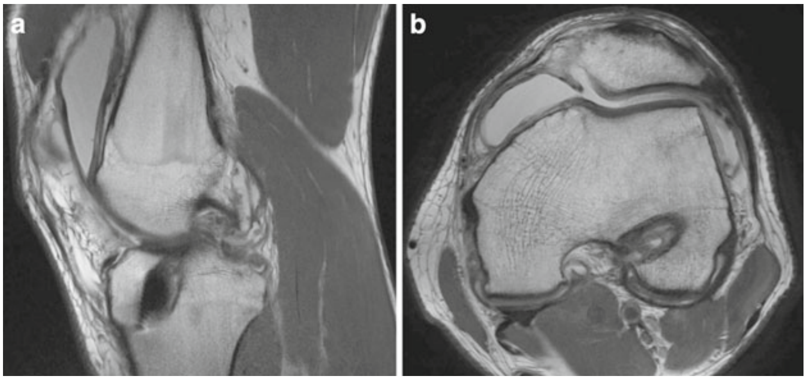

Fig. 17.5 (**a**) Sagittal and (**b**) axial MRI of tibial and femoral tunnel positions, respectively. Minimal evidence of tunnel widening is present in these images. CT imaging may be used to more effectively evaluate osseous architecture if necessary

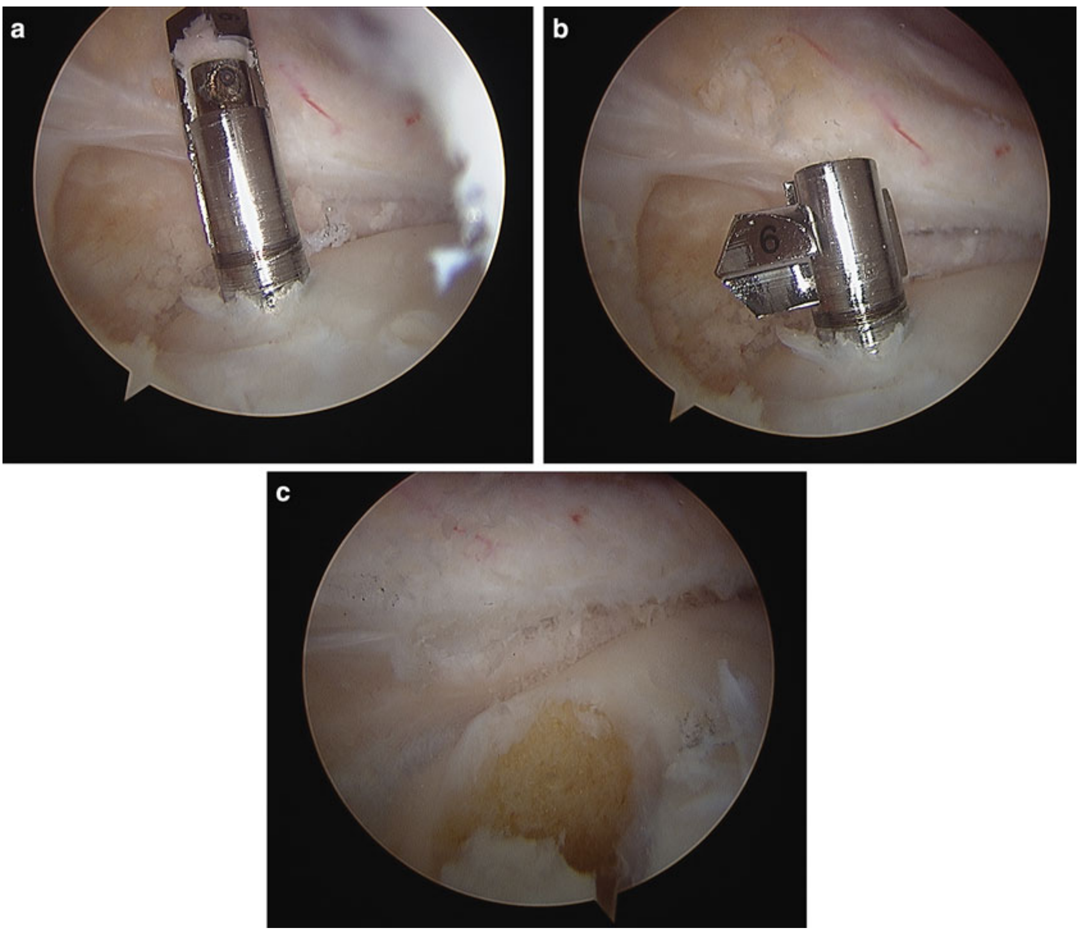

Fig. 17.6 Arthroscopic view of the posterior, medial compartment. (**a**) The retrocutting drill (Retrodrill, Arthrex™) can be placed using an alignment guide in a standard guidepin fashion. (**b**) The cutting piece is deployed, and (**c**) the blind socket is then created using the reverse cutting technique

Surgical Technique

Compartment Preparation

Diagnostic arthroscopy should be performed prior to MAT in revision ACL reconstruction. Radiographic and clinical findings should be visually confirmed and chondral surfaces should be inspected to rule out advanced arthrosis. This inspection is particularly important if the index and revision surgeons differ.

Following diagnostic arthroscopy, the residual meniscal tissue in the desired transplant compartment should be debrided until punctate bleeding is encountered within 1–2 mm of the peripheral rim. Preservation of meniscal vasculature is an important factor in meniscal repair or transplantation. Vascular penetration of the peripheral 10–30 % of the medial meniscus and 10–25 % of the lateral meniscus occurs from the inferior medial and lateral geniculate arteries [45]. The blood supply from this plexus in addition to synovial fluid diffusion serves to provide nutrition to the menisci. Vessels from the capsular periphery provide a source for vascular ingrowth into the transplant.

The osseous insertions of the anterior and posterior horns should also be identified for anatomic transplant tunnel or slot placement. A sub-posterior cruciate ligament (PCL) medial femoral condylar notchplasty or sub-ACL lateral femoral condylar notchplasty may then be performed to provide increased visualization of the posterior horn insertion. This notchplasty will also allow improved passage of the bone plug or keyhole bridge. An open posteromedial or posterolateral approach should also be utilized in preparation for inside-out meniscal capsular suturing.

Allograft Preparation

Preparation of the meniscal allograft directly depends on the fixation method desired by the revising surgeon. This method should be determined during preoperative planning. Intraoperatively, the hemiplateau or full plateau with the attached meniscal allograft should be inspected prior to patient sedation to confirm tissue quality. Following confirmation, excess soft tissue should be removed from the plateau leaving only meniscal tissue and bone. The anterior and posterior horns should then be identified and marked with a sterile marker to ensure anatomic placement and minimize confusion. The hemiplateau can then be machined for either bone plug or keyhole fixation. Sutures are placed through the bone plugs to aid in graft placement and fixation. A traction suture should also be placed at the junction of the middle and posterior third of the meniscus. This suture serves to facilitate meniscal orientation and reduction during placement (Fig. 17.7).

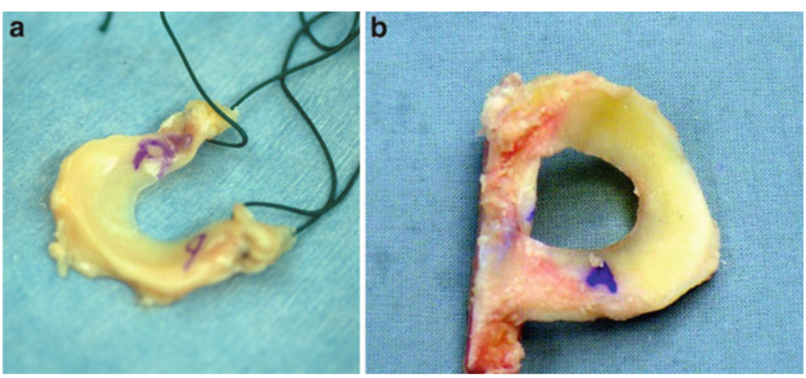

Fig. 17.7 Photograph demonstrating the prepared meniscal allograft including markings for anterior and posterior orientation, traction suture placement, and (**a**) fashioned bone plugs or (**b**) keyhole slot

Surgical Pearls

As mentioned previously, MAT in revision ACL reconstruction can be performed using a bone plug or keyhole technique. The decision regarding which technique to use is largely dependent upon surgeon preference and familiarity. Surgical technique specifics have been previously documented for both techniques and should be reviewed if necessary [3, 46].

Several key points will help ensure successful concomitant meniscus transplant and revision ACL reconstruction. Specific attention should be paid to tunnel and slot placement in the revision ACL setting. In this regard, consideration should be placed on the surgical procedure order. The authors' prefer to perform the requisite procedures in the following order for a bone plug technique: (1) drill ACL tunnels, (2) drill posterior meniscal horn tunnel, (3) reduce the meniscus allograft into the knee with passage of posterior horn sutures, (4) drill anterior meniscal horn tunnel and pass sutures, (5) reduce ACL graft into the knee, (6) secure ACL in femoral socket, (7) secure meniscal horn sutures over bone bridge (when using bone blocks in individual tunnels), (8) suture meniscus to capsule, and (9) secure ACL in tibial tunnel. This surgical order optimizes visualization and improves meniscal allograft passage.

Several techniques may be utilized to facilitate surgical ease and minimize complications. During ACL tibial tunnel reaming, tibial aperture placement should be moved slightly medial, to allow placement of a second tunnel more distally and centrally for the meniscus posterior horn tunnel. This adjustment will not compromise ACL function and will reduce the potential for tunnel communication. Communication between the posterior horn and tibial ACL tunnels may also be avoided by drilling the posterior horn meniscus tunnel from the lateral tibial cortex. While this technique exposes the anterior compartment of the lower leg, it requires only a 2 cm incision with an associated dissection that can be repaired with minimal patient morbidity. Blind socket creation with a reverse cutting drill may also be used to minimize tunnel communication. This technique can be used for both posterior and anterior tunnels, although the current authors prefer to use this technique only for the posterior socket. Instead, an outside-in technique is used for anterior socket drilling. If a keyhole technique is selected, the tibial ACL tunnel entrance should be placed medial and distal to avoid communication with the lateral meniscal allograft slot. If tunnel communication does occur, care should be taken to confirm adequate meniscal allograft and tibial ACL fixation. Tunnel communication with adequate fixation has not been associated with detrimental effect to either the ACL or the meniscal allograft [47]. Finally, the revising surgeon may consider utilizing a smaller ACL graft of 8 or 9 mm diameter if patient-specific tibial anatomy is particularly small. This smaller tunnel will reduce the risk of tunnel violation. However, in general the authors favor using a relatively large graft during revision ACL reconstruction.

In the rare situation, in which both medial and lateral MAT are required with revision ACL reconstruction, the current authors have utilized a modified keyhole technique. This technique is performed using a bulk tibial plateau allograft including medial and lateral menisci and the osseous intercondylar eminence. This bulk allograft is then prepared in a similar manner as previously described for the keyhole technique. However, a single osseous bridge is maintained at the intercondylar eminence that connects both medial and lateral menisci. A single keyhole at the center of the intercondylar eminence is also fashioned. The slot for the dovetail component of the keyhole is then placed at the patient's intercondylar eminence with care taken to remove all surrounding excess bone. The entire construct is then placed through a medial parapatellar arthrotomy and fixed in the aforementioned fashion. The revision ACL tibial tunnel can them be drilled through this construct to allow ideal placement of the tibial aperture.

Concomitant Procedures

Malalignment and failed ACL reconstruction may be associated with an absent meniscus and preserved articular cartilage. In this unique setting, malalignment should be addressed with a realignment osteotomy and concomitant ACL reconstruction. A staged meniscal transplant can then be planned if the patient continues to be symptomatic following surgical recovery. However, consideration may be given to concomitant osteotomy, revision ACL reconstruction, and meniscal allograft transplant in younger patients. This management method should optimize knee stability and chondral protection.

Postoperative Rehabilitation

Postoperative rehabilitation following meniscal transplant and revision ACL reconstruction begins with knee range of motion limited to 90° of flexion. Flexion angles great than 90° increase loads to the posterior meniscal horn and should be avoided for the first 4 postoperative weeks. Focus should be placed on obtaining full extension and preserving quadriceps function with braced straight leg raises and quadriceps isometric contraction in extension. Toe touch weight bearing is maintained with a double-upright hinged knee brace for 4 weeks followed by incremental progression to full weight bearing by 6 weeks. Progressive range of motion is allowed after 4 weeks with continued bracing. Strengthening should begin at approximately 6–8 weeks as range of motion gradually improves. The brace is discontinued at approximately 4–6 weeks. Light jogging is allowed at 4 months based on restoration of appropriate strength, endurance, coordination, and balance. Return to high impact activities is generally not recommended following meniscus transplantation, but may be considered at 6–8 months depending on the patients goals and desires, and after careful discussion regarding risk to the transplanted meniscus. A common dilemma facing the surgeon in the setting of combined meniscus transplantation and revision ACL reconstruction is that the patient usually expects to return to high impact activities, while such activities may compromise durability of the transplanted meniscus. These factors are all discussed with the patient preoperatively.

Concomitant ACL and Meniscal Transplant Surgical Outcomes

Several previous studies have documented the synergism between the menisci and ACL in knee stability. Restoration of meniscus function via MAT should be considered in any revision ACL reconstruction. Previous data have demonstrated complete resolution of symptoms in 85 % of patients following ACL or PCL reconstruction with concomitant MAT [47]. Moreover, retrospective data from ACL reconstruction with concomitant MAT demonstrated 86 % normal or nearly normal IKDC scores and almost 90 % normal or nearly normal Lachman and pivot shift test scores [48]. No significant differences were observed between the transplanted compartment and the contralateral knee compartment. These data suggested that ACL reconstruction with concomitant MAT may play a synergistic role in chondroprotection and knee stability [48]. Yoldas et al. [49] compared 34 MAT in 31 patients; 11 patients were isolated MAT, while 20 patients had MAT with concomitant ACL reconstruction. No significant differences were documented in activities of daily living scale or sports activities scale with respect to the meniscal transplant compartment, degree of chondrosis identified at the time of arthroscopy, or the concomitant ACL reconstruction. Additionally, no significant differences in radiographic joint-space narrowing were identified. Long-term (minimum 8.5 year follow-up) data following medial MAT with concomitant ACL reconstruction demonstrated 88 % normal or nearly normal IKDC symptom evaluation scores and 75 % normal or nearly normal IKDC functional evaluation scores [50]. These studies suggest that MAT with concomitant ACL reconstruction can produce excellent outcomes, and the synergy between the two structures may produce improved results. However, despite good subjective outcomes, direct imaging evaluation of transplanted meniscus tissue has shown progressive degenerative changes in the tissue, and there is currently very little data to suggest that the transplanted meniscus truly functions as a normal meniscus. Further study is needed to identify improved methods of graft processing and sterilization, surgical technique, and methods to enhance biologic incorporation of the graft in order to optimize the results of this procedure.

Summary

The combination of ACL reconstruction and MAT may produce a synergistic effect for chondroprotection and knee stability. This effect may be particularly relevant in the setting of revision ACL reconstruction, as meniscus loss is often present and can lead to increased strain on an ACL graft. Since the failure rates are generally higher in revision ACL surgery compared to primary reconstruction, careful consideration of meniscus status is prudent. A thorough preoperative history, physical examination, and radiographic evaluation should be performed to ascertain the contributors to ACL reconstruction failure. Lower extremity alignment, chondral and meniscal injury, tunnel widening, tunnel position, and prior ACL reconstruction status should be assessed.

Early and mid-term results support the benefit of ACL reconstruction with concomitant MAT from both a chondroprotective and stability standpoint. However, large scale, long-term outcome data are lacking in the literature. Despite good subjective outcomes, direct imaging evaluation often demonstrates progressive degenerative changes in the transplanted meniscus. Meniscus transplantation in the setting of ACL reconstruction may function more to protect the ACL graft during the early period of ACL graft incorporation rather than have a long-term "chondroprotective" effect. For this reason, careful patient selection and counseling regarding the potential long-term patient outcome including increased risk for arthrosis should be performed. Young patients with ACL and meniscal deficiency and minimal chondral injury represent a unique situation in which MAT and ACL reconstruction can be extremely beneficial. Optimizing knee stability and improving chondral protection through ACL reconstruction and concomitant MAT should be considered, especially in this setting.

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18 Cartilage Surgery in Revision ACL Reconstruction

Albert O. Gee and Riley J. Williams III

Introduction

The anterior cruciate ligament (ACL) in the knee is commonly injured with an incidence reported between 36.9 and 80 per 100,000 person-years [1–3]. In the young and active patient population, ACL reconstruction is performed to restore knee stability, protect against future meniscal injury and return patients to pre-injury activity levels. It is estimated that between 2 and 6 % of primary ACL reconstructions will fail [4]. Many of these patients ultimately will undergo revision ACL surgery.

Cartilage injuries associated with ACL tears are common. Concomitant cartilage abnormalities at the time of revision ACL reconstruction occur at a rate between 10 and 70 % [5–18]. This represents a significant difference compared to cartilage lesions encountered at the time of primary ACL reconstruction [19]. Although the majority of these cartilage lesions do not play an important role in overall knee joint stability, in the ACL deficient knee, left untreated they represent potential for poor clinical outcome after revision ACL surgery [7, 17, 20].

ACL deficiency is a contraindication to cartilage repair therapies [21]. The persistent knee instability leads to a high likelihood of repair failure due to increased shear stress on the articular cartilage of the knee. Therefore, revision of a failed ACL reconstruction is important not only from the standpoint of ligament stability and return to athletic participation but as protection for the cartilage repair. The primary goal of surgical intervention should be directed toward the reestablishment of joint stability and congruity through ligament reconstruction coupled with cartilage restoration strategies when indicated. The purpose of this chapter is to discuss the approach to cartilage repair surgery in the setting of revision ACL reconstruction.

"Bone Bruise" and Articular Cartilage Injury Associated with ACL Rupture

Patients with ACL deficiency are at increased risk for future cartilage problems and posttraumatic osteoarthritis compared to healthy individuals. This process of articular cartilage degeneration may be independent of ACL status, with several studies recently showing continued cartilage degradation despite stable ACL reconstruction [22, 23].

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Fig. 18.1 Sagittal fat-suppressed T2-weighted MRI sequence demonstrates typical bone marrow edema pattern ("bone bruise") after acute anterior cruciate ligament tear

The significance of the bone marrow edema pattern that is commonly associated with ACL injury remains poorly understood. These "bone bruises," areas of increased signal intensity best visualized on the T2-weighted MRI images (Fig. 18.1), are present in approximately 80 % of ACL tears [24, 25]. This bone marrow edema pattern represents evidence of transchondral injury that results from the impact that occurs during the pivot-shift phenomenon as the posterolateral aspect rotates forward and the tibia impacts the anterolateral femur. These lesions are most commonly seen after acute ACL ruptures on the posterolateral tibia and the anterolateral femoral condyle. Studies that followed these lesions on MRI over time have shown that the bone marrow edema improves with time. However, the damage to the overlying cartilage is irreversible [26–28].

Histologically, these areas of articular cartilage have been shown to undergo chondrocyte and matrix degeneration [29]. This has been corroborated by Potter et al. using MRI studies to follow patients with isolated ACL tears over time [22]. Their study identified acute cartilage damage overlying the areas of bone bruising at the time of injury as well as ongoing cartilage loss with time despite undergoing ACL reconstruction. Unfortunately, the investigators found that the rate of cartilage loss accelerated at 5–7 years after initial injury and was not limited to the lateral hemijoint where the original impaction occurred. Instead, the medial and patellofemoral compartments showed the highest rate of cartilage loss.

Clinical Approach

Surgical decision-making for the treatment of focal cartilage lesions in the setting of ACL deficiency should proceed in a logical fashion and should not be altered by the decision-making regarding the ACL. Once ACL reconstruction or ACL revision reconstruction is planned, the approach to the concomitant cartilage lesion should not differ from that of an isolated lesion. Thus, the surgical indications remain unchanged and include:

1. Isolated chondral or osteochondral lesion of the knee condyles, trochlea, or patella
2. Symptoms of knee dysfunction (pain, recurrent effusion, mechanical symptoms)
3. Normal or correctable knee ligament stability
4. Normal or correctable alignment
5. Functional meniscus tissue (>50 % native meniscal volume)

Contraindications to cartilage repair:

1. Degenerative knee osteoarthritis
2. Systematic inflammatory disorders (e.g., rheumatoid arthritis)
3. Collagen or vascular disorders
4. Obesity
5. Chronic use of immunosuppressive medication (e.g., corticosteroids)

The surgeon should have a clear approach to articular cartilage injuries of the knee and must take into account both patient and surgeon factors in the decision-making process. The first step is to identify the factors that will affect treatment on the patient's side. This starts with categorization of the likely etiology of the chondral defect.

Most commonly, cartilage defects occur secondary to traumatic injury, chronic degeneration or an abnormality in the underlying bone such as avascular necrosis (AVN) or osteochondritis dissecans (OCD). In the setting of an ACL deficient knee, most commonly the cause is traumatic, but this is not always the case. Therefore, careful thought must be given to the etiology in order to address this in advance of or concomitant with ACL reconstruction.

The next consideration is the characteristics of the cartilage lesion which should include:

1. Size
2. Location
3. Grade
4. Lesion morphology

It is important to obtain as much of this information as possible preoperatively as this impacts surgical decision-making. This is best achieved through the use of cartilage-sensitive MRI imaging. However, sometimes the true nature of the lesion will not be apparent until it is visualized intra-operatively and the surgeon must be prepared for this possibility.

During the evaluation process, one must not forget to determine the global condition of the knee and the lower extremity. If there are abnormalities that could jeopardize the success of the cartilage repair these will need to be addressed. Ligament deficiencies should be corrected by repair or reconstruction. Any meniscus tear(s) should be appropriately debrided, repaired or replaced with allograft transplantation. Limb malalignment may need to be corrected using an osteotomy and most importantly, the patient should have preserved articular cartilage surfaces (Grade 2 or better) throughout the remainder of the joint.

Special note should be made concerning multiple focal cartilage defects. Although this is not an absolute contraindication to multiple repairs, the surgeon should proceed with caution in these situations as this likely represents early generalized cartilage degeneration. One must pay particular attention to bipolar (i.e., opposing condyle-plateau or patella-trochlea) lesions which have been noted in studies to fare poorly when they have been treated using osteochondral allografts [30, 31].

Preoperative Planning

Prudent preoperative planning for cartilage repair must also take into consideration patient-related characteristics. These include:

1. Age
2. Body mass index (BMI)
3. Level of demand
4. Systemic conditions of disease
5. Patient functional needs
6. Patient expectations
7. Ability to comply with rehabilitation

The age and BMI have importance when deciding on treatment options as there have been studies that demonstrated a negative clinical effect of increasing age and patients with higher BMIs undergoing specific cartilage restoration techniques [32, 33]. The level of demand of the patient and functional need should also be considered as these have implications for treatment decisions. The elite collegiate or professional athlete will place a vastly different demand on his knee than the middle-aged "weekend warrior" and so different treatment regimens should be considered in those situations.

One additional aspect of preoperative planning involves assessment of the surgeon's own characteristics. This refers to the insight of the surgeon into his surgical skills and abilities with the many varied techniques that have evolved for cartilage repair and regeneration. The different surgical treatments can vary in their degree of technical difficulty, which must be taken into consideration along with the surgeon's level of experience and comfort with each procedure.

Patient Evaluation

The patient evaluation begins with a thorough history and physical examination. Specific attention is given to previous treatments, especially in regards to previous ACL reconstruction, including graft type and concomitant intra-articular findings at the index surgery. The mechanism of reinjury should be sought and the etiology of ACL graft failure should be pursued. Obtaining arthroscopic images from the previous surgeries can be helpful in understanding the status of the cartilage at the time of the index reconstruction and for future preoperative planning.

The initial imaging studies should include plain radiographs of the knee, including weight-bearing anteroposterior (AP), 40° posteroanterior (PA), lateral, Merchant's view. The bilateral standing hip-knee-ankle AP view can also be helpful in determining overall limb-alignment. Further imaging with cartilage-sensitive MRI, which is the imaging modality of choice in these cases, is essential. This allows the surgeon to evaluate the previous ACL graft (or lack thereof) and assesses the meniscus as well as articular cartilage for any concomitant abnormalities.

Special attention must be paid to the patient with patellofemoral joint cartilage lesion(s) in the setting of a previous ACL reconstruction. In this case, it is not uncommon for pain and/or mechanical symptoms stemming from the patellofemoral articulation to be reported by the patient as a subjective history of knee instability. This subtlety must be discerned by the clinician by detailed history taking, a thorough knee examination and MRI evaluation for the status of the previous ACL graft and the status of the cartilage surfaces.

Current Cartilage Repair Strategies

Articular cartilage injuries and their treatment remain difficult problems in orthopaedics. The broad categories of treatment options available to the surgeon include:

1. Mechanical debridement
2. Intrinsic repair enhancement: marrow stimulation
3. Whole tissue transplantation
    (a) Osteochondral autograft (mosaicplasty)
    (b) Osteochondral allograft
4. Cell-based repair
5. Cell and scaffold-based repair
6. Scaffold-based repair

Mechanical Debridement

This involves the arthroscopic debridement of any chondral flaps and general lavage of the knee joint without any attempt to fill the cartilage defect. This is used as a palliative therapy as it serves to remove the potential mechanical and biochemical sources of pain but does not repair the lesion(s). This procedure is indicated in the setting of early generalized cartilage degeneration where other repair strategies are contraindicated.

Marrow Stimulation

The goal of marrow stimulation, or microfracture, is recruitment of marrow-based stem cells to the site of the cartilage defect by perforation of the subchondral plate at the base of the lesion. This is a simple and low-cost option and can be used in small and large lesions. This technique requires a stable blood clot to form and fill the defect. The clot contains cells and growth factors that ultimately fill the defect with fibrocartilage. The disadvantages of this technique include the lengthy postoperative rehabilitation process and that microfracture achieves fibrocartilaginous healing which is structurally inferior to hyaline cartilage.

The success of microfracture has been shown to be dependent on adequate fill of the defect and this is dependent on good surgical technique [34–36]. Preparation of a well-contained lesion at the time of surgery is critical and involves the debridement of the surrounding zone of cartilage injury back to a healthy rim of cartilage that will serve to "shoulder" the clot. Debridement of the calcified cartilage layer found at the base of the lesion also facilitates stable clot adhesion and is important for success of this technique [37]. Also, the perforations into the subchondral bone must be of sufficient depth to reach marrow elements and visualization of fat-droplets at the time of microfracture ensures that this has been achieved (Fig. 18.2).

Postoperatively, patients are maintained non-weight bearing for a minimum of 6 weeks as early weight bearing can lead to collapse of the subchondral plate or flattening or dislodgement of the clot. Continuous passive motion (CPM) from 0 to 60° is initiated immediately and continued for the first 6 weeks. CPM should be performed for 6–8 h per day and the flexion may be increased 10° per day until full motion is achieved. Isometric exercises and dynamic quadriceps strengthening is

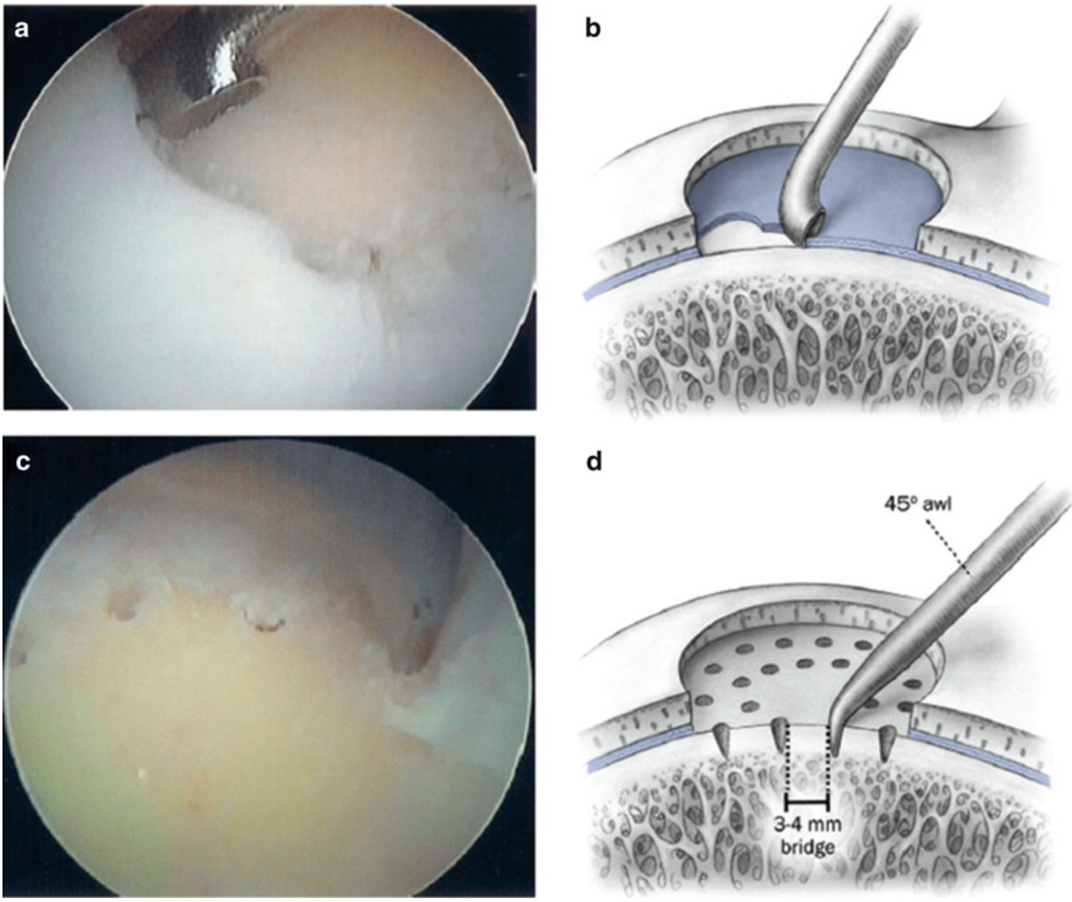

Fig. 18.2 (**a**, **b**) Demonstrate the creation of a well-shouldered lesion to achieve a stable base for filling of the defect with a clot and adhesion of the clot after microfracture. The calcified cartilage layer at the base of the lesion must be removed to allow clot adhesion. (**c**, **d**) Show that channels must be of sufficient depth to ensure penetration of the subchondral plate and communication with the marrow (reproduced with permission from Bedi A, Feeley BT, Williams RJ III. Management of articular cartilage defects of the knee. J Bone Joint Surgery Am. 2010;92:994–1009)

started 1 week after surgery under the guidance of a physical therapist and water exercises and stationary bicycle therapy is initiated at 2 weeks if range of motion allows. Pivoting and jumping activities are prohibited until a minimum of 4 months after surgery. Running is restricted until 6 months after surgery and return to high-level sports is permitted at 8–12 months depending on quadriceps and core strength.

Steadman and his colleagues have reported success with microfracture for full-thickness traumatic cartilage defects at an average follow-up period of 11 years [33]. Mithoefer and his colleagues also showed that 67 % of 48 patients had good to excellent response who underwent microfracture for lesions between 1 and 4 cm^2. In their analysis, the authors noted that lower BMI was a predictor of better outcomes and that the initial clinical response deteriorated with time in 47 % of elite athletes [32, 38]. Several other studies have investigated microfracture for cartilage lesion in elite professional athletes in football and basketball and reported over 70 % return to play postoperatively [39, 40].

Whole Tissue Transplantation

Osteochondral Autograft Transfer/ Mosaicplasty

Osteochondral autograft transfer, also known as mosaicplasty, is used to treat focal full-thickness

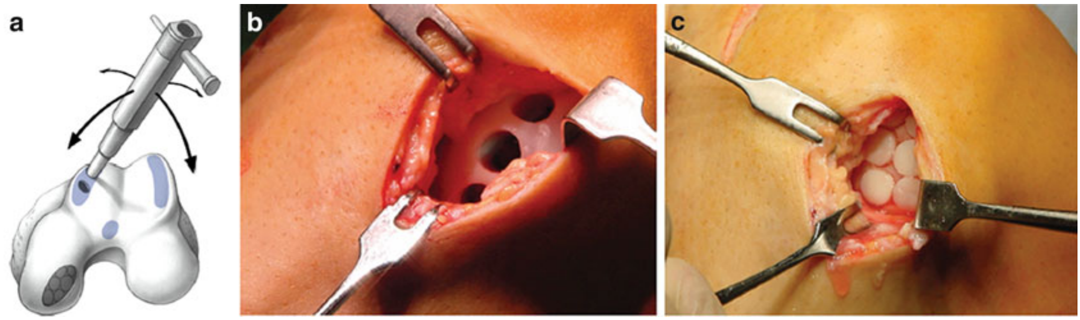

Fig. 18.3 (**a**) Schematic drawing demonstrating the autologous osteochondral transplantation technique. (**b**) The donor region along the trochlear margin can be accessed through a small arthrotomy and visualized with the knee in extension. (**c**) Flexion exposes the recipient chondral defect through the same exposure and allow placement of grafts in the desired configuration to fill the lesion (reproduced with permission from Bedi A, Feeley BT, Williams RJ III. Management of articular cartilage defects of the knee. J Bone Joint Surgery Am. 2010;92:994–1009)

cartilage defects most commonly occurring from traumatic etiologies and it can also address lesions associated with significant bone loss such as OCD. This technique involves the transplantation of multiple small cylindrical osteochondral plugs (forming a mosaic) into a larger sized cartilage defect from the less weight-bearing aspects of the knee joint. The advantages of this procedure include the fact that viable hyaline cartilage is directly transplanted into the defect, the grafts are press-fit and do not require additional fixation, the rehabilitation process is relatively short, and the procedure is performed in a single-stage either arthroscopically, or arthroscopically aided with a mini-arthrotomy.

The main disadvantages of the procedure are the donor site morbidity and the limitations in terms of size of defects that this technique can address due to the autologous nature of the donor plugs (the osteochondral plugs are taken from the periphery of the patellofemoral joint and/or the area adjacent to the intercondylar notch) (Fig. 18.3). The indication for mosaicplasty is a focal full-thickness cartilage lesions ranging from 1 to 5 cm^2. Osteochondral transfer is more technically demanding than other techniques such as microfracture and usually requires an open arthrotomy. Other limitations include the persistence of gaps in the mosaicplasty, graft subsidence with weight-bearing, and donor-recipient site mismatch in terms of cartilage orientation, thickness and mechanical properties [41].

Several studies of mosaicplasty have shown good clinical success in the treatment of Outerbridge grade III and IV lesions [42, 43]. Hangody showed clinical success with this technique at long-term follow-up on full-thickness cartilage lesions on the femoral, tibial and patellofemoral articulations with minimal donor site morbidity [44]. Nho et al. performed a retrospective review of isolated patellar chondral lesions treated with this technique and showed a significant clinical improvement in IKDC score and MRI evidence of complete or near complete fill in all plugs at final follow-up [45]. Ozturk and his colleagues showed similar results using mosaicplasty in a series of 19 patients and reported 85 % good to excellent results at a mean follow-up of almost 3 years [46].

When compared with microfracture, osteochondral autograft transfer has shown better clinical results and biopsy specimens taken from both groups at second-look arthroscopy demonstrated better repair with osteochondral autograft. The authors of the study concluded that the osteochondral autograft transplantation was superior to marrow stimulation for patients under the age of 40 years [47].

Osteochondral Allograft Transplantation

This procedure entails the transplantation of a cadaver graft into the cartilage lesion. As the donor graft can be tailored to the size, location and depth of the cartilage defect, there is improved fit and fill of the plug when compared to mosaicplasty. As with mosaicplasty, this procedure is performed arthroscopically assisted

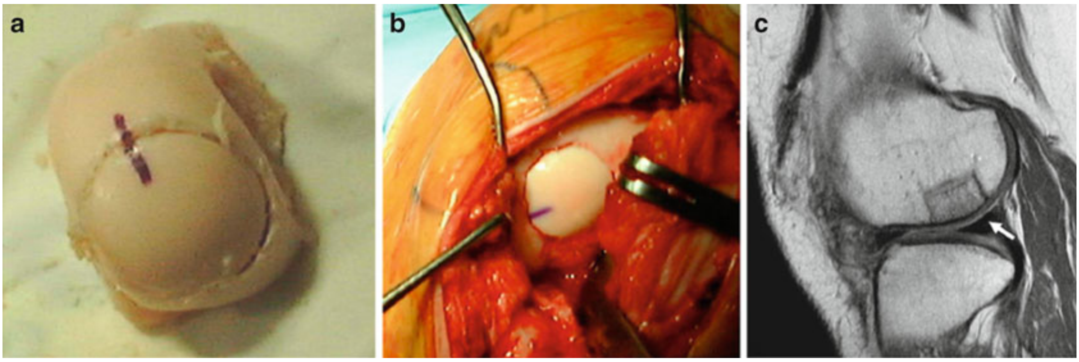

Fig. 18.4 (**a**) Harvesting of an osteochondral allograft dowel from a hemicondylar specimen with the size and radius of curvature matched to the recipient. (**b**) Implantation with circumferential flush congruity at the recipient site for the treatment of an osteochondritis dissecans lesion of the femoral condyle. Corresponding pen marks are made at the 12, 4, and 8 o'clock positions in an effort to optimally match the orientation and surface congruity between the donor graft and the recipient defect. (**c**) Sagittal fast spin-echo magnetic resonance image made at 24 months after implantation of the osteochondral allograft. There is excellent lesion fill and congruency with the adjacent native cartilage interface. The graft demonstrates articular cartilage signal (*arrow*) that is isointense compared with the native hyaline cartilage (reproduced with permission from Bedi A, Feeley BT, Williams RJ III. Management of articular cartilage defects of the knee. J Bone Joint Surgery Am. 2010;92: 994–1009)

with a mini-arthrotomy. Using specialized proprietary instrumentation, a cylindrical osteochondral plug is obtained from the allograft (Fig. 18.4), preferably from the same location of the same hemijoint such that the contour and shape matches the donor site. The recipient site is prepared using a cylindrical punch which is slightly smaller in diameter which allows for press-fit fixation without additional hardware.

There are several advantages of allograft transplantation including the ability to address larger size cartilage defects with a single osteochondral plug which better reproduces the contour of the surrounding cartilage, no donor site morbidity, and the surgery can be performed in a single-stage in combination with the ACL reconstruction. Concerns with this technique include high cost and donor tissue availability, the rare possibility of disease transmission, and graft rejection [48].

A number of investigations of osteochondral allograft transplantation have shown durable and reliable clinical outcomes for the treatment of posttraumatic cartilage injuries as well as OCD [30, 31, 49, 50]. Several studies have shown over 80 % success using this technique for isolated unipolar full-thickness cartilage lesions up to 8 cm^2, but much poorer results were noted in patients who had allograft transplantation for the treatment of bipolar lesions, or who had more systemic derangement of the knee joint, including osteoarthritis, inflammatory arthritis and limb malignment [30, 31, 49, 51]. Overall survival rates of this technique have been shown to be over 65 % at 14 year follow-up [52].

Autologous Chondrocyte Implantation

This cell-based technique was originally described in 1994 by Brittberg, Peterson and colleagues [53]. Autologous chondrocyte implantation (ACI) is a two-staged procedure in which autologous chondrocytes harvested arthroscopically from the patient during the first-stage are processed and expanded in a laboratory and are implanted back into the defect under a periosteal patch in the second-stage (Fig. 18.5). The main advantage of ACI is that it can be used to treat large (2–10 cm^2) uncontained lesions as long as the subchondral bone is well preserved.

Additionally, histologic studies have shown that, when successful, this technique fills the defect with hyaline-like cartilage tissue which may have better biomechanical properties and durability than fibrocartilage [53, 54]. The disadvantages of

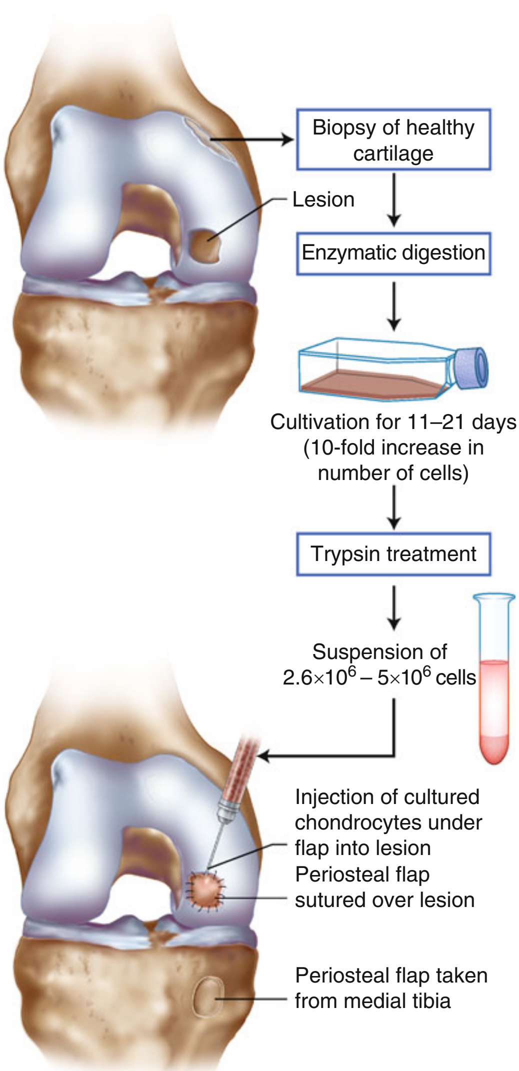

Fig. 18.5 Diagram demonstrating the two-step autologous chondrocyte implantation (ACI) process

ACI are the need for two procedures, higher technical demand with the potential for full arthrotomy (depending on the location of the lesion and type of patch used to cover the defect) and the extremely high cost of the technique.

Brittberg et al. [53] demonstrated good to excellent results in 14 of 16 femoral condyle chondral lesions ranging from 1.6 to 6.5 cm^2 at 4 year follow-up. Only 2 of 7 patients with ACI for patellar lesions showed as good result, however. Second-look biopsies showed hyaline-like cartilage in 11 of 15 femoral lesions and 1 of 7 patellar lesions. Since that time, longer follow-up periods in their series have shown a significant learning curve as graft failure in the hands of the same investigators diminished as they gained facility with the procedure. They also noted that their outcomes when treating patellar lesions with ACI improved when better attention was paid to correcting patellar maltracking at the time of implantation [55]. ACI has been shown to have durable clinical success in the majority of patients (51 of 61 had good to excellent results) at a mean follow-up of 7.4 years [54].

ACI has also been evaluated as a salvage method for failed previous treatment of chondral lesions in the knee. Zaslav and his colleagues showed that 76 % of 126 patients who were revised using ACI showed good clinical results at an average of 4 years [56].

Comparing ACI to other cartilage repair techniques, several studies have shown superior result to both microfracture and osteochondral autograft transplantation. Investigators noted superior repair characteristics at second-look arthroscopy compared to the other techniques, although the recovery process was more prolonged in the ACI group compared to osteochondral autograft [43, 57].

One of the major concerns of ACI relates to its high complication rate. Adverse events following ACI have been tabulated by the US Food and Drug administration from 1996 to 2003 [58]. During that time, 294 adverse events were reported, with graft failure the most common complication (24.8 %), followed by delamination (22.1 %) and tissue hypertrophy (17.7 %). Over 90 % of these 294 patients had to undergo at least one operation as a result of an adverse event. Thus, the surgeon should understand that this procedure is not without a significant learning curve and a significant potential for a complication that will likely require another operation.

Other Cell- and Scaffold-Based Repair Methods

More recent cell-based techniques have emerged in an effort to improve upon the results of ACI. These second-generation techniques improve upon ACI by coupling harvested chondrocytes with bioabsorbable and biocompatible scaffolds which provide a matrix for cell infiltration and survival during the preimplantation process of expansion. Two such scaffolds are Matrix-associated chondrocyte implantation (MACI (Genzyme Europe, Netherlands)) which uses a porcine membrane made up of collagen type I/III and Hyalograft C (Anika Therapeutics, Bedford, MA), which provides a three-dimensional matrix derived from benzylic ester of hyaluronic acid. The theory behind these scaffolds is recreation of the native milieu of the chondrocyte, thereby inhibiting dedifferentiation of chondrocytes during the cell-expansion phase, and also serving to distribute cells more evenly throughout the defect.

This technique eliminates the need for periosteal flap coverage of the defect and the associated morbidity of flap harvest from the proximal tibia. It also simplifies the procedure as these cell-seeded scaffolds can often be fixed to the lesion without the need for suture, and if the lesion is accessible, can be implanted arthroscopically. Although there is favorable animal and small human trials data for both MACI and the Hyalograft C [59–71], this technique remains experimental in the United States at this time and lacks long-term clinical outcomes data to prove its efficacy and durability.

Synthetic Scaffold-Based Repair

Fully synthetic, biphasic scaffolds that attempt to recreate separate cartilage and bone components of the osteochondral defect have also shown encouraging results in animal studies and small clinical trials [72, 73]. The TruFit™ (Smith and Nephew, Memphis, TN) implant is one such implant that has been approved for use in human applications and is commercially available, but remains investigational. The implant is made up of a combination of polylactide-co-glycolides (PLG), polyglyoclides (PGA), calcium sulfate, and surfactant and is a porous, biodegradable implant with a bilayer design which provides both a bone phase and an overlying cartilage phase with mechanical properties of each phase that are similar to the adjacent native bone and cartilage tissue. It is intended to stimulate cellular and matrix ingrowth into the implant as the synthetic component degrades over time (Fig. 18.6).

The advantages to this implant are its unlimited supply to address lesions of all sizes without any donor site morbidity or potential for disease

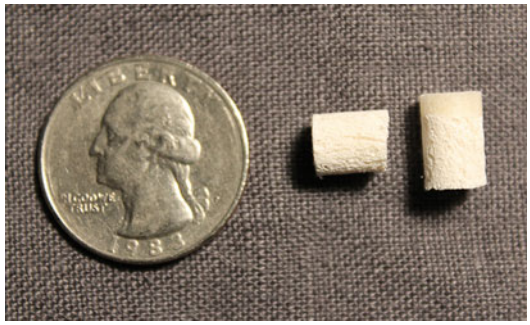

Fig. 18.6 Picture of a fully synthetic biodegradable multiphase implant that attempts to match the adjacent articular cartilage and underlying subchondral bone morphologically and mechanically (TrueFit CB, Smith and Nephew, Memphis, TN)

transmission. However, the cost of the implant and the paucity of clinical studies with sufficient follow-up time should prompt the surgeon to proceed with caution when considering this treatment option, at present.

Outcomes of Simultaneous ACL Revision and Articular Cartilage Repair

Unfortunately, there are no studies to our knowledge looking at outcomes after ACL revision and cartilage procedure performed at one time. What little literature exists on this topic comes from a few studies of outcomes after simultaneous cartilage repair and primary ACL reconstruction. In a recent systematic review, Brophy et al. found a total of six small case series with limited follow-up duration and all but one of those series was retrospective in nature. Together they demonstrated good clinical results using a variety of patient reported outcomes with several different cartilage repair techniques including ACI, mosaicplasty and periosteal transplant. Oddly, there is no data on the use of the microfracture technique in this setting [74].

Timing of Surgery for ACL and Cartilage

Concomitant articular cartilage defect and ACL deficiency can present the surgeon with timing complexities that must not be overlooked [75].

First, the surgeon must recognize that despite advances in the quality and resolution of MRI, the possibility exists that focal cartilage lesions may go undetected until the time of revision ACL surgery. With the knowledge that associated cartilage problems have been reported as high as 70 % at the time of revision ACL surgery, the surgeon should make every effort to detect symptomatic lesions preoperatively for the sake of planning and patient education. As this is not always possible, this scenario should be discussed with the patient before surgery and thought should be given to the patient's level of demand and functional expectations to aid in sound intra-operative decision-making when cartilage injuries are discovered unexpectedly.

In the setting of ACL revision with prior knowledge of a symptomatic articular cartilage defect, the surgeon can be prepared with the appropriate treatments which can be discussed with the patient in advance and allografts and equipment made available at the time of surgery. In these situations, all potential repair strategies can be considered and treatment selection is based on lesion size, location and morphology and taking into account patient demand (see following section). Except for ACI, all other cartilage procedures can be performed at the time of ACL revision with an all-arthroscopic or open arthroscopically assisted approach depending on the location and size of the defect (Fig. 18.7). The cartilage biopsy for an ACI procedure can be taken prior to revision surgery and both the second-stage implantation of expanded cells and ACL revision can be performed 4–6 weeks later, or the cartilage biopsy can be taken at the time of the revision and the ACI can be performed as a separate second-stage.

When a focal cartilage lesion is detected unexpectedly at the time of surgery, the decision-making process becomes more complicated. Without prior discussion with the patient, cartilage repair strategies such as allograft transplantation may not be ethical to perform, not to mention that allograft availability would be unlikely without prior planning. Otherwise, based on the size and location of the defect, microfracture, mosaicplasty and ACI are all possible treatment options assuming that the specialized surgical equipment is available for each procedure (for ACI only the cartilage biopsy can be taken at the initial surgery and a staged repair will be done at a later time). Large defect size eliminates mosaicplasty as a potential treatment due to donor site morbidity. Microfracture, on the other hand, is not limited by the size of the lesion, is simple to do and requires very little in the way of specialized equipment. Furthermore, microfracture adds very little morbidity to the ACL surgery and does not preclude the future use of alternate repair strategies if it were to fail.

The surgeon should keep in mind that when significantly large cartilage lesions are identified unexpectedly at the time of ACL surgery, the cartilage procedure can be delayed until after ACL revision surgery and postoperative rehabilitation have been completed. At that time, based on patient factors and the extent of cartilage injury, the remaining lesion can be treated as an isolated problem, using the same algorithm that is presented below.

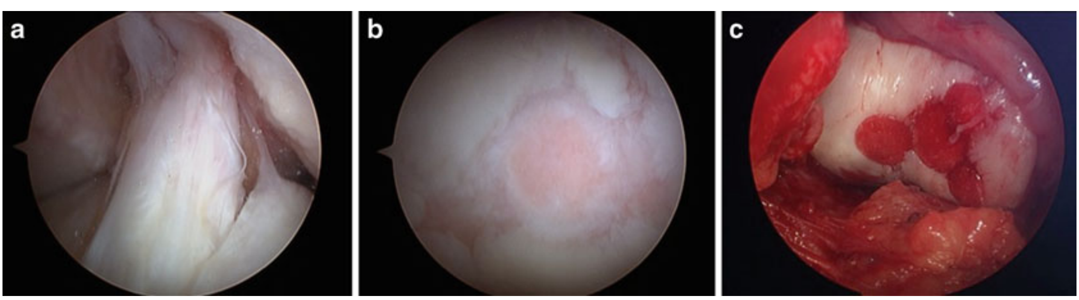

Fig. 18.7 Intra-operative images of a failed ACL graft (**a**) and a large trochlear osteochondral lesion (**b**) noted at the time of ACL revision surgery. (**c**) The trochlear lesion was treated with several synthetic osteochondral plugs (TrueFit CB, Smith and Newphew, Memphis, TN)

Treatment Algorithm

With the variety of surgical options that are available for cartilage repair, an algorithm is helpful to the surgeon in making sound clinical decisions about treatment. Our surgical treatment algorithm is based on three important factors which are: (1) the lesion size, (2) the demand level of the patient and (3) whether the lesion has been surgically treated previously (Fig. 18.8). The size and previous treatment modality can be obtained

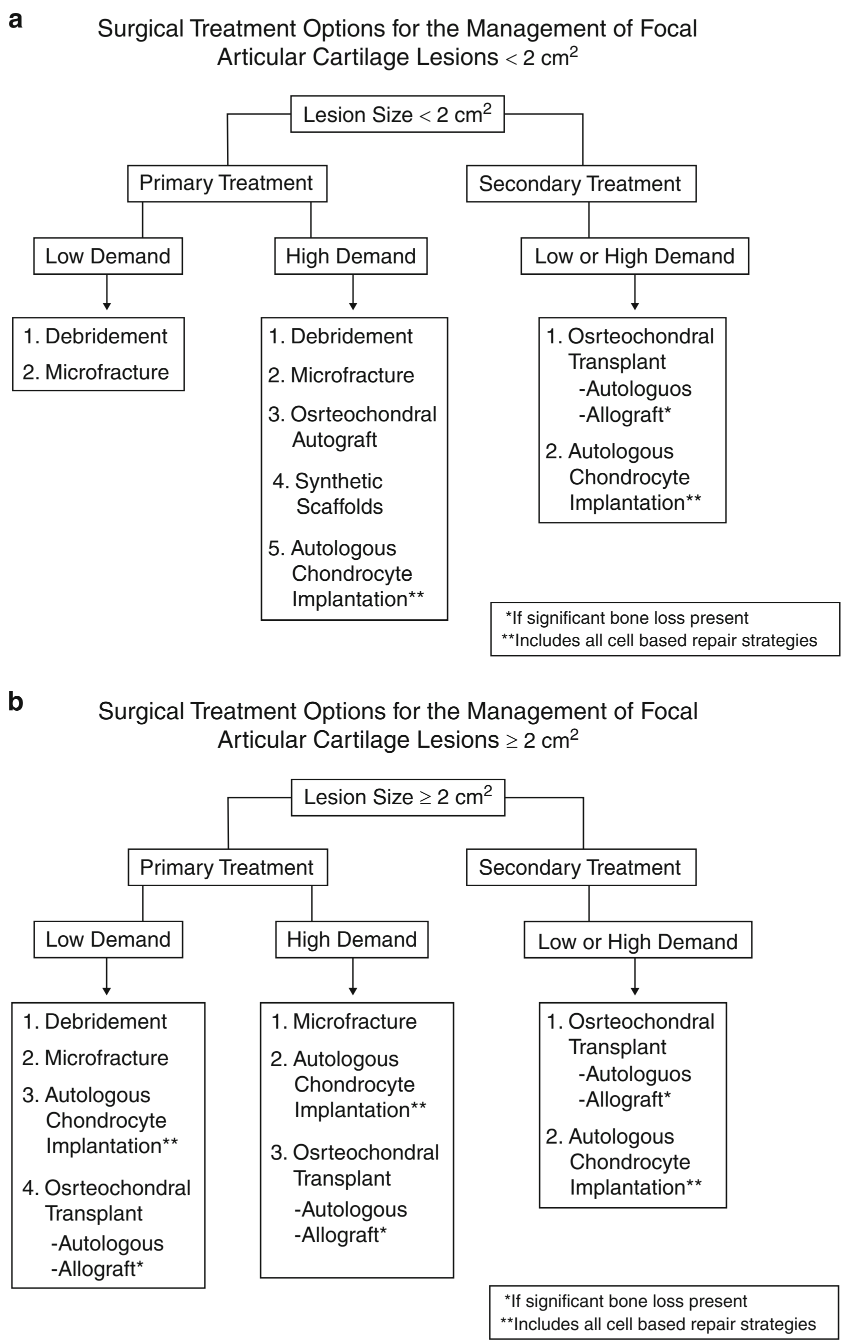

Fig. 18.8 (**a**, **b**) Articular reconstruction algorithm. This algorithm takes into account lesion size, patient demand level and the application of any previous surgical intervention as the primary considerations in determining the appropriate treatment

from the preoperative MRI, arthroscopic images and operative reports from previous procedures, and/or at the time of the revision ACL reconstruction if the cartilage reconstruction will be staged. A distinction is made at 2 cm^2 and between high- and low-demand patients. High- vs. low-demand is determined by whether the patient plans to engage in sporting activities or is a strenuous laborer for more than 2 days out of the week. We believe this provides the surgeon with a logical and relatively simple framework for thinking about articular cartilage injury and its many treatment options.

Conclusion

Articular cartilage injuries are among the most difficult problems in orthopaedics. ACL deficiency in this setting adds to the complexity of the problem. However, many good options for treatment of articular cartilage lesions are available and new and exciting therapies are on the horizon. Once the decision is made to revise the failed ACL reconstruction, evaluation and treatment of the cartilage lesion is largely independent of the ACL, as long as consideration is given to the timing of the cartilage repair. Outcomes of combined ACL and cartilage restoration remains limited in the literature, but with emerging technologies in both cartilage imaging and cartilage repair strategies, there is much optimism for future improvements in the care of this challenging problem.

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19 Medial Collateral Ligament Laxity in Revision ACL Reconstruction

Iftach Hetsroni, Gian Luigi Canata, and Robert G. Marx

Introduction

The medial collateral ligament (MCL) is the primary restraint to valgus stability of the knee. At 20–30° flexion it provides approximately 80 % of the restraining force, whereas at full extension, it provides approximately 60 % of the restraining force with the posteromedial capsule, posterior oblique ligament (POL), and ACL providing the remaining restraint [1]. Therefore, the importance of recognizing and addressing dysfunction of this ligament in the setting of ACL reconstruction surgery cannot be overemphasized. Failure to do so can result in excessive valgus stress applied to the ACL graft, leading to graft failure [2, 3].

In this chapter, the anatomy of the MCL is reviewed. Clinical tools for assessing MCL laxity are then described, followed by surgical management options and clinical outcomes after surgery.

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Anatomy of the MCL

The MCL has three major components: (1) the superficial MCL, which is the largest; (2) the deep MCL, and; (3) the POL [4]. The superficial MCL originates on an average of 3.2 mm proximal and 4.8 mm posterior to the medial epicondyle and inserts on the proximal tibia, just anterior to the posteromedial crest of the tibia and posterior to the pes anserinus insertion [4]. The deep portion of the MCL is a thickened part of the medial joint capsule, lying deep to the superficial part of the MCL, and has meniscotibial and meniscofemoral components. The femoral attachment is 12.6 mm distal and deep to the femoral attachment of the superficial MCL, and the tibial attachment lies just distal to the edge of the articular cartilage of the medial tibial plateau, 3.2 mm distal to the medial joint line [4]. The POL, primarily functioning as an additional medial knee restraint when the knee is extended, is a fibrous extension of the distal aspect of the semimembranosus that blends with the posteromedial joint capsule. Its major and central portion attaches on the femur 7.7 mm distal and 2.9 mm anterior to the gastrocnemius tubercle [4], which is just proximal and posterior to the femoral insertion of the superficial MCL.

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Assessment of MCL Dysfunction

History: Patients with combined ACL and MCL deficiencies are likely to complain of a sense of instability primarily during activities that involve planting with pivoting or cutting maneuvers. While this presentation is typical to patients with an isolated ACL deficiency as well, the addition of MCL deficiency may also result in a sense of valgus instability in particular, which may occur during changing directions or while passing a soccer ball with the injured limb. In rare chronic cases of MCL attenuation in patients with valgus malalignment, valgus thrust gait may develop, resulting in a sense of the injured knee becoming more knocked-kneed during the stance phase of the gait cycle. This is analogous to varus thrust gait that may develop in chronic cases of lateral constraints attenuation.

Physical examination: Physical examination should begin with assessment of alignment and gait. Specific attention should be paid to valgus malalignment with or without noticeable valgus thrust gait. When excessive valgus is confirmed with hip-to-ankle AP X-rays, it may suggest that valgus moments applied to the medial ligaments play a role in the instability. Therefore, varus-directed osteotomy to correct the alignment should be thought of as a first step before ligament reconstruction is considered [5]. This may result in decreasing valgus moments and consequently may lead to the resolution of the sense of instability. In some cases, this procedure may avoid the need for ligament reconstruction. Following assessment of alignment and gait, the knee is examined for intra-articular fluid, patellofemoral joint pain, tracking and stability, range of knee flexion and extension, and cruciate and collateral ligament laxity. The uninjured contralateral knee is used as a baseline for comparison. MCL laxity should be tested and graded with valgus stress applied at 0° and at 20–30° knee flexion. MCL laxity Grade 0 corresponds to 0–2 mm side-to-side medial opening difference, Grade 1+ corresponds to 3–5 mm difference, Grade 2+ corresponds to 6–10 mm difference, and Grade 3+ corresponds to more than 10 mm difference [6–8].

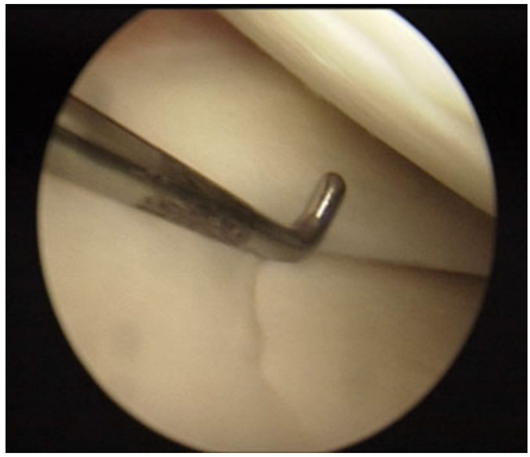

Fig. 19.1 Arthroscopic view of a left knee, suggesting Grade 2+ MCL laxity

Imaging: Stress X-rays can also be used to provide further quantification of medial laxity. However, the amount of medial opening on stress X-rays that correlates with a specific grade of MCL laxity has not been well documented in vivo. Recently, reference values were provided, but this was tested in a cadaveric model using elderly subjects, which may not apply to young or middle-aged living humans [9].

Examination under anesthesia: The operated knee should be examined under anesthesia and compared with the nonoperated side for range of motion and ligament laxity prior to arthroscopic surgery. Physical examination of the MCL relies both on the patient's ability to relax and the clinician's skill to detect the amount of medial opening and the presence or absence of an endpoint. In the anesthetized patient, ligament evaluation is facilitated, without muscle guarding.

Arthroscopic evaluation: Following arthroscopic examination of the knee, a quantitative assessment of medial compartment opening can be performed using the tip of the arthroscopic probe as a scale after its length is measured and confirmed outside the knee. Medial compartment opening of above 5 mm is suggestive of Grade 2+ MCL laxity [10] (Fig. 19.1), whereas 10 mm or more medial opening in chronic cases is suggestive of Grade 3+ MCL laxity [11] (Fig. 19.2).

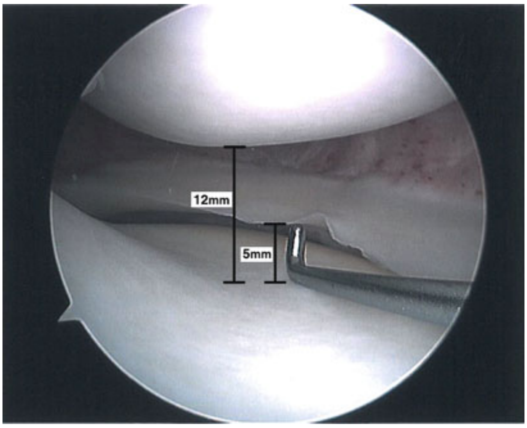

Fig. 19.2 Arthroscopic view of a right knee, suggesting Grade 3+ MCL laxity

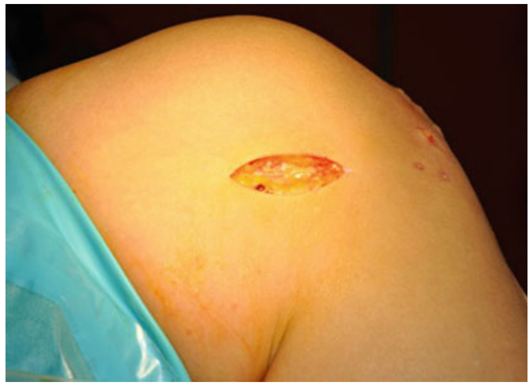

Fig. 19.3 A small incision over the medial epicondyle. Reprinted from Canata GL, Chiey A, Leoni T. Surgical technique: does mini-invasive medial collateral ligament and posterior oblique ligament repair restore knee stability in combined chronic medial and ACL injuries? Clin Orthop Relat Res. 2012;470:791–797, with permission from Springer

Surgical Approaches to Address MCL Dysfunction

Direct repair with medial and *posteromedial plication/reefing*: Direct repair with medial plication has been described in the setting of primary ACL reconstruction [10, 12]. We use this technique in the setting of revision ACL reconstruction when there is mild increased side-to-side laxity in the MCL [10].

Surgical technique [10]: After the ACL graft is fixed and medial opening of > 5 mm is observed with the use of the arthroscopic probe, a short longitudinal incision over the medial epicondyle is made (Fig. 19.3). The retinaculum is then incised to reveal the medial ligament structures (Fig. 19.4). The MCL and POL are then sutured proximally to the medial epicondyle (Fig. 19.5) with three figure-of-eight sutures using Number 2 Ethibond® (Ethicon) (Fig. 19.6). The figure-of-eight sutures advance the MCL and POL proximally towards the medial epicondyle. Each is started at the area of the medial epicondyle and extends approximately 1 cm distally, one aiming directly distally, one aiming distally and slightly anteriorly, and one aiming distally and slightly posteriorly (the direction of the POL). The sutures are tied and tension is checked in extension and in flexion (Fig. 19.7). Postoperative rehabilitation guidelines are similar to those for isolated ACL

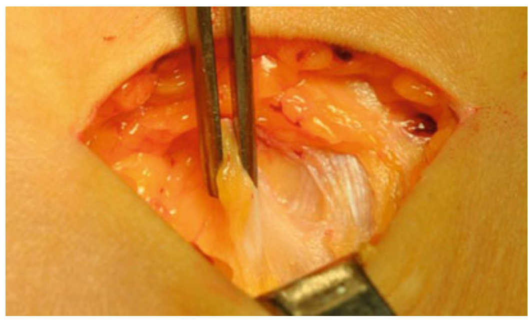

Fig. 19.4 Laxity of medial restraints is shown. Reprinted from Canata GL, Chiey A, Leoni T. Surgical technique: does mini-invasive medial collateral ligament and posterior oblique ligament repair restore knee stability in combined chronic medial and ACL injuries? Clin Orthop Relat Res. 2012;470:791–797, with permission from Springer

reconstruction with two exceptions: keeping crutch-protected gait for 4 weeks, and using a knee brace for 6 weeks without motion restriction. Weight-bearing is permitted as tolerated from the day after surgery. Recently, in a group of 36 patients with a mean age of 37 years (range, 15–70), who underwent this technique and were followed for more than 2 years, the following outcomes were reported [10]: mean subjective IKDC score improved from 36 preoperatively to 94 at latest follow-up, mean KOOS improved from 45 preoperatively to 93 postoperatively,

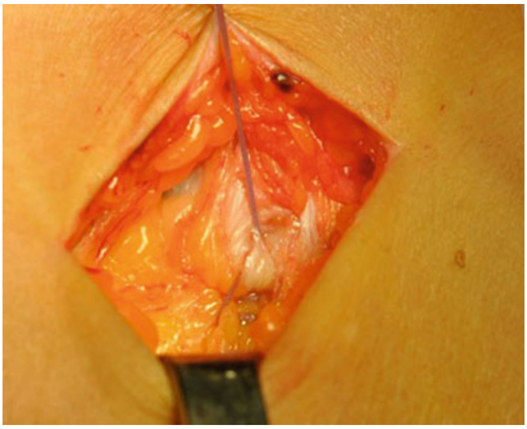

Fig. 19.5 Medial tissue is tightened up to the epicondyle area. Reprinted from Canata GL, Chiey A, Leoni T. Surgical technique: does mini-invasive medial collateral ligament and posterior oblique ligament repair restore knee stability in combined chronic medial and ACL injuries? Clin Orthop Relat Res. 2012;470:791–797, with permission from Springer

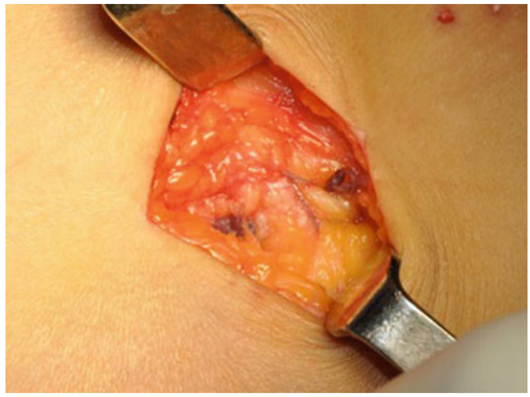

Fig. 19.7 End of procedure (MCL and POL have been advanced proximally to the medial epicondyle). Reprinted from Canata GL, Chiey A, Leoni T. Surgical technique: does mini-invasive medial collateral ligament and posterior oblique ligament repair restore knee stability in combined chronic medial and ACL injuries? Clin Orthop Relat Res. 2012;470:791–797, with permission from Springer

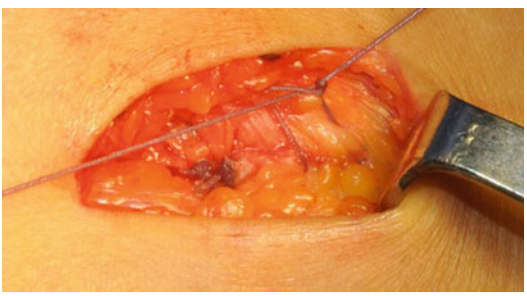

Fig. 19.6 Nonabsorbable sutures placed in the MCL. Reprinted from Canata GL, Chiey A, Leoni T. Surgical technique: does mini-invasive medial collateral ligament and posterior oblique ligament repair restore knee stability in combined chronic medial and ACL injuries? Clin Orthop Relat Res. 2012;470:791–797, with permission from Springer

mean Lysholm score improved from 40 preoperatively to 93 postoperatively, and valgus and external rotation laxities were normal in all cases.

MCL reconstruction: This procedure should be reserved for revision ACL cases where Grade 2+ or 3+ medial laxity is detected. Surgical techniques which have been described to reconstruct the MCL include semitendinosus autograft with preservation of the tibial insertion [13–16], allograft tissues [17, 18], and double-bundle reconstructions [8, 15, 17–19]. Drawbacks related to these techniques include a long incision across the medial aspect of the knee with up to 20° loss of knee flexion or extension in 20 % of the operations [16], keeping the semitendinosus insertion distally and using it as an MCL graft [13–16] resulting in a too-anterior tibial attachment (i.e., the tibial insertion of the MCL should be posterior to the pes anserinus [4, 20]), harvesting a dynamic medial stabilizer that applies adduction moment during gait (i.e., semitendinosus) in a knee with medial laxity, and the relative complexity of double-bundle reconstructions, compared to single-bundle reconstructions, corresponding to their need for multiple attachment sites on the femur as well as on the tibia and more graft tissue, and number of fixation devices (i.e., screws, washers, staples, etc.) required [8, 15, 17–19].

Recently, we described a new technique to reconstruct the MCL that uses Achilles tendon allograft [11]. Benefits include avoiding donor site morbidity, secure fixation with bone-to-bone healing on the femur, small skin incisions that do not cross the knee, and isometric reconstruction. Open physis of the distal femur is an absolute contraindication for this procedure. Relative

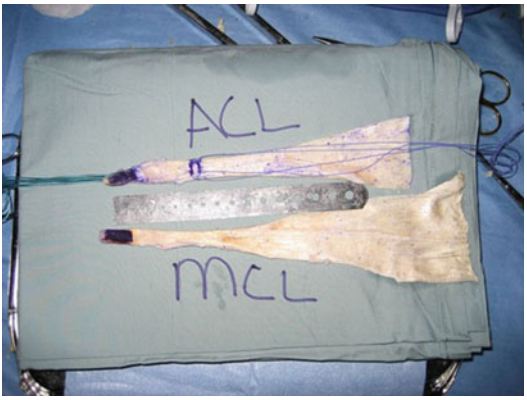

Fig. 19.8 The Achilles allograft is prepared on a side table. Reprinted from Marx RG, Hetsroni I. Surgical technique: medial collateral ligament reconstruction using Achilles allograft for combined knee ligament injury. Clin Orthop Relat Res. 2012;470:798–805, with permission from Springer

contraindications for this surgery include any factor that may substantially increase the risk of postoperative complications. These include: (1) active infection; (2) inability to adhere to postoperative rehabilitation guidelines; (3) severe soft tissue trauma; and (4) comorbidities such as diabetes and morbid obesity.

Surgical technique [11]: With the patient under anesthesia, after confirming MCL laxity that requires reconstruction as indicated previously by physical examination and arthroscopic examination, the following steps are carried out (after fixing the cruciate graft on the femur only): (1) the Achilles allograft is prepared creating a 9-mm diameter by 18-mm length bone plug (Fig. 19.8); (2) a 3-cm longitudinal skin incision is made over the medial femoral epicondyle; (3) a guide pin is inserted 3–5 mm proximal and posterior to the medial femoral epicondyle, parallel to the joint line, and in a 15° anterior direction to avoid the intercondylar notch. Location of the pin is confirmed with fluoroscopy (Fig. 19.9); (4) the skin is undermined from the femoral guide pin to the anatomic MCL insertion on the tibia, creating a tunnel for the graft under the subcutaneous fat (Fig. 19.10); (5) a nonabsorbable suture loop is placed around the guide pin and brought distally under the skin through the tunnel just created; (6)

Fig. 19.9 Location of the pin is confirmed with fluoroscopy. Reprinted from Marx RG, Hetsroni I. Surgical technique: medial collateral ligament reconstruction using Achilles allograft for combined knee ligament injury. Clin Orthop Relat Res. 2012;470:798–805, with permission from Springer

Fig. 19.10 Skin is undermined to create a tunnel for the graft across the knee. Reprinted from Marx RG, Hetsroni I. Surgical technique: medial collateral ligament reconstruction using Achilles allograft for combined knee ligament injury. Clin Orthop Relat Res. 2012;470:798–805, with permission from Springer

the distal suture is held against the tibia at the estimated anatomic insertion, just posterior to the pes anserinus insertion. Isometricity is tested through knee motion from 0 to 90°. The tibial insertion point is modified, if needed, until the loop is isometric; (7) the isometric point is

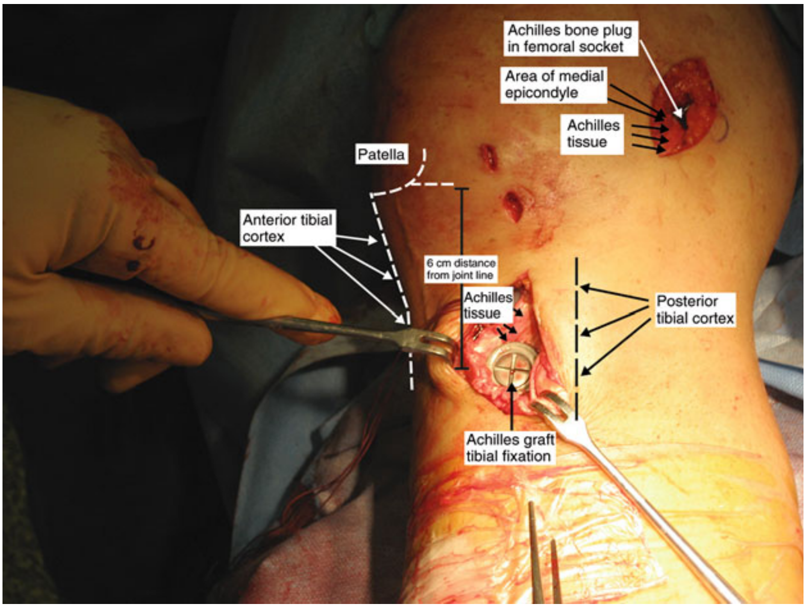

Fig. 19.11 The MCL graft is fixed at the isometric point on the tibia. Reprinted from Marx RG, Hetsroni I. Surgical technique: medial collateral ligament reconstruction using Achilles allograft for combined knee ligament injury. Clin Orthop Relat Res. 2012;470:798–805, with permission from Springer

marked on the tibia with a Bovey; (8) soft tissue around the femoral guide pin is débrided to allow for insertion of the Achilles bone plug into a socket created around this pin later; (9) a 9-mm diameter reaming is performed over the guide pin to a depth of 20 mm; (10) the Achilles bone plug is inserted into the femoral socket and fixed with a 7-mm diameter by 20-mm length metal interference screw; (11) the Achilles tendon tissue is passed under the skin and distally; (12) the cruciate graft is now tensioned and fixed on the tibia; (13) the MCL graft is tensioned with the knee at 20° flexion under varus stress and fixed at the isometric point on the tibia with a 4.5-mm cortical screw and a 17-mm spiked washer (Fig. 19.11); and (14) subcutaneous tissue and skin are closed. Tunnels position and hardware placement are confirmed postoperatively with radiographs (Fig. 19.12).

We followed a group of 14 patients with a mean age of 34 years (range, 19–60 years), which underwent this MCL reconstruction technique, and was evaluated at a minimum 2 years after the reconstruction [11]. The following outcomes were reported [11]: ROM examination demonstrated that, in 12 of the 14 patients, range of knee motion was maintained and symmetric compared with the uninjured knee. In the group of patients that had MCL reconstruction with primary ACL reconstruction, none had loss of knee motion. In the group that had MCL reconstruction with revision ACL reconstruction, one patient had 15° knee flexion loss. One patient who had MCL reconstruction with ACL/PCL/LCL/PLC reconstruction had 15° knee flexion loss as well. Side-to-side ligament integrity examination revealed that all reconstructed MCL grafts had a firm end point on valgus stress test with no or minimal side-to-side differences (i.e., no side-to-side difference in 11 patients and Grade 1+ in three patients). One patient who had MCL reconstruction with primary ACL reconstruction and one patient who had MCL reconstruction with revision ACL reconstruction had pivot shift Grade 2+. Both reported possibly feeling unstable during cutting but not in everyday activities. All other ligament laxity tests were symmetric and normal. IKDC-subjective, Lysholm, and KOOS-sports scores were 91 ± 6, 92 ± 6, and 93 ± 12, respectively, in cases of MCL

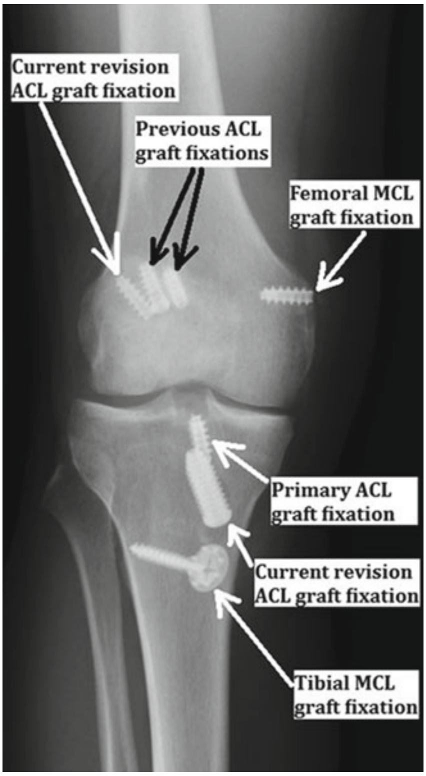

Fig. 19.12 Postoperative knee AP view. Reprinted from Marx RG, Hetsroni I. Surgical technique: medial collateral ligament reconstruction using Achilles allograft for combined knee ligament injury. Clin Orthop Relat Res. 2012;470:798–805, with permission from Springer

reconstruction with primary ACL reconstruction. These patients also demonstrated return to preinjury activity levels. In cases of MCL reconstruction with revision ACL reconstruction, despite restoration of Grade 0–1+ valgus stability with the MCL graft, functional scores were inferior, and patients did not return to their preinjury activity levels.

Discussion of outcomes after MCL reconstruction: Aside from our recent description of an MCL reconstruction technique using Achilles allograft [11], there are only two studies reporting ROM and function in patients that had MCL reconstruction with a single graft in all patients in a combined MCL and cruciate reconstruction [15, 16]. Both described a technique that uses the semitendinosus tendon with preservation of the insertion site at the pes anserinus on the tibia, creating anterior and posterior limbs to reconstruct the MCL. However, in both studies, the group of patients was heterogeneous and included isolated MCL reconstructions as well as concomitant cruciate reconstructions, but ROM was reported for all patients as one group, not differentiating the combined reconstructions from the isolated MCL reconstructions. In one of these, which included six cases of isolated MCL reconstruction and 18 cases of MCL with another cruciate reconstruction, the investigators found motion limitation between 5 and 10° in extension or in flexion in five patients (21 % of the patients) [15], whereas in the other study, which included 11 cases of isolated MCL reconstruction and 39 cases of MCL with another one or both cruciate ligament reconstructions or posterolateral corner reconstruction, the investigators noticed motion loss of between 5 and 20° in extension or in flexion in 10 patients (20 % of the patients) [16]. Both studies did not report ROM specifically for the combined reconstructions, and therefore the comparison to the technique described here, using the Achilles allograft, is limited.

All MCL grafts, using the Achilles allograft technique [11], demonstrated Grade 0–1+ valgus laxity on physical examination. Bone-to-bone healing on the femur, strong and broad Achilles tendon allograft tissue, isometric reconstruction, and secure fixation on both insertion sites may all account for this. This is comparable to previous reports after double-bundle MCL reconstruction in a combined ligament reconstruction scenario that described Grade 0–1+ valgus laxity in more than 90 % of their cases [21].

Mean IKDC-subjective and Lysholm knee scores demonstrated excellent (i.e., above 90 points) [22–24] function in patients with MCL reconstruction and primary ACL reconstruction, using the Achilles allograft technique [11]. This is comparable to the mean Lysholm score reported by others when creating a double-bundle MCL reconstruction with the semitendinosus, preserving its tibial insertion [15]. Mean KOOS subscores in the Achilles allograft technique were between 77 and 96 for the five categories of the score in cases with primary ACL reconstruction, which is comparable to another study that created a double-bundle MCL reconstruction and reported mean KOOS subscores between 75 and 89 for MCL reconstruction in a multiligament reconstruction scenario, the vast majority of which were MCL with ACL reconstructions [16]. In patients with the Achilles allograft MCL reconstruction with revision ACL reconstruction, IKDC-subjective, Lysholm, and KOOS subscores demonstrated inferior outcome [11]. Because revision ACL reconstructions are associated with inferior outcomes compared with primary ACL reconstructions for multiple reasons [25, 26], this result was expected. Tegner and Marx activity level scores demonstrated patients with concomitant primary ACL reconstruction were able to return to preinjury activity levels. Their scores were mean 6 and 7 points, respectively, indicating that cutting and pivoting sports on a recreational level may be a realistic goal after this Achilles allograft MCL reconstruction. However, when this technique is performed in the setting of revision ACL reconstruction, return to pre-injury activity levels is less predictable despite normal knee laxity.

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Posterolateral Corner Deficiency in Revision ACL Reconstruction

20

Michael K. Shindle, Bruce A. Levy, Mark Clatworthy, and Robert G. Marx

Introduction

Posterolateral corner (PLC) injury is an increasingly recognized entity and is generally associated with other ligament disruptions. Missed PLC injuries increase the failure rates for both anterior cruciate ligament (ACL) and posterior cruciate ligament (PCL) reconstructions. Thus, for a failed ACL reconstruction, the PLC should always be evaluated as a potential etiology. Numerous PLC reconstructions have been described with varying degrees of success. Recent trends have shifted toward anatomic reconstruction techniques.

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Anatomy and Biomechanics

The PLC is composed of both static and dynamic stabilizers that together provide varus and external rotatory stability to the knee. The three primary static stabilizers include the fibular collateral ligament (FCL), the popliteofibular ligament (PFL), and the posterolateral capsule [1]. The popliteus tendon controls both dynamic and static posterolateral rotation of the knee. The PFL, which branches from the popliteus tendon and assumes its course to the fibular styloid, is an important stabilizer of external rotation [2].

The FCL is the primary static restraint to varus opening of the knee [3]. The femoral origin is typically located just proximal and posterior to the lateral epicondyle in a small depression between the lateral epicondyle and the supracondylar process. Distally, the FCL inserts on the fibula approximately 8 mm posterior to the most anterior aspect of the fibular head [4].

Clinical Evaluation

The most common mechanism of injury to the PLC involves a combined hyperextension and varus force to the knee. Hyperextension is also a common mechanism of injury to the ACL. In a situation where a patient has a failed ACL reconstruction, the PLC has to be evaluated for an acute injury as well as for the possibility that a PLC injury was initially missed. Failure to

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recognize a PLC injury is a known predisposing factor for failure of primary ACL reconstruction. Thus, a careful history should always be obtained.

Patients may present with standing varus malalignment and demonstrate a varus thrust during the stance phase of gait. For an acute injury, there may be acute tenderness to palpation or ecchymosis about the posterolateral aspect of the knee. Ligamentous examination is performed on both knees to provide a comparison between the injured and normal state. Noyes et al. described a varus classification as primary varus, double varus, and triple varus [5]. Primary varus refers to varus malalignment due to the underlying tibiofemoral osseous alignment but there is no associated posterolateral ligament deficiency or abnormal lateral joint opening. Double varus includes an associated deficiency of the FCL and varus tibiofemoral malalignment leading to abnormal lateral joint opening. Triple varus includes a deficiency of all of the posterolateral structures including the FCL, varus osseus malalignment as well as a recurvatum (hyperextension) deformity.

Physical exam should include tests for both varus and rotational deformities. Varus testing is performed at 0° and 30° of flexion. Varus opening at 0° is indicative of a severe posterolateral injury and an associated cruciate injury. Isolated injuries to the posterolateral structures usually result in maximum varus opening at 30° flexion, but there may be instances where there is a minimal varus deformity with significant rotational instability, such as with a popliteus injury or PFL injury.

The most commonly used test to assess external rotation is the dial test. Although this test can be done in the supine position, it is typically performed in the prone position. The examiner places one hand behind the posterior proximal tibia for support to ensure the tibia is maintained in a reduced position. With the other hand, the examiner holds the patient's foot and externally rotates the foot at both 30° and 90° of flexion. A 10° difference in external rotation at 30° is evidence of pathology to the PLC. When examination at 90° of flexion reveals a decrease in the amount of external rotation compared to 30°, then injury to the PLC is isolated. When there is further increased external rotation at 90°, then a combined PCL/PLC injury is present. Recently, Marx et al., described the "posterolateral spin test." Typically this is performed in the supine position with the hip and knee flexed to 90° [6]. With the knee flexed at 30° or 90° the step-off of the lateral tibial plateau from the lateral femoral condyle can be palpated with the examiner's thumb to determine the amount of posterolateral spin compared with the normal side. This is accomplished by palpating the step-off of the lateral tibial plateau in relation to the lateral femoral condyle. By examining posterior lateral rotation at the knee as opposed to the foot, measurement error is avoided due to possible rotation at the tibia, ankle, or foot that can occur with the dial test. Decreased step-off compared to the normal side is considered a positive test.

The external rotation recurvatum test is performed by picking up the great toe of the affected limb in full extension. A positive test is observed when the tibia falls into asymmetric ER and recurvatum relative to the femur due to disruption of the PLC, ACL, and PCL. Lastly, the external rotation drawer test is performed at 90° of knee flexion with the foot in external rotation. Grading is similar to a standard posterior drawer examination, as the examiner feels the amount of posterior translation according to prominence of the anteromedial tibial plateau margin (medial step-off).

Imaging

Routine standing anteroposterior (AP) and lateral radiographs as well as bilateral hip to ankle films are obtained. In particular, alignment is measured and compared to the contralateral limb. Malalignment is defined as varus deformity >5° compared to the contralateral side or alignment that falls within the medial compartment. Magnetic Resonance Imaging (MRI) is paramount to assess ligamentous status, all associated intra-articular pathology (cartilage, meniscus), and previous tunnel position and size.

Bilateral comparison stress radiographs (or fluoroscopy) may be helpful to determine the extent of varus laxity. La Prade et al. demonstrated that a side-to-side difference of approximately 2.5 mm on varus stress testing at 20° is indicative of an isolated FCL injury [7]. If the side-to-side difference is greater than or equal to 4 mm, combined FCL and PLC injuries exist [7].

Classification

Lateral ligament injuries occur in a variety of patterns associated with cruciate ligament injuries, or more rarely, in isolation. The most commonly used classification system for PLC injuries was described by Hughston et al. which defines the injury mainly based on varus instability [8]. Grade I injuries are sprains without tensile failure of any capsule-ligamentous structures, with little or no varus instability (0–5 mm). Grade II injuries are partial injuries with minimal abnormal laxity (6–10 mm). Grade III injuries are complete disruptions with significant laxity (>10 mm), probably representing associated injuries.

Fanelli proposed a classification system on posterolateral instability of the knee that correlates physical findings with corresponding injuries [9]. This classification system is divided into three groups based on the severity of injury. The first group (PLI A) correlated increase in external rotation on physical examination with injuries to the PFL and popliteus tendon. The second group (PLI B) correlated increase in external rotation and increased varus laxity of approximately 5 mm at 30° knee flexion with injuries to the PFL, popliteus tendon, and FCL. The third group (PLI C) correlated increase in external rotation and gross varus laxity of 10 mm at 30° of knee flexion with injuries to the PFL, popliteus tendon, FCL, lateral capsule, and ACL/PCL. This classification system does not take into account isolated FCL injuries and bony avulsions of the lateral and posterolateral structures [9].

Boyd described a new classification system which considers the location of the injury, as well as the specific ligaments injured on the PLC (both isolated and combined), and addresses both soft tissue injury and bony avulsions (Table 20.1) [10].

Table 20.1 Classification of posterolateral corner injuries

Type I	Isolated ligamentous injury of the posterolateral corner (PLC), including the FCL, popliteus, or popliteofibular ligament injury
Type IIa	Combined ligamentous injury of the PLC, including injury to the distal FCL and biceps femoris, with either avulsion or fracture of the fibular head
Type IIb	Combined ligamentous injury of the PLC, including injury to the FCL and popliteus, occurring at the proximal femoral region
Type IIIa	PLC knee injury with some combination of FCL (proximal, distal, or midsubstance), popliteus (proximal, midsubstance, or musculotendinous), biceps femoris (distal, musculotendinous), posterolateral capsule, IT band
Type IIIb	PLC knee injury, Type IIIa with uni-cruciate or bi-cruciate injury

FCL indicates fibular collateral ligament; IT, iliotibial

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Treatment

If an acute injury occurs in the setting of a failed ACL reconstruction, numerous options are available. If there are distal avulsions of the FCL/biceps femoris complex, then acute repair may be indicated, especially in the setting of bony avulsions or complete distal avulsions off of the fibula. However, Stannard et al. and Levy et al. have both shown higher failure rates with repair as opposed to reconstruction in the setting of acute FCL/PLC injury [11, 12]. In the setting of a revision ACL procedure combined with a PLC reconstruction, we prefer an anatomic reconstruction technique.

LaPrade et al. described the “true anatomic” technique [13]. Biomechanical testing on cadavers in the laboratory was translated into a clinical series that evaluated outcome. This technique reconstructs the FCL, the PFL, and the popliteus tendon complex with tunnels at each anatomic origin and insertion site. The authors reported on 46 patients with combined PLC and cruciate ligament injuries with a mean follow-up of 4.3 years. They found significant improvements in IKDC scores for varus stress testing, external rotation at 30°, and the reverse pivot shift as well as improved performance of the single-leg hop test [12]. However, this technique is technically challenging and requires a more extensive exposure and the creation of additional tunnels.

Our preference is an anatomic reconstructive technique (Fig. 20.1) that is less complex than some other anatomic techniques and does not require the creation of a tibial tunnel, which is particularly advantageous in the setting of a revision ACL reconstructive procedure [14]. However, if the patient has asymmetric hyperextension, then we may elect to add a popliteal-based graft similar to that described by Laprade et al., [13] and Fanelli et al. [15].

For our standard technique, we fix the ACL revision graft on the femur. Definitive fixation of the ACL on the tibia is deferred at this point. The incision is carried out over the lateral epicondyle extending toward the anterior border of the fibula. Anterior and posterior full-thickness flaps are raised to expose the iliotibial band and the biceps femoris muscle complex. The peroneal nerve is identified posterior to the biceps femoris and followed proximally and distally to ensure that it is not tethered through its course and enabling its protection throughout the procedure with the aid of a vessel loop. The iliotibial band is then incised in line with the skin incision. The anterior and posterior borders of the fibula are identified, and subperiosteal dissection is performed, by use of a Bovey and small Cobb. After exposure of the fibular head, access to the anterior sulcus of the popliteus and insertion of the FCL is created with dissection over the lateral aspect of the femur. A tract is developed from the posterior border of the fibula, underneath the biceps femoris, and toward the popliteus sulcus for later passage of the graft. Under fluoroscopic control, a K-wire is passed through the anterior one-fifth of the popliteal sulcus and then overreamed with a 9-mm reamer to a depth of 20 mm (Fig. 20.2). A nonirradiated fresh-frozen Achilles tendon allograft with a 9 × 20-mm bone plug on one end and 7-mm graft along its tendinous portion is prepared (Fig. 20.3). One of us [MC] does not have access to allograft tissue, so hamstring autograft is used instead. The bone plug of the allograft is then placed into the tunnel created at the popliteus sulcus and secured with an 8 × 20-mm interference screw allowing for bone–bone fixation (Fig. 20.4). After securing the graft, the fibular tunnel is then prepared. Under fluoroscopic guidance, a K-wire is passed from the anterolateral fibula at the attachment site of the FCL to the posteromedial down-slope of the fibular styloid, where the PFL attaches to the posterior border of the fibula (Fig. 20.4). Once in the appropriate position, the K-wire is then overreamed with a 7-mm reamer. The graft is passed underneath the biceps femoris through the tract that was previously developed, and a suture passer is passed anterior to posterior through the 7-mm hole in the fibula. At this point, the graft is passed posterior to anterior through the fibula, recreating the popliteal fibular ligament. The graft is then looped back over to the lateral epicondyle at the insertion of the FCL, approximately 18.5 mm proximal and posterior to the popliteus tendon insertion, to re-create the FCL. Once again, under fluoroscopic control, a Beath pin is passed at the FCL insertion to ensure that its path is not intruding on other reconstructed ligament tunnels (Fig. 20.5). With the Beath pin in place, the graft is checked for isometry in flexion and extension (Fig. 20.6).

Once isometry is attained, a 7-mm drill is passed over the Beath pin to a depth of approximately 40 mm (Fig. 20.7). The Beath pin technique is used to pass the graft from the lateral to the proximal and medial side of the knee. The Beath pin and sutures are pulled out of the medial side of the knee to apply tension to the graft construct. Definitive fixation of the revision ACL reconstruction is performed at this point. Then, the graft is tensioned with the leg at approximately 30° of flexion, 10° to 15° of internal rotation, and maximum valgus. The graft is secured with an 8 × 30 bioabsorbable screw, completing the FCL reconstruction (Fig. 20.8). The FCL and PFL limbs of the graft are now imbricated with No. 1 Ethibone suture (Ethicon, Somerville, NJ).

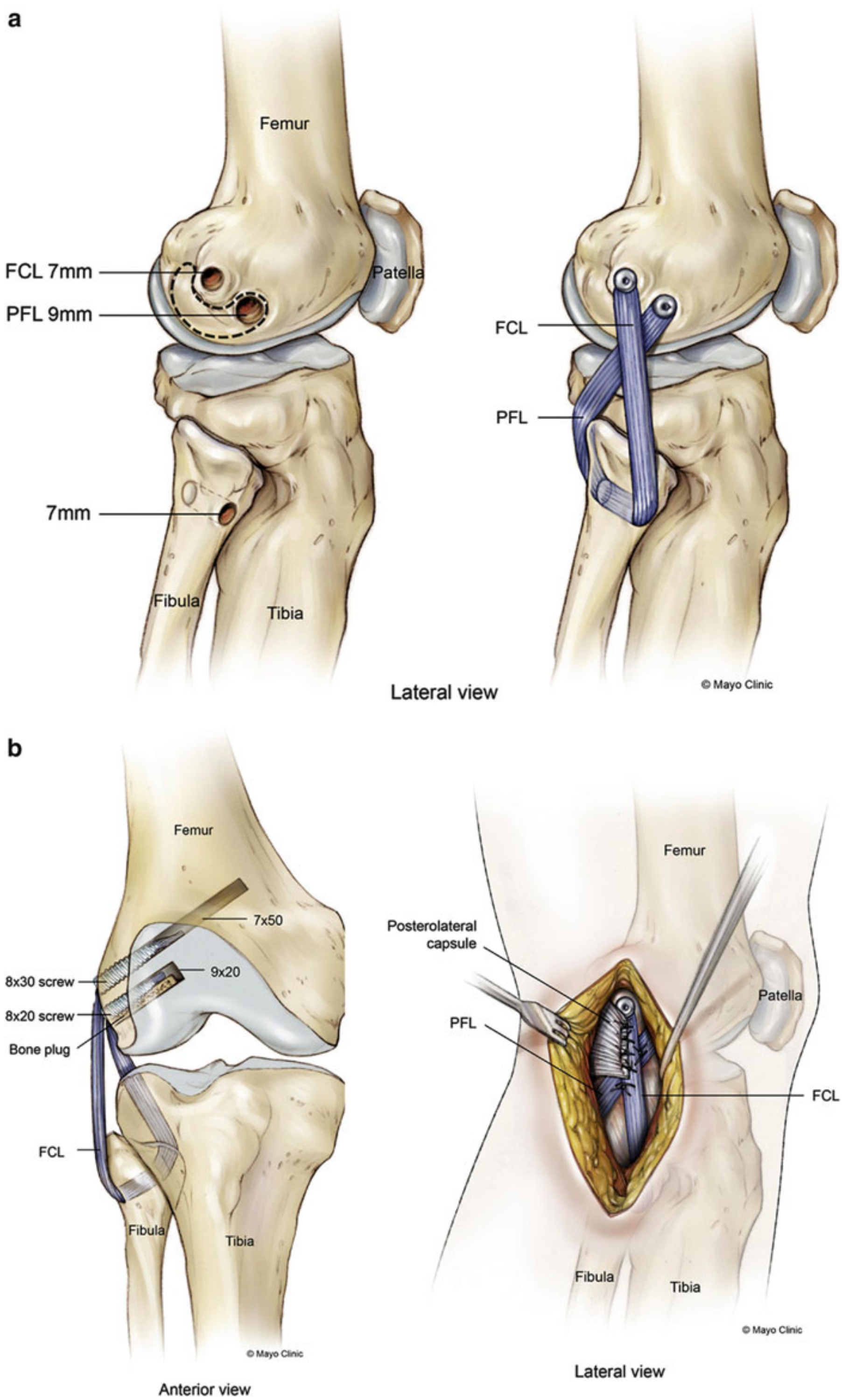

Fig. 20.1 (**a**) Tunnel placement and graft construct. (**b**) Graft construct, followed by posterolateral capsular shift. Reproduced from Schechinger SJ, Levy BA, Dajani KA, Shah JP, Herrera DA, Marx RG. Achilles tendon allograft reconstruction of the fibular collateral ligament and posterolateral corner. Arthroscopy 2009;25:3;232–42, with permission from Elsevier

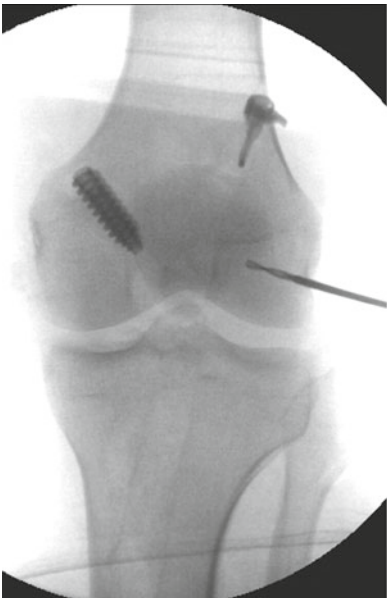

Fig. 20.2 Fluoroscopic anteroposterior view of K-wire position for femoral tunnel in popliteal sulcus. Reproduced from Schechinger SJ, Levy BA, Dajani KA, Shah JP, Herrera DA, Marx RG. Achilles tendon allograft reconstruction of the fibular collateral ligament and posterolateral corner. Arthroscopy 2009;25:3;232–42, with permission from Elsevier

Fig. 20.3 Achilles tendon allograft with 9 × 20-mm bone plug and 7-mm graft. Reproduced from Schechinger SJ, Levy BA, Dajani KA, Shah JP, Herrera DA, Marx RG. Achilles tendon allograft reconstruction of the fibular collateral ligament and posterolateral corner. Arthroscopy 2009;25:3;232–42, with permission from Elsevier

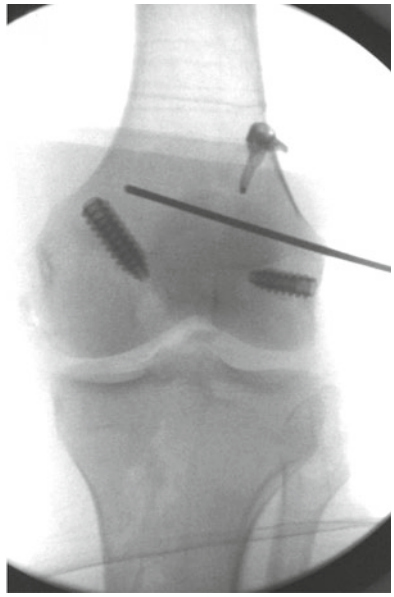

Fig. 20.4 Fluoroscopic anteroposterior view of bone block secured with metal interference screw at popliteal sulcus and K-wire placement for fibular tunnel. Reproduced from Schechinger SJ, Levy BA, Dajani KA, Shah JP, Herrera DA, Marx RG. Achilles tendon allograft reconstruction of the fibular collateral ligament and posterolateral corner. Arthroscopy 2009;25:3;232–42, with permission from Elsevier

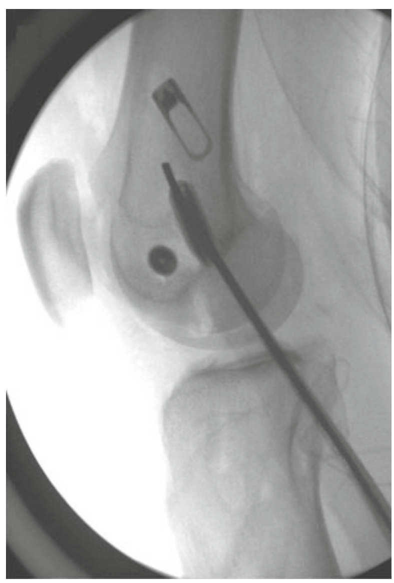

Fig. 20.5 Fluoroscopic lateral view of K-wire position for femoral tunnel at isometric point, adjacent to lateral epicondyle. Reproduced from Schechinger SJ, Levy BA, Dajani KA, Shah JP, Herrera DA, Marx RG. Achilles tendon allograft reconstruction of the fibular collateral ligament and posterolateral corner. Arthroscopy 2009;25:3;232–42, with permission from Elsevier

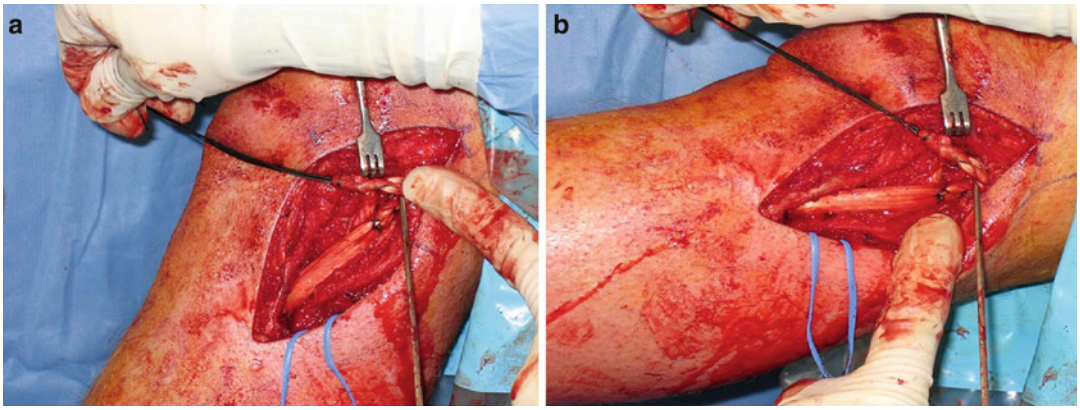

Fig. 20.6 (**a**) Intraoperative photograph of isometric point at 90° of flexion. (**b**) Intraoperative photograph of isometric point in full extension. Reproduced from Schechinger SJ, Levy BA, Dajani KA, Shah JP, Herrera DA, Marx RG. Achilles tendon allograft reconstruction of the fibular collateral ligament and posterolateral corner. Arthroscopy 2009;25:3;232–42, with permission from Elsevier

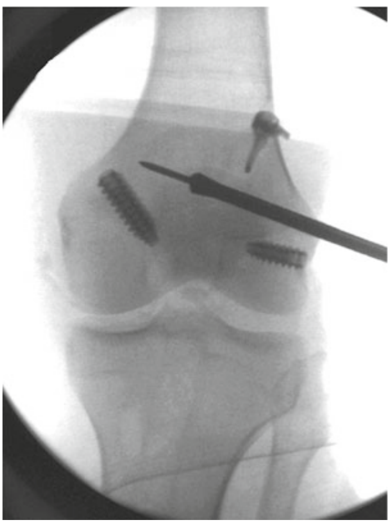

Fig. 20.7 Fluoroscopic anteroposterior view of FCL tunnel reamed with a 7-mm reamer to a depth of approximately 40 mm. Reproduced from Schechinger SJ, Levy BA, Dajani KA, Shah JP, Herrera DA, Marx RG. Achilles tendon allograft reconstruction of the fibular collateral ligament and posterolateral corner. Arthroscopy 2009;25:3;232–42, with permission from Elsevier

Fig. 20.8 Intraoperative photograph of FCL and PFL ligament reconstruction. Reproduced from Schechinger SJ, Levy BA, Dajani KA, Shah JP, Herrera DA, Marx RG. Achilles tendon allograft reconstruction of the fibular collateral ligament and posterolateral corner. Arthroscopy 2009;25:3;232–42, with permission from Elsevier

The posterolateral capsular shift is then performed in the following manner. If redundant, the capsule is released off the distal femur with subperiosteal resections with a Bovey and Cobb. Multiple suture anchors are placed at the distal femoral capsular origin and the capsule is then tied down accordingly back to its anatomical location. Then the remaining redundant capsular tissue is tied over the graft construct with three or four #1 long sutures alternatively, in the setting of redundant capsule it can be plicated with multiple figure of eight sutures. Alternatively, in the setting of redundant capsule it can be plicated with multiple figure of eight sutures (Fig. 20.9).

All wounds are irrigated with normal saline solution, and the iliotibial band fascia is closed with interrupted No. 1 Ethibond suture, the subcutaneous layers are closed with No 2-0 Vicryl (ethicon), and the skin is closed by use of running 3-0

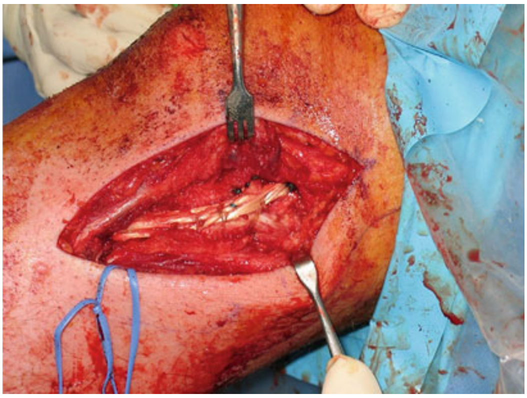

Fig. 20.9 Intraoperative photograph of posterolateral capsular shift. Reproduced from Schechinger SJ, Levy BA, Dajani KA, Shah JP, Herrera DA, Marx RG. Achilles tendon allograft reconstruction of the fibular collateral ligament and posterolateral corner. Arthroscopy 2009;25:3;232–42, with permission from Elsevier

Monocryl (Ethicon) with Steri-Strips (3M, St Paul, MN). Postoperative radiographs are obtained.

This reconstruction technique is similar to that described by Arciero [16]. However, this technique is unique in that the posterolateral capsule is then imbricated to our ligamentous reconstruction to further enhance varus and external rotatory instability.

When performing a combined revision ACL reconstruction and FCL/PLC reconstruction, the authors typically perform the ACL revision surgery first and, when that is complete all the way through to graft fixation, then the FCL/posterolateral reconstruction is performed. This way the tunnels created by the FCL and PLC reconstruction can be identified with the use of lateral and AP fluoroscopic views to ensure that the FCL and PLC tunnels do not impede on the ACL revision tunnels.

Postoperative Rehabilitation

The authors follow the rehabilitation program described by Fanelli et al. [17–19]. The knee is immobilized in full extension for the first 3 weeks in a brace. In week 4, patients begin passive prone range of motion to a maximum of 90°. The rehabilitation brace with a slight valgus moment is worn at all times, except for bathing. The patient is allowed toe-touch weight-bearing only during the 6 weeks, then progressive weight-bearing as tolerated. A custom valgus unloader brace is applied during weight-bearing activities after 4 months. Return to higher demand activities is delayed until 12 months after surgery.

As an alternative, Laprade et al. [20] have recently described their postoperative protocol for combined injuries of the cruciate and PLC. Their patients are non-weight-bearing for 6 weeks, but begin immediate range of motion out of the brace with a goal of 90° of knee flexion by the second week and full range of motion by the 16th week. In all of these protocols, the consistent theme is avoidance of open kinetic changes hamstring strengthening for at least 4 months after surgery.

Role of High Tibial Osteotomy (HTO)

A failed ACL/PCL/lateral-sided reconstruction associated with varus malalignment is a clear indication for a valgus-producing proximal tibial osteotomy combined with revision ligament surgery or as an isolated procedure. A biplanar osteotomy that changes the sagittal plane tibial slope can also be performed depending on the status of the ACL and PCL.

In the chronic setting, gait is observed to identify a varus (lateral) thrust and limb alignment is measured using hip-to-ankle radiographs. In the case of an ACL/PCL/FCL/PLC-deficient knee with varus malalignment and a lateral thrust, we recommend a first-stage valgus-producing proximal tibial osteotomy and a second-stage multiligament knee reconstruction, if necessary.

Arthur et al. [21] studied 21 patients with chronic posterolateral instability and varus malalignment. They determined that a valgus-producing proximal tibial osteotomy restored knee stability and gait mechanics sufficiently and a second-stage ligament reconstruction was not necessary in approximately 40 % of their patients. They also noted a high graft failure rate when limb alignment was not corrected before knee ligament reconstruction surgery.

Summary

There are many etiologies for failed ACL reconstruction. Failure to recognize and address a PLC injury may be a predisposing factor. A correct diagnosis requires an accurate history as well as an appreciation of the subtleties of a complete knee examination. If revision surgery is indicated, we prefer an anatomic technique utilizing an Achilles tendon allograft reconstruction of the FCL and PLC and the selective use of HTO for chronic cases.

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21 Osteotomy for Slope Correction Following Failed ACL Reconstruction

Robert A. Magnussen, Diane L. Dahm, and Philippe Neyret

Introduction

Anterior cruciate ligament (ACL) injury and its subsequent reconstruction are increasingly common. Today's reconstructive and rehabilitation techniques are often successful in alleviating symptoms and allow many patients to return to an active lifestyle; however, excellent results are not universal. Although arthrofibrosis, extensor mechanism failure, progression of degenerative disease, and infection can harm outcomes of ACL reconstruction, the most frequent reason patients undergo revision ACL reconstruction is recurrent instability [1–3].

Numerous authors have stressed that successful revision ACL reconstruction depends on identification and treatment of the reason for failure of the primary reconstruction [1, 4, 5]. Technical error is widely believed to be the most common reason for failure [2, 5, 6]. This broad category includes tunnel malposition as well as the failure to address associated anatomic factors that can increase stress on ACL grafts and increase failure rates [7]. These factors include associated medial and lateral capsuloligamentous injuries (including posteromedial and posterolateral instability), meniscal loss, and pathologically increased posterior tibial slope. Relatively little attention has been paid to the influence of tibial slope on stability.

The goal of this chapter is to explore the role of tibial deflexion osteotomy in improving the outcome of revision ACL reconstruction. We will address the rationale, indications, technique, and outcomes of this procedure.

Rationale

Although the ACL is the primary restraint to anterior tibial translation, the contribution of other anatomic structures in preventing abnormal tibial motion cannot be ignored. These include the posterior horn of the medial meniscus, medial and lateral capsuloligamentous structures, and osseous anatomy. The role of osseous anatomy and in particular the posterior slope of the tibial plateau has garnered more interest in recent years.

Theoretically, increased posterior tibial slope leads to a tendency for the femur to slide backward relative to the tibia, decreasing load on the PCL and increasing load on the ACL [7]. In a clinical series, H Dejour and Bonnin

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demonstrated that increased anterior tibial translation on monopodal stance views correlated with increased posterior tibial slope in patients with an intact ACL as well as those with chronic anterior laxity [8]. Several cadaveric studies have confirmed this relative anterior tibial translation following increases in tibial slope by 5–10° [9, 10]. Although these studies did not note any increase in ACL strain when compressive loads were applied [9, 10], a more recent cadaveric study simulating a jump-stop did reveal increases in both anterior tibial acceleration and ACL strain associated with increased posterior tibial slope [11]. A computer model recently published by Shelburne et al. predicted increased ACL loads during walking in patients with higher degrees of posterior tibial slope [12].

The theory that increased posterior tibial slope results in higher ACL strains and thus a higher risk of ACL rupture has led numerous authors to compare tibial slope between patients with ACL injuries and uninjured controls. While the results have been somewhat inconsistent, a majority of authors have noted increased posterior tibial slope in the ACL-injured group relative to controls in certain populations [13–17].

Further evidence of the impact of posterior tibial slope on the risk of ACL injury comes from cases of iatrogenic increases in posterior tibial slope. The most common cause of slope alterations is opening wedge high tibial osteotomy (HTO). When reporting results of simultaneous ACL reconstruction and valgus-producing HTO, H Dejour et al. reported increased anterior tibial translation in patients in whom the osteotomy resulted in increased slope [18]. A case report of ACL rupture following trivial trauma in such a patient has been published [19]. Several authors have recognized slope alteration as a relatively common finding following HTO and have published recommendations for avoiding this complication [20, 21].

Because increased tibial slope is associated with increased anterior tibial translation and potentially stress on the ACL, it follows that increased slope would lead to increased stress on ACL grafts following both primary and revision ACL reconstruction.

Indications

While posterior tibial slope almost certainly impacts tibial translation and likely the stress on ACL grafts, it is likely a relatively small contributor to ACL graft failure. Given this fact and the relatively invasive nature and long recovery time of slope correction, tibial deflexion osteotomy is indicated in very few patients. Careful clinical and radiographic examinations are key for the accurate identification of these rare patients. Such patients are likely more common in the revision ACL population than in the primary ACL population.

We recommend addressing tibial slope with a deflexion osteotomy in patients with a posterior tibial slope greater than 13° relative to a line perpendicular to the long axis of the tibia as measured on a lateral plain radiograph associated with significant chronic anterior laxity evidenced by increased anterior tibial translation of at least 10 mm compared to the contralateral knee on comparative monopodal stance radiographs [7, 22]. While the presence of increased posterior tibial slope is required to consider the addition of a tibial deflexion osteotomy to a revision ACL reconstruction, its presence alone is not sufficient. Without significantly increased anterior tibial translation on monopodal stance views as described above, we do not recommend the addition of a deflexion osteotomy regardless of posterior tibial slope. In these patients, the reconstructed ACL is likely not adversely affected by the tibial slope.

In our experience, the largest effects of posterior tibial slope on tibial translation are seen in patients with associated early degenerative change and/or meniscal pathology that allows excessive anterior tibial translation. Both conditions are more commonly noted in the revision ACL population [18, 23] and are not easily correctable.

Technique

When performing tibial deflexion osteotomy in association with revision ACL reconstruction, numerous factors must be considered regarding technique for both the osteotomy and the ACL reconstruction itself, including graft choice. The technique described below utilizes a BTB graft. Ipsilateral BTB autograft is preferred with a contralateral graft or BTB allograft utilized as a second choice depending surgeon and patient preference and allograft availability. While the technique can be easily modified for the use of soft tissue grafts, we believe there are several advantages to using BTB in this particular situation. First, because the graft often spans the osteotomy site, the presence of bone plug rather than soft tissue in the tunnel may improve the stability of the osteotomy following fixation and may contribute to healing of the osteotomy. Second, patients undergoing ACL reconstruction with BTB autografts are more likely to lose some extension compared to those undergoing reconstruction with hamstring autograft [24]. Because recurvatum can result from a deflexion osteotomy, such extension loss is in these patients is an advantage rather than a complication.

The procedure begins with an examination under anesthesia to assess the Lachman and pivot-shift compared to the contralateral side. The degree of hyperextension (if any) in both limbs should also be noted. The case then proceeds with graft harvest, generally an ipsilateral BTB. We prefer a longitudinal incision along the medial border of the patellar tendon from just proximal to its origin on the patella to a point just distal to the tibial tuberosity. This incision allows harvest of the BTB graft as well as performance of the osteotomy. Following graft harvest, one can proceed with an arthroscopic evaluation of the knee and address any additional intra-articular pathology. The femoral tunnel can be drilled utilizing whatever method is comfortable for the surgeon. The tibial tunnel is then created using standard techniques. We prefer to drill a complete tibial tunnel rather than a blind socket to ensure appropriate graft placement after the osteotomy (see below). As with all cases of revision ACL reconstruction, previous tunnel locations must be considered and dealt with appropriately.

Following creation of the tunnels, the tibial deflexion osteotomy proceeds. Osteotomy should be performed with the knee in 90° of flexion to minimize risk to neurovascular structures.

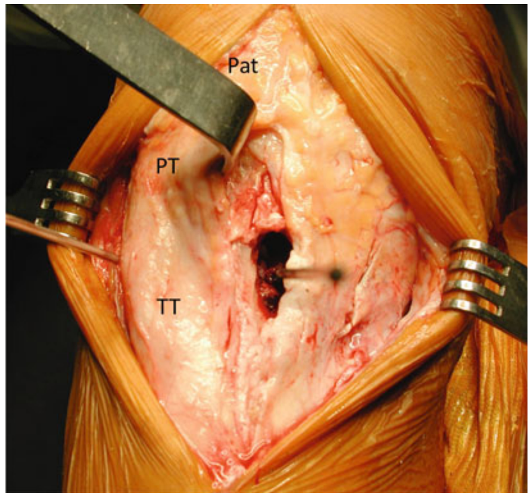

Fig. 21.1 An intra-operative photograph of a right knee in a patient undergoing revision ACL reconstruction in association with a tibial deflexion osteotomy. Guidepins have been placed medial and lateral to the patellar tendon (PT) just proximal to the tibial tubercle (TT). The patella (Pat) is also labeled

The anterior closing wedge osteotomy is performed just proximal to the attachment site of the patellar tendon. First, one must obtain adequate exposure. This includes clearly demarcating both sides of the patellar tendon as well as exposing the proximal tibia. On the medial side, the superficial MCL is elevated at the anticipated level of the cut and a Hohmann retractor is placed to protect it. Laterally, the anterior fascia of the tibialis anterior muscle is divided near its proximal end and the proximal portion of the muscle belly is elevated from the tibia, exposing the bone to the expected level of the cut.

The first guidepin is placed medial to the patellar tendon a few millimeters proximal to the tibial tuberosity (about 3 cm below the joint line). The guidepin is angled proximally toward the center of the PCL insertion and advanced into the posterior tibial cortex. Avoidance of significant penetration of the posterior cortex with guidepins or later with the oscillating saw is critical to prevent neurovascular injury. A second, parallel guidepin is placed just lateral to the patellar tendon (Fig. 21.1). Additional guidepins are placed proximal to the first two to guide the superior cut. The starting point of these guidepins depends of

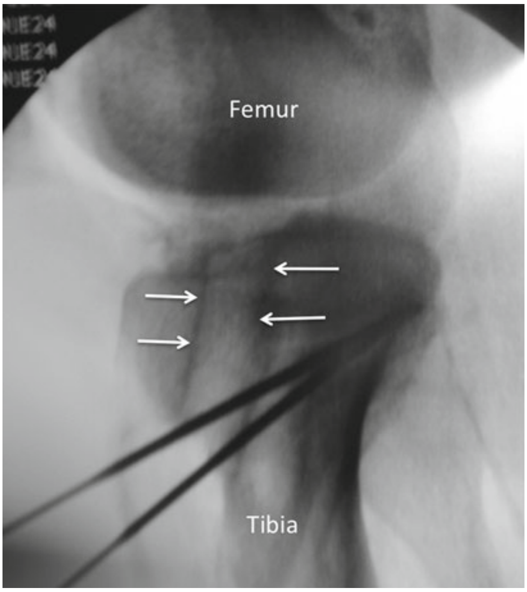

Fig. 21.2 An intra-operative lateral fluoroscopic image of a right knee in a patient undergoing revision ACL reconstruction in association with a tibial deflexion osteotomy. Guidepins have been placed demarcating the superior and inferior cuts of the planned osteotomy. The pins converge of the posterior cortex. The tibial tunnel (*arrows*) for the ACL graft is visible

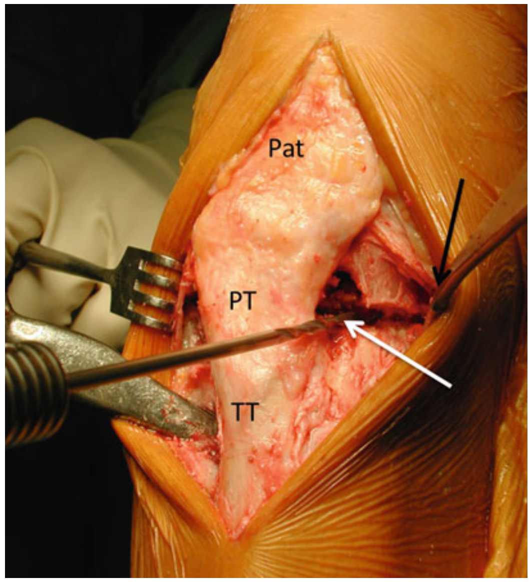

Fig. 21.3 An intra-operative photograph of a right knee in a patient undergoing revision ACL reconstruction in association with a tibial deflexion osteotomy. The osteotomy has been completed and the bone wedge removed. A 3.5 mm drill (*white arrow*) is being used to perforate and weaken the posterior cortex prior to osteotomy closure. The patellar (Pat), patellar tendon (PT), and tibial tubercle (TT) are labeled. The superficial medial collateral ligament is being retracted medially (*black arrow*) to protect is and improve visualization as during the cut

the degree of closing that is desired. As a general rule, each 1 mm of closing results in a slope change of approximately 2°. Thus if a correction of 10° is desired, superior guidepins are placed 5 mm above the initial set of pins. They are then advanced to the same point on the posterior cortex and their position is confirmed by fluoroscopy (Fig. 21.2). It is critical that the pins enter the posterior tibial cortex proximal to the tibial insertion of the posterior capsule of the knee joint in the area of the tibial attachment of the PCL. This location is key to ensuring the integrity of the posterior hinge during closure of the osteotomy.

With retractors in place protecting the superficial MCL and patellar tendon, the lower cut of the osteotomy is made under the lower pins with an oscillating saw. Care must be taken to complete the cuts on the medial and lateral cortices while keeping the posterior cortex intact. The upper cut is then completed in the same manner and the anterior bone wedge is removed. The posterior cortex is then perforated numerous times with a 3.5 mm drill, weakening it prior to closing the osteotomy (Fig. 21.3). When the posterior hinge is sufficiently weakened, the osteotomy site will be seen to close slightly. One can then gently extend the knee, closing the osteotomy. Fixation is achieved with two large staples, one on either side of the patellar tendon (Fig. 21.4). Care must be taken to avoid placing the medial staple through the tibial tunnel. There is a tendency at this point to create a varus angulation of the tibia, which must be avoided by ensuring symmetrical closure of the osteotomy site. The impact of the osteotomy on patellar height is minimal and no adverse effects have been noted. After the osteotomy is fixed, the reamer is again passed through the tibial tunnel to smooth out any malalignment that resulted from the osteotomy. The graft is then passed and secured according to the surgeon's preferred technique (Fig. 21.4).

The change in tibial slope frequently leads to excessive recurvatum in the reconstructed knee relative to the preoperative state and the

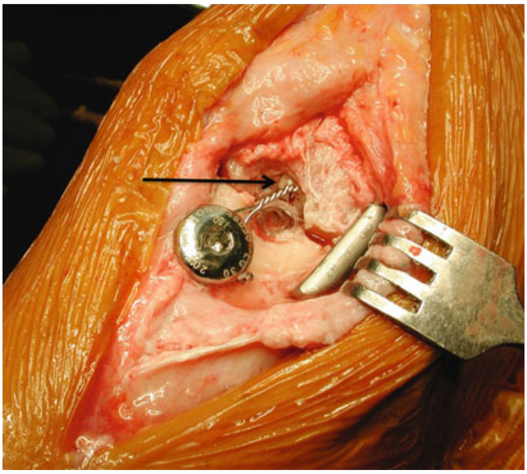

Fig. 21.4 An intra-operative photograph of a right knee in a patient following revision ACL reconstruction in association with a tibial deflexion osteotomy. The osteotomy has been fixed with two metal staples, the medial of which is visible. The ACL graft has been fixed in the tibia with an interference screw backed up with a wire tied around a post (*arrow*)

contralateral side. Because this recurvatum can lead to stretching of the graft and early failure, we prefer to perform a posteromedial capsular advancement to normalize extension. This procedure is performed through the same incision by dissection posteromedially around the knee and releasing the posteromedial capsule from its origin on the posteromedial femur just proximal to the flexion surface of the medial femoral condyle. Two suture anchors are then placed where the capsule was released and the sutures are passed through the capsule 5–10 mm distally. Tying the sutures retensions the capsule and eliminates the recurvatum.

Postoperative rehabilitation is quite different from that following a standard ACL reconstruction. The knee is placed in a brace and passive motion from 10 to 90° of flexion is initiated immediately. A continuous passive motion (CPM) machine may be useful. Full extension is avoided for 6 weeks postoperatively to protect the posteromedial capsular advancement and avoid recurvatum. Weight-bearing is allowed 8 weeks following surgery. Anti-coagulation is recommended until weight-bearing is allowed.

Potential complications include surgical site infection, deep venous thrombosis (DVT), neurovascular injury, nonunion of the osteotomy site, over- or under-correction of tibial slope, and the creation of an iatrogenic varus deformity of the tibia. Careful preoperative planning and attention to detail intra-operatively can minimize these risks.

Outcomes

There is little data available on the outcome of tibial deflexion osteotomy performed in association with ACL reconstruction. D Dejour et al. reported a series of 22 knees with chronic anterior laxity and excess tibial slope (average 16.5°) [25]. They performed deflexion osteotomy in all 22 patients and associated ACL reconstruction in 18 of the patients. They noted improved results in the patients in whom both procedures were performed and recommended the combined procedure. A good outcome has also been reported in a case of bilateral congenital absence of the ACL treated with ACL reconstruction and tibial deflexion osteotomy [26].

Unfortunately, there are no published studies comparing the results of revision ACL reconstruction with or without associated tibial deflexion osteotomy in patients with chronic anterior instability and increased posterior tibial slope. Our experience has been that slope correction and good control of tibial slope can be reproducibly obtained with this technique (Fig. 21.5).

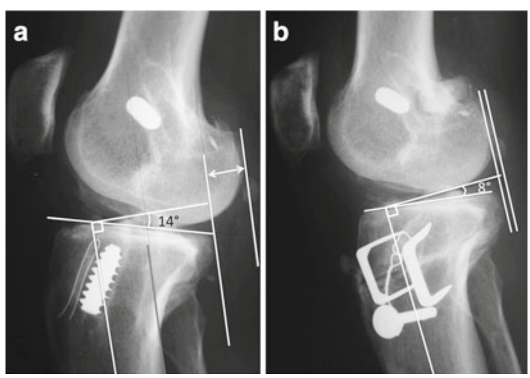

Fig. 21.5 Preoperative (**a**) and postoperative (**b**) lateral monopodal stance radiographs of a patient treated with revision ACL reconstruction and tibial deflexion osteotomy. The posterior tibial slope has been reduced from 14° preoperatively to 8° postoperatively. The anterior tibial translation has decreased from 12 to 2 mm following the procedure

Conclusions

In spite of the success of modern ACL reconstruction in providing a stable knee and returning a majority of athletes to sport, the incidence of failure remains unacceptably high. In rare cases, excessive posterior tibial slope may contribute to such failures. Combined revision ACL reconstruction and tibial deflexion osteotomy may improve outcomes in these carefully selected patients. Further work is needed to confirm the utility of this approach and more clearly define indications.

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Osteotomy for Malalignment Following Failed ACL Reconstruction

22

Davide Edoardo Bonasia, Massimiliano Dragoni, and Annunziato Amendola

Introduction

Failed anterior cruciate ligament reconstruction (ACLR) represents a challenge in orthopedic sports medicine and surgeons should be prepared to encounter many different clinical situations that require individualized management. The goal in failed ACLR revision is to restore function and stability of the knee, according to the patient's age and activity level. A close investigation of the surgical technique adopted in the primary ACLR, positioning of the tunnels, patient's history, mechanism of failure, associated instabilities, lower limb alignment, and knee range of motion is crucial for appropriate decision making for failed ACLR. One of the causes of ACLR failure is associated lower limb malalignment. The limb alignment should be evaluated both in the coronal plane and in the sagittal plane. Varus alignment is commonly encountered in primary ACLR and in ACL revision. A correct assessment of the type of varus (primary, double, or triple) is essential for planning surgical management. The presence of a varus thrust should also be appreciated and can determine the surgical technique. A high percentage of patients with varus knees and ACL deficiency have a high adduction moment during walking [1]. In the early stance phase after heel-strike, a varus thrust can occur owing to the adduction moment [2]. The varus thrust can increase tension in the ACL graft and lead to failure of the graft. One study showed that in varus knees the mean adduction moment (35 % greater than that of controls preoperatively) decreased to less than normal values after high tibial osteotomy (HTO) with ACL reconstruction [3]. Whether this reduction alters the long-term natural history is not known.

Malalignment in the sagittal plane can also affect knee stability in the setting of ligamentous injury and ACL revision surgery. Increased tibial slope allows increased anterior tibial translation due to the tendency of the femur to slide backward along the tibial slope [4].

Anterior cruciate ligament failure due to hyperextension represents a challenge for the surgeon. Indeed, increasing the tibial slope will correct the hyperextension but the anterior tibial translation can be magnified [5]. If the slope is severely increased the risk of ACL reconstruction failure is amplified.

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In the past, knee instability was considered a contraindication for osteotomy. More recently, the importance of coronal and sagittal alignment in knee stability has been clarified and instability can be an indication for HTO alone or combined with ACL revision. This chapter describes the indications, planning, timing, and surgical technique of HTO alone or combined with ACL revision in the setting of ACLR failure.

History and Physical Examination

A thorough evaluation of medical and surgical history is mandatory to assess patients with failed ACLR. History regarding the mechanism of the first injury, associated ligamentous, meniscal, or cartilage lesions, and the primary ACLR technique are essential. Information regarding the type of graft used, surgical technique (i.e., transtibial/anteromedial femoral tunnel drilling, proximal over the top positioning of the graft), and fixation devices is necessary for correct planning. Previous operative records, clinic notes, radiographs, and intraoperative arthroscopic images can provide important details regarding the initial injury and primary ACLR. Return to daily activities and sports after the primary surgery should be investigated.

The symptoms of the patients with ACL rerupture may include giving way episodes, pain, swelling, stiffness, limp, and locking or catching. Subjective instability due to pain should be distinguished from instability related to ACL deficiency.

On the physical examination, the entire lower limb should be assessed. Lower extremity alignment, gait pattern, muscle tone, knee ROM, and previous incisions should be evaluated. As previously mentioned, coronal malalignment should be thoroughly assessed. Varus alignment is a common finding and the type of varus (primary, double, and triple varus) must be determined. Primary varus refers to the overall tibiofemoral varus osseous alignment (including medial meniscus and medial tibiofemoral articular cartilage loss). Double varus entails varus osseous alignment combined with separation of the lateral tibiofemoral compartment due to lateral ligamentous damage (lateral condylar lift-off). The triple varus knee refers specifically to varus alignment due to: (1) tibiofemoral osseous alignment, (2) increased lateral tibiofemoral compartment separation, and (3) varus recurvatum in extension due to the abnormal increase in external tibial rotation and knee hyperextension, with involvement of the entire posterolateral ligament complex [6]. When present, varus thrust should be noted while evaluating the gait of the patient. Quadriceps muscle circumference should be measured and compared with the contralateral leg to assess any muscle atrophy. Passive and active ROM should be evaluated to assess the presence of flexion contracture, extension lag, hyperextension, or markedly decreased ROM. Surgical scars should be considered in order to plan the surgical approach.

A thorough ligamentous and soft tissue examination should be performed to assess associated instability to ACL deficiency. Anterior drawer, Lachman, and pivot shift tests should be performed to assess the degree of anterior and rotary instability. The integrity of the posterior cruciate ligament (PCL) should be evaluated with posterior drawer, quadriceps active tests, and posterior sag sign. Medial and lateral collateral ligaments should be tested by varus/valgus stress tests in full extension and 30° of knee flexion. External Rotation Tests at 30° and 90° of knee flexion will help evaluate the integrity of the posterolateral corner (PLC).

Radiographic evaluation includes bilateral antero-posterior (AP) views in extension, tunnel views at 30° of flexion or Rosenberg views at 45° of flexion [7]. Lateral and skyline views are obtained as well. A weight-bearing hip-to-ankle AP view is obtained to evaluate varus or valgus malalignment. Radiographs reveal tunnel placement, tunnel expansion, bone loss, and the presence of metal hardware, which may interfere with the revision surgery. In addition, lateral views provide important information about the posterior tibial slope. A CT scan should be obtained in order to better evaluate location and widening of the tunnels. MRI is required to assess graft integrity and any other bone or soft tissue pathologies (meniscal or ligamentous lesions, osteochondral defects, etc.).

Indications

In cases of failed ACLR secondary to malalignment, a varus alignment with or without an increased posterior tibial slope may be present. Our indications for HTO (alone or combined with ACL revision) in failed ACLR include:

1. Double or triple varus
2. Increased posterior tibial slope (>10°)
3. Medial compartment osteoarthritis
4. Symptomatic osteochondral defects of the medial compartment (HTO + ACL revision + Cartilage repair)
5. Hyperextension (it is essential to carefully determine the role of alignment in this situation in order to avoid worsening the ACL instability by increasing the sagittal slope)

Correction of varus alignment, along with osteotomy is indicated in double or triple varus knees [3, 8], in order to decrease the stress in the neoligament. Even if both opening wedge and closing wedge HTOs can be performed, opening wedge osteotomy allows an easier correction on the sagittal plane (decreasing the slope), according to the plate position. With a more posterior positioning of the plate with spacer, the slope is usually decreased. Opening wedge HTO is the authors' preferred technique compared to closing wedge HTO, and the reasons include: (1) possibility of a multiplanar correction; (2) no need for proximal tibiofibular joint disruption or fibular osteotomy; (3) less risk to the common peroneal nerve; and (4) the possibility of a limited surgical approach on the medial side of the knee (sometimes using the previous scars) when combined ACL revision is performed. However, closing wedge HTO still represents a valid alternative option. Closing wedge HTO usually results in a decreased slope, which may help reduce the stress in the neoligament, and a faster callus formation than with opening wedge HTO. Our indications for closing wedge HTO include patients with bone healing problems (i.e., smokers, although smoking is a relative contraindication to HTO).

After ACLR failure, HTO can be performed alone or combined with ligament reconstructions (in most cases ACL and/or PLC or lateral plasty) in a single-staged or a two-step procedure (Fig. 22.1). In young, active patients with high functional requests, our tendency is to correct the

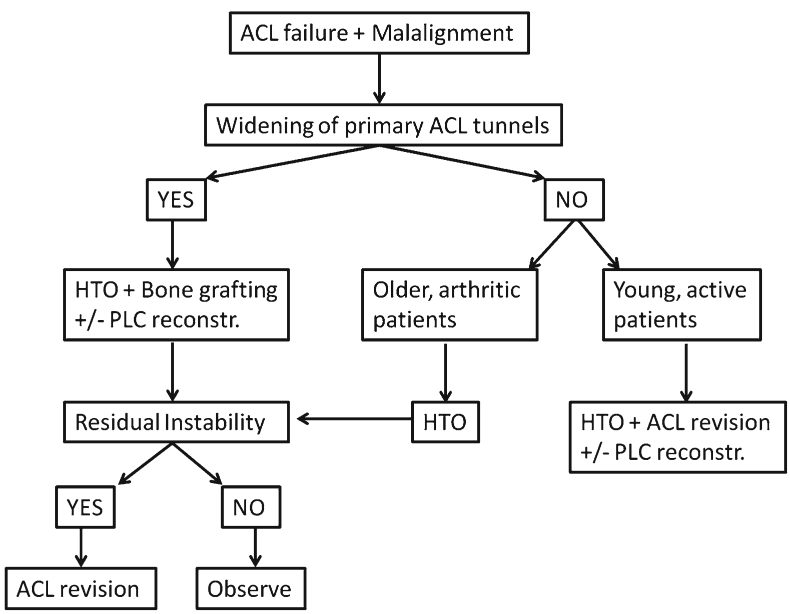

Fig. 22.1 Algorithm for the treatment of failed ACLR and malalignment (see text)

alignment as well as the instability of the knee (HTO + ACL revision +/− PLC reconstruction). In older patients with arthritic knees and lower activity level, HTO with correction of the varus alignment and a reduction of the tibial slope is usually sufficient to relieve pain and provide stability to the knee. If the knee instability persists after the HTO, ligament reconstruction is then performed.

Occasionally, a two-stage procedure is indicated also in young active patients with tibial/femoral tunnel widening (>16–17 mm) and malalignment after failed ACLR. In this case, HTO and bone grafting of the tunnels with or without PLC reconstruction is performed first, and then ACL revision is performed after 6 months. When necessary, PLC reconstruction is performed according to the surgeon's preferred technique.

ACL failure due to knee hyperextension certainly represents a challenge for the orthopedic surgeon. Decreasing the tibial slope can help provide stability to the knee, but may also result in increased hyperextension, mostly with closing wedge HTO. In these cases, our current approach is to decrease the slope with opening wedge HTO and, if instability persists, perform an ACL revision.

According to the single case, nonanatomic ligamentous reconstruction techniques may be considered. Between these techniques, the following should be mentioned: (1) Marcacci's technique with proximal over the top positioning of the graft and lateral extra-articular tenodesis [9]; and (2) isolated lateral extra-articular tenodesis with fascia lata [10]. Even if not anatomic, Marcacci's technique has numerous advantages, and these include: (1) proximal over the top position, without concerns regarding the previous femoral tunnel; (2) increased rotary stability of the knee; (3) easy proximal and distal fixation; and (4) lateral tenodesis, which provides varus stability in case of lengthened PLC structures. This technique can be performed with hamstring autograft as well as with tibialis anterior or Achilles tendon allografts. The graft should be at least 28 cm long.

Rarely, varus distal femoral osteotomy (DFO) can be indicated after failed ACLR. The indications include:

1. Lateral compartment osteoarthritis.
2. Symptomatic osteochondral defects of the lateral compartment (DFO + ACL revision + Cartilage repair).
3. Chronic medial collateral ligament tear and severe valgus malalignment (DFO + ACL revision + medial collateral ligament reconstruction/retensioning).

In these cases, a medial closing DFO is performed with or without combined procedures. This technique allows for a quick healing and a single surgical approach on the medial side of the knee if ACL revision, cartilage repair, or medial collateral ligament reconstruction/retensioning is associated. Lateral opening wedge DFO can also be considered.

Treatment

Preoperative Planning

The HTO is described by Dugdale et al. [11] with a slight valgus overcorrection (3–5°) in knees with medial arthritis. In this scenario, the mechanical axis should pass through a point located at 62.5 % of the width of the tibial plateau, right lateral to the tip of the lateral tibial spine. In young, active patients a correction to neutral alignment (50 % of the tibial plateau) is planned [12]. Opening wedge HTO is planned drawing a line from this point (62.5 or 50 %) to the femoral head center, and another line from this point and ankle joint center (Fig. 22.2a). The angle obtained represents the angle of correction (α) [alpha]. The osteotomy line (ab) is defined from medial (≅4 cm below the joint line) to lateral (tip of the articular fibular head). This measurement is transferred to both rays of the α angle from the vertex (a^ib^i and a^ic). In this manner, two identical segments, which are equal to the osteotomy length, define the α [alpha] angle. Next, the segments are connected by another line (b^ic) which is used as the base of an isosceles triangle and corresponds to the opening wedge that should be obtained medially at the osteotomy site (Fig. 22.2a).

The tibial slope is assessed on lateral view radiographs (Fig. 22.2b). The slope normally varies from 0 to 18° [13]. The amount of tibial slope

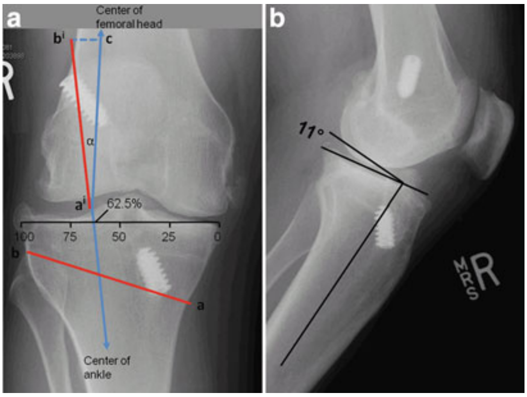

Fig. 22.2 Patient with failed ACLR, varus malalignment, and knee arthritis. (**a**) Planning for opening wedge HTO in the coronal plane (AP view), with a slight valgus overcorrection, considering the medial arthritis (see text). (**b**) Evaluation of the posterior tibial slope on the lateral view

correction depends on the starting value. Minimal correction is required when the slope is less than 8°, while a larger correction is needed when the slope exceeds 10°.

The planning for closing wedge is similar to opening wedge HTO. However, the osteotomy is different and entails two cuts, but the α [alpha] angle is calculated as previously described. The proximal cut is usually horizontal and is placed 2–2.5 cm below the joint line. The proximal and distal osteotomy should define the angle of correction (α) [alpha]. The tibial slope is usually decreased after a closing wedge HTO. However, it is more difficult to accurately modify or correct the tibial slope using this procedure.

Surgical Technique

According to surgeons' preference, either opening wedge or closing wedge HTO can be performed. The ACL graft and the reconstruction surgical technique is also a matter of the surgeon's preference.

Opening Wedge HTO

The surgery is performed with the patient on a radiolucent operating table [14, 15]. A lateral post is positioned at the level of the thigh, to allow the foot to be dropped out of the table and to achieve at least 120° of knee flexion. Intravenous antibiotic prophylaxis is administered. A tourniquet is placed around the proximal thigh. A skin marker is used to identify the medial joint line, the tibial tubercle and patellar tendon, and the posteromedial border of the tibia. The leg is elevated and the pneumatic tourniquet inflated. A 5–8 cm incision is created from 1 cm below the medial joint line midway between the medial border of the tibial tubercle and posteromedial aspect of the tibia [5, 14, 15]. The incision can be performed more lateral and extended proximally in case of concurrent ACL revision with patellar tendon autograft. If hamstring autograft is preferred, harvesting of the graft is performed at this point, in order to avoid damage to the tendons during the exposure of the anteromedial (AM) tibia. The sartorius fascia is exposed by a sharp dissection and the pes anserinus is then retracted distally with a blunt retractor, exposing the superficial medial collateral ligament (sMCL). A Cobb elevator is used to partially detach the distal sMCL insertion. A blunt Homann retractor is passed deep to the MCL to protect posterior neurovascular structures. Next the medial border of the patellar tendon is identified and protected throughout the whole procedure with a second blunt lever. A guidewire is drilled through the proximal tibia from medial to lateral under fluoroscopic control. The starting point of the wire is the anteromedial tibia at the level of the superior border of the tibial tubercle (about 4 cm distal from the joint line). The wire must be inserted aiming the tip of the fibular head (1 cm below the lateral articular surface) [5, 14, 15]. The tibial osteotomy is performed immediately distal to the guide pin to protect against proximal migration of the osteotomy into the joint (Fig. 22.3). The direction of the osteotomy in the sagittal plane is critical and should be parallel to the proximal tibial joint slope. The tendency to make the osteotomy perpendicular to the long axis of the tibia should be avoided because this will create a very thin bony fragment posteriorly because of the physiological posterior tibial slope [13, 14]. The anterior and medial cortices are cut with a small oscillating saw under direct vision. Then the osteotomy is deepened within 1 cm of the lateral

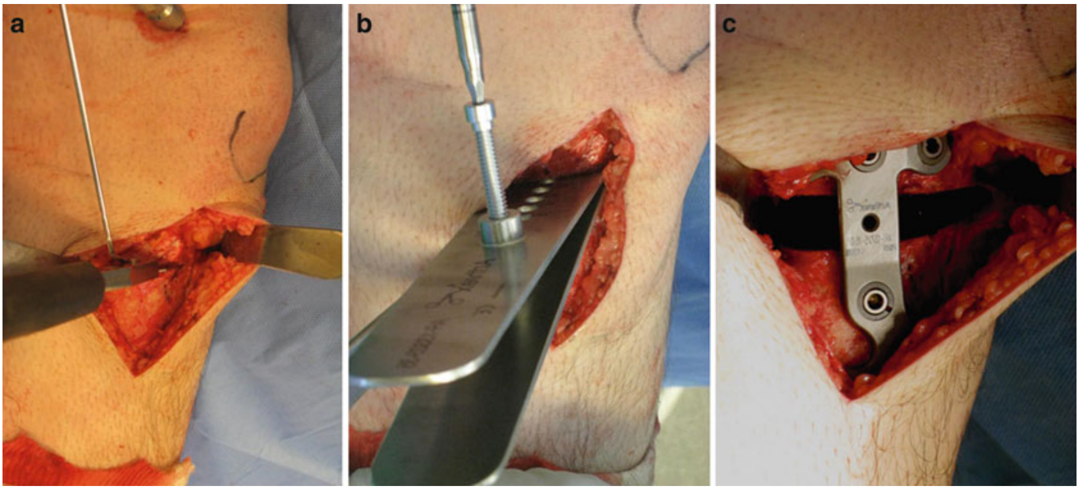

Fig. 22.3 Intra-operative pictures. (**a**) After positioning the guide wire and cutting the cortex with an oscillating saw, the osteotomy is performed with graduated osteotomes under fluoroscopic control, making sure to leave intact the lateral hinge (1 cm from the lateral cortex). (**b**) When the bone cut has been completed anteriorly and posteriorly and some degrees of opening are noted with valgus stress, the osteotomy site can be distracted. (**c**) Plating is performed next

tibial cortex using thin, flexible osteotomes (Fig. 22.3). The osteotomy should be taken to within 1 cm of the lateral tibial cortex, using intermittent fluoroscopy and graduated osteotomies [16]. The mobility of the osteotomy is checked by gentle manipulation of the leg with a valgus force and encouraged, if needed, piling up two or three osteotomes [5, 14, 15]. Graduated wedges are then engaged into the osteotomy and advanced slowly, until the desired opening is achieved. An intact lateral hinge is mandatory to improve the stability of the osteotomy. Intraoperative alignment is checked intermittently under fluoroscopy and, once the desired correction is achieved, with an alignment rod centered on the hip and ankle joints. According to the preoperative planning, the rod should lie at 62.5 or 50 % of the tibial width, as measured from medial to lateral. The sagittal plane correction should also be assessed by fluoroscopy and by looking carefully at the amount of osteotomy opening. Considering the triangular shape of the tibia, if the opening at the level of the anteromedial tibia is half of the opening at the level of the posteromedial tibia, the preexisting slope is maintained. The slope can be adjusted according to the correction planned on the sagittal plane by moving the wedges (and the plate) anterior or posterior. Once the desired correction has been achieved and plate positioning determined, the osteotomy is fixed with a plate and the wedges are removed. Various plates are available for fixation of the opening wedge osteotomy: conventional, locking, butterfly, long or short plates, with or without a spacer [17]. In order to further decrease the tibial slope, one distal screw is positioned and then the knee is kept in full extension while inserting the first proximal screw. In this fashion, the osteotomy gap closes anteriorly and the slope decreases. Fluoroscopic control is necessary to assess proximal and distal positioning of the screws. If a conventional Puddu plate is used, attention should be paid to position the proximal screws more posteriorly than usual, in order to have enough bone for the tibial tunnel, if ACL revision is concurrently performed. For the same reason, when using a long locking T plate (Fig. 22.3), the most anterior screw should not be inserted proximally [17]. Alternatively, all proximal screws are positioned and, if the tibial tunnel is interfering with one of them, this is removed and repositioned. The osseus gap can be filled using the preferred bone graft (autograft, allograft, or substitutes) [17–22]. Corticocancellous autograft or allograft is recommended for an opening measuring >10 mm. Conversely, bone grafting is optional for smaller corrections.

Closing Wedge HTO

Many variations of lateral closing wedge osteotomy have been described in the literature, but all are based on the principle to correct the alignment achieved by removing a laterally based wedge of bone and closing the resultant defect [11, 23–25]. A longitudinal midline incision is performed when concurrent ACL revision is performed using patellar tendon autograft. If allograft or hamstring autograft are chosen, a lateral hockey stick incision can be used. The midline incision has the advantage of being universal and can be used subsequently for knee reconstruction or replacement without the concern for skin bridge vascularity. Dissection is carried out through the lateral aspect of the knee. The fascia of the anterior compartment is exposed and incised along the anterolateral (AL) crest of the tibia, leaving a 5 mm cuff for later closure. A Cobb elevator is used to elevate proximally the tibialis anterior muscle and the iliotibial band. The common peroneal nerve is not routinely exposed but is palpated and protected throughout the procedure. Many techniques have been described for the proximal tibiofibular joint, including: (1) joint excision or disruption, (2) fibular osteotomy (10 cm distal from the fibular head), and (3) excision of the fibular head. The lateral edge of the patellar tendon is identified and a retractor is positioned underneath it. A second retractor is placed on the posterolateral tibial edge, in order to protect the neurovascular structures. Using this approach, the proximal tibia is exposed and a laterally based wedge can be removed with an angular cutting guide. The base of the wedge should be 2–3 mm smaller than the planned osteotomy. In order to reduce the risk of intra-articular fracture, the outer cortex and large portion of the wedge can be removed with saw cuts, along with the medial half using a combination of curettes, rongeurs, and osteotomes, to within 1 cm of the medial cortex. Completeness of wedge removal is assessed by fluoroscopic control. Once the osteotomy is closed, the position and the alignment are checked with the fluoroscopy. Fixation can be achieved using two staples, a contoured T-plate or a locking plate [5, 14, 15]. After the osteotomy is fixed, the ACL revision is performed at the same time or during a second surgery.

As previously mentioned, when more than 16–17 mm of tunnel expansion is present, a two-stage procedure is preferred and grafting of the previously used tunnels is performed. Visualization of the tibial tunnel is usually achieved with the arthroscope into the tunnel. Expanded tibial tunnel can be filled with bone graft using a small tamp in an inferior to superior direction. According to the surgeon's preference, either autologous graft from iliac crest or allograft bone chips can be used. The femoral tunnel is best visualized with the arthroscope in the anteromedial portal. An accessory medial portal can be made and a small arthroscopic cannula introduced in order to provide access and avoid wash out of the bone graft. Dry arthroscopy is also an option to prevent efflux of bone chips. Serial radiographs are taken to confirm complete consolidation of the tunnels before second-stage ACL-reconstruction, which usually is performed after 6 months. CT scan is also useful to assess tunnel consolidation.

ACL Revision

Surgical technique and graft selection are based on the surgeon's preference and the primary ACLR. In general, the use of allograft in revision surgery has some advantages, including: (1) less surgical trauma; (2) less surgical time; and (3) the possibility of ordering different grafts according to the specific case. Soft tissue graft is preferred by the authors (i.e., tibialis anterior allograft). These grafts allow for tunnel and fixation variability, particularly on the tibial side where the osteotomy is present. If mild tunnel widening is present, Bone Patellar Tendon Bone (BTB) or Achilles tendon allografts with larger bone blocks can be used.

A complete diagnostic arthroscopy is performed through standard anterolateral (AL) and anteromedial (AM) portals. Concomitant pathologies such as meniscal tears and chondral lesions are assessed at this point. The remaining

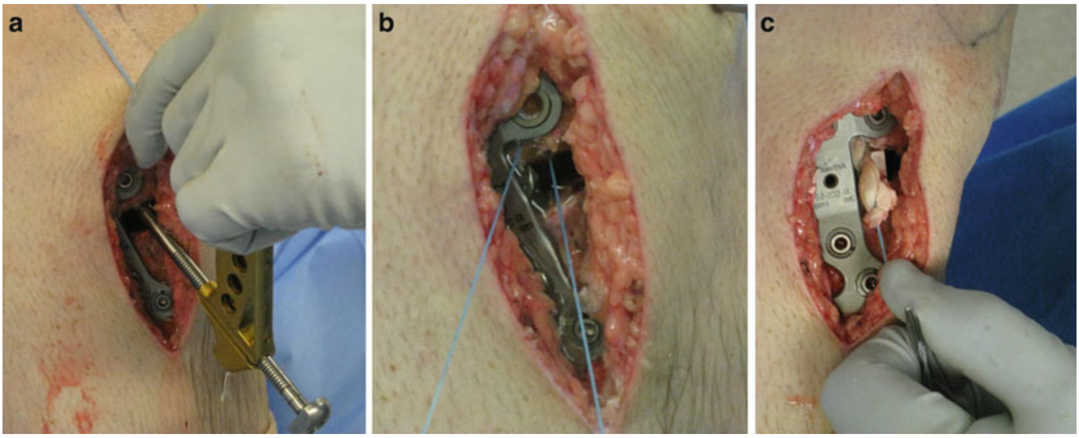

Fig. 22.4 Intra-operative pictures with (**a**) tibial tunnel preparation. (**b**) Note that sometimes the proximal anterior screw of the plate, needs to be removed and repositioned to allow for the tibial tunnel drilling. (**c**) After femoral tunnel drilling and proximal fixation, the soft tissue graft is inserted into the joint and fixed distally

neo-ligament stump is removed using a mechanical shaver, so that the femoral and tibial footprints are clearly identified. A minimal notchplasty may be necessary and is performed with a shaver or an acromioplasty burr.

If tunnel placement and graft fixation can be achieved without interference from previous fixation, the hardware can be retained. Otherwise, fixation devices are removed together with granulation tissue, in order to allow graft incorporation.

Tibial Tunnel Placement

A variable-angle ACL guide is inserted into the joint through the AM portal (Fig. 22.4). While proximally the tibial tunnel should enter the joint in the anatomic ACL footprint, the inclination of the tunnel can vary according to the placement of primary ACLR tunnel/hardware or HTO plate/screws. A guide pin is drilled inserted into the proximal tibia and advanced to touch the femur, close to the position decided for the femoral tunnel. In this way, the length of the tibial tunnel and intra-articular portion of the neo-ligament can be measured with another identical pin. The pin is then retrieved 0.5 mm above the tibial articular surface and the tibial tunnel drilled with an appropriately sized reamer. If the tunnel is interfering with one of the plate screws, the hardware is removed, the tibial tunnel is drilled, and the screw is positioned in another direction if possible (Fig. 22.4). This is done under direct visualization and before the graft is passed into the tunnel.

Femoral Tunnel Placement

Ideally, an AM portal femoral tunnel drilling is preferred to transtibial drilling, in order to obtain a more anatomical position of the graft. Alternatively, an outside-in femoral tunnel drilling via a two-incision technique can be used. Both techniques allow for a femoral socket independent of the tibial tunnel. The two-incision technique provides an accessory lateral incision over the lateral distal femur, splitting the iliotibial band, and allows introduction of the ACL guide through either the anterolateral portal or around the femur from the over-the-top position. A more oblique or horizontal tunnel can be made to avoid the prior tunnels. A guide pin can then be directed into the joint and then overreamed in a standard fashion. The accessory medial portal can also be used to create a separate femoral socket. A guide pin is then placed into an accessory AM or the AM portal, directed into the femoral ACL footprint, and then driven through the lateral cortex of the femur. The knee must be hyperflexed at 120° before guidewire passage, in order to have a longer, more anteriorly directed tunnel. This helps to avoid blowout of the posterior wall. The exit of the guidewire should be at a point above the superior pole of the patella and anterior to the midline of the femur. The knee remains hyperflexed, and the guidewire can then be overreamed to create the femoral socket. When placing the reamer through the accessory medial portal, care must be taken to avoid damage to the articular cartilage of the medial femoral condyle. A No. 2 braided shuttling suture is looped and passed through the eyelet of the guide pin. The guide pin is pulled from the lateral side of the thigh, retrieving the two free ends of the suture proximally and keeping the loop outside the AM portal. An arthroscopic grasper is inserted into the tibial tunnel and the loop of the suture is then retrieved out of the tibial tunnel distal aperture. The graft is then inserted into the joint and fixed.

Graft Fixation

Once tunnel preparation has been accomplished, the bone quality and relative size of the graft might be evaluated to achieve an adequate fixation. Author's preferred fixation for the revised neo-ligament is as follows. When using a BTPB graft, fixation is achieved with interference screws on both femoral (first) and tibial sides. When using a soft tissue auto- or allograft, fixation is achieved proximally with an extracortical flip button device and distally with an interference screw. If the lateral cortex of the femur is damaged by primary ACLR, a transfixation device or interference screw can be used.

Rehabilitation

Postoperatively, 0–90° active range of motion in a hinged knee brace and toe-touch weight-bearing are allowed immediately. At 6 weeks, according to radiographic evidence of bone healing, the hinged brace is discontinued, ROM is no longer restricted, and weight-bearing is increased to 50 % of body weight. At 12 weeks, new X-rays are taken and, if consolidation is complete, full weight bearing is allowed. Physical therapy is continued for 3 more months and return to sports is allowed at 6–12 months after surgery.

Results

HTOs have increased in popularity in the ACL-deficient knee. The overall results of osteotomies either alone or combined with ligamentous reconstruction are encouraging.

Fowler et al. reported significant improvement in 7 ACL chronic-deficient knee with varus alignment/trust treated with HTO alone [26]. Fifty ACL-deficient knees with acquired varus were treated by Dejour et al. with HTO and ACL reconstruction. The authors showed a 91 % satisfaction rate, although the rate of return to leisure activities was only 65 % [27]. In the study by Noyes et al. on HTO in ACL-deficient knees, the authors reported reduction of pain in 71 %, elimination of giving way in 85 %, and resumption of light recreational activities in 66 % of patients [3]. Williams et al. retrospectively compared closed wedge HTO alone with simultaneous combined ACL reconstruction and closed wedge HTO in patients with chronic ACL deficiency, medial compartment arthritis, and varus deformity. They concluded that the simultaneous procedure had superior short-term outcomes and lower complication rate [28]. Bonin et al. found that simultaneous combined ACL reconstruction and closed or open wedge HTO controls anterior laxity, allows many patients to return to sports, and does not result in a rapid progression of osteoarthritis, showing satisfactory long-term results [29]. Boss et al. treated 27 patients with combined BTB ACL reconstruction, augmented with the Kennedy-ligament device, and HTO (24 lateral closing and 3 medial opening). Seventy-five percent of patients stated that they were satisfied and would have the operation again [30]. Imhoff and Agneskirchner performed simultaneous ACL reconstruction and HTO in 58 patients, with improvement in pain, swelling and instability symptoms in all of them, and a low complication rate [31]. Willey et al. retrospectively reviewed 35 patients treated with either HTO or DFO associated with concomitant additional knee reconstruction surgery. The rate of complications was similar to the rate seen in cases of osteotomy done alone. They suggested that combined osteotomy and knee ligament reconstruction is safe and has advantages for both surgeons and patients [32].

Conclusions

Even if little evidence is available regarding HTO in failed ACL surgery, the importance of limb alignment for successful ACL revision surgery is widely accepted. Even if HTO is almost never indicated in malaligned knees with acute ACL tear, malalignment can contribute to ACL failure.

No decision-making algorithms are available regarding HTO in failed ACLR and every case should be carefully studied and planned (See case 1 and 2 in Figs. 22.5, 22.6, 22.7, and 22.8). The decision to carry out HTO following failed ACLR depends on many factors related to the patient and the primary ACLR.

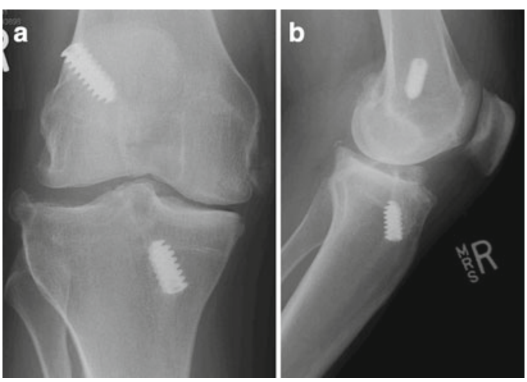

Fig. 22.5 Case 1: A 41-year-old female patient with failed ACLR, varus malalignment, and knee arthritis in (**a**) AP, and (**b**) lateral views. Despite severe knee arthritis, joint preservation with ACL revision and HTO was performed, considering the young age of the patient and the symptoms (mainly instability)

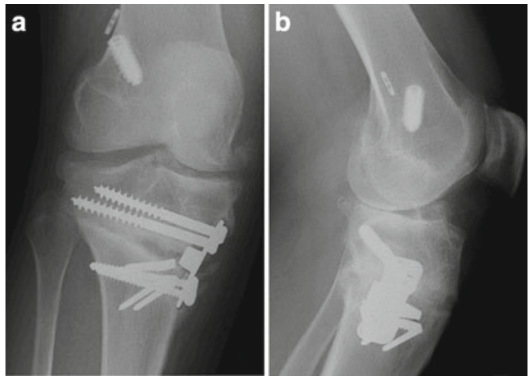

Fig. 22.6 Case 1: Postoperative radiographs after HTO and ACL revision with soft tissue allograft (proximal extracortical fixation and tibial fixation with staples). (**a**) AP and (**b**) lateral views. Note in (**b**) the posterior plate positioning, in order to decrease the tibial slope

Fig. 22.7 Case 2: A 37-year-old female patient with bilateral failed ACLR and varus malalignment

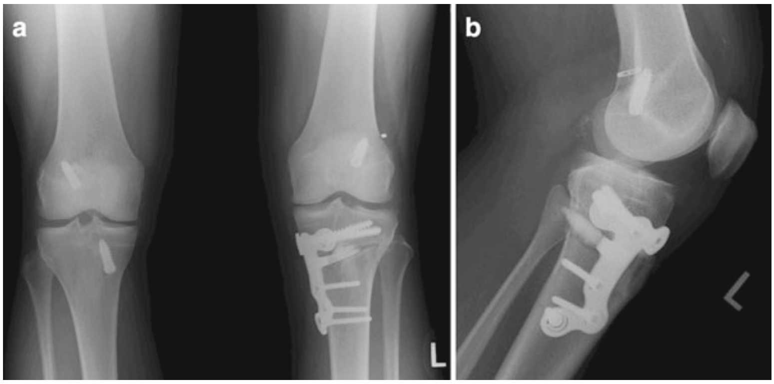

Fig. 22.8 Case 2: Postoperative radiographs after hardware removal from the tibia, HTO, and ACL revision with soft tissue allograft (proximal extracortical fixation and tibial fixation with interference screw). (**a**) AP and (**b**) lateral views

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Navigation for Revision ACL Reconstruction

23

Stefano Zaffagnini, Tommaso Bonanzinga, Bharat Sharma, Nicola Lopomo, Cecilia Signorelli, Giulio Maria Marcheggiani Muccioli, and Maurilio Marcacci

Introduction

With increasing primary anterior cruciate ligament (ACL) reconstructions performed every year, and the high level of activity expected by the patients, revision procedures are becoming a problem in orthopedic practice. The incidence of failure of the primary procedure has been reported to be 3–25 %; however, the true incidence is hard to determine and it is probably underreported [1–5]. In spite of the improvement of surgical techniques, it is commonly reported that outcomes for revision surgery remain poor when compared with primary procedures [4, 6–10]. Revision ACL cannot be approached in the same manner as primary ACL reconstruction, due to many technical issues that are not present in the primary setting. Considerations include, but are not limited to, bone tunnel defects and incorrect tunnel placement. Moreover, in such a scenario it becomes crucial to identify any possible associated secondary restraint ligamentous laxity, which might have been a cause of the failure of the primary reconstruction or might have occurred during the reinjury.

In the past decade, computer technologies were introduced into orthopedic surgical practice for preoperative or intra-operative planning and to enhance the accuracy and safety of the procedure. Computer-aided surgery (CAS) enables the surgeon to continuously monitor the position of instruments in relation to the patient's anatomy and the operative plan. More recently, attention has been paid to the importance of using CAS as an intra-operative evaluation system to provide a preliminary estimation of the surgical result, allowing the surgeon to adjust the surgical treatment to the individual patients' features. This concept fits well for knee surgery [11, 12]. CAS enables a global and accurate kinematic evaluation during surgery to reach parameters as close as possible to the normal knee.

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Computer-Assisted Orthopedic Surgery

Computer-assisted orthopedic surgery (CAOS) was first used in neurosurgery for the required precision [13, 14]. Its early adaptation into orthopedic surgery was for arthroplasty and arthroscopy, borrowing instrumentation from neurosurgery [13, 15]. Over the last 2 decades, CAOS has been progressively adapted across the orthopedic subspecialties of joint replacement and ligament reconstruction with dedicated tools, protocols, and surgical instruments [16]. These techniques have been driven by the constant improvement in computing technology and data acquisition [15]. CAOS techniques are broadly divided into active and passive modalities, based on whether it performs or guides the surgical procedure, respectively [13, 16, 17]. Depending on the role and acquisition of anatomical images, CAOS could use preoperative images, intra-operative images, or biomechanics (image-less) to map the region of interest [16]. While research into the clinical efficacy of CAOS in primary and revision ACL reconstruction is ongoing, several conclusions are available for clinical application in ACL revision surgery.

The primary instrument used in CAOS is a "tracking sensor" that recognizes signals from markers attached to instruments or bone. This helps orient the operative field and the instrument in space. Markers, known as dynamic reference frames, are implanted into the femur or tibia to track the movement of the bone. The knee can be represented either as an image in the operative field, or in motion over a coordinate system, depending on whether the system is image or image-less-based [14].

Active CAOS systems have not yet been adapted into routine clinical practice. Passive CAOS are available for three broad applications in ACL ligament reconstruction, especially in the case of revision surgery: preoperative planning, intra-operative guidance, and intra-operative evaluation of the reconstruction. Hardware, software systems and intra-operative protocols for these three applications for CAOS have been standardized and are in use in clinical settings [16].

Preoperative Surgical Planning

CT- or MRI-based preoperative images can be employed in image-based CAOS to allow for surgical planning. CAOS allows a three dimensional planning environment; unlike the 2D CT or MRI images. Parameters related to tunnel orientation like osseous entry, tunnel length, and osseous exit can be planned [17, 18]. The length of the graft, its isometry and impingement, either on the PCL or the inter-condylar notch, can be estimated prior to surgery [13, 17].

Intra-operative Guidance

Intra-operatively, these above parameters can then be tracked in a three dimensional operative field or kinematic model created by the CAOS using image-based or kinematic evaluation [14]. This not only allows real-time input into the spatial orientation of the patient, graft and instruments but also the ability to run simulations in the system prior to critical steps [13, 14, 17]. Therefore, the CAOS enables the surgeon to visualize the effect and accuracy of technical decisions before they are actually executed. In effect, it provides the as yet unavailable reversibility to surgical procedures. The operator may choose to reorient or redo a step based on the simulation, without having to actually carry it out.

Intra-operative Evaluation

CAOS can be used to intra-operatively evaluate the efficacy of the reconstruction using clinical and biomechanical tests [13, 14, 17]. The representation of the operative field or motion in coordinate system visualizes various clinical and biomechanical tests that are used to check graft behavior in situ and can be quantitatively studied intra-operatively with a clinical test like Lachman, Anterior Drawer, and Pivot Shift (Fig. 23.1a, b). The values obtained can be compared with those before fixation of the graft. These tests allow a final opportunity to correct the procedure prior to definitive graft fixation [13, 14, 17].

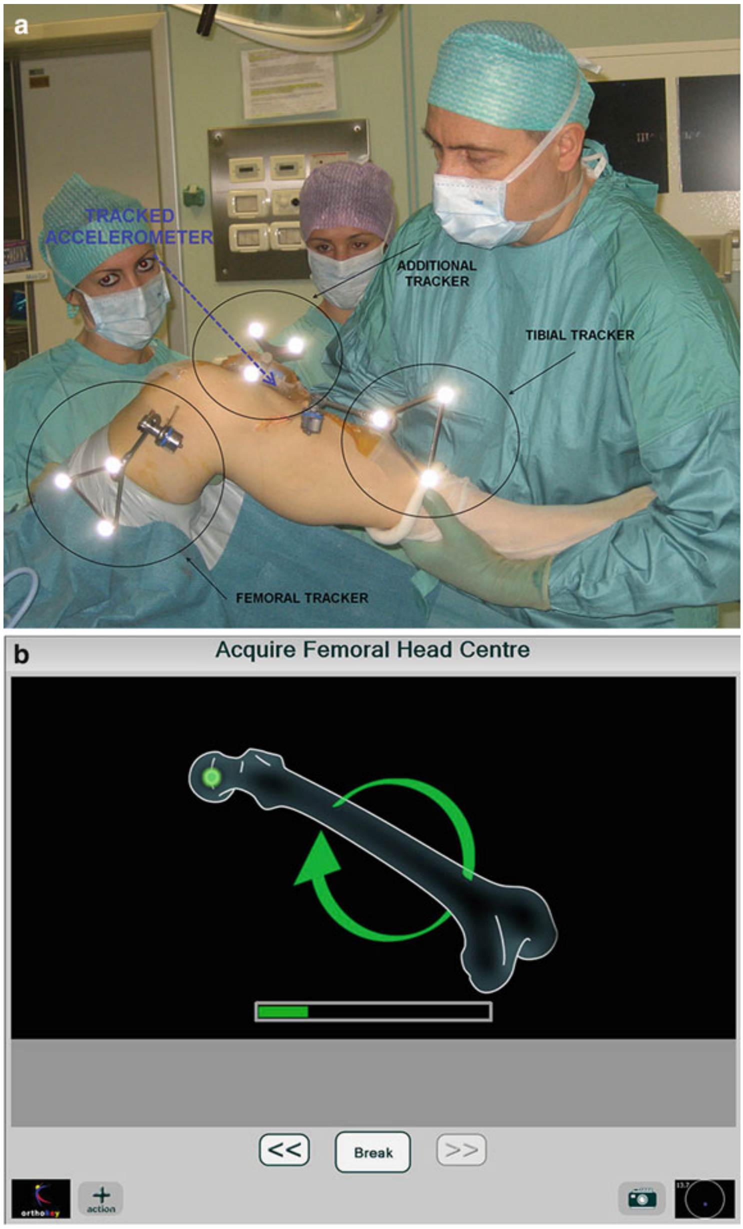

Fig. 23.1 (**a**, **b**) The hip center is acquired through pivoting the limb

Surgical Technique

The surgical technique recommended by the authors is a non-anatomical, double-bundle ACL reconstruction, involving fresh-frozen, non-irradiated Achilles tendon allograft with soft tissue fixation [19]. The navigation system (BLU-IGS, Orthokey LLC, Lewes, DE, USA) consists of a commercial optoelectronic localizer and custom acquisition software for kinematic analysis. This is used to intra-operatively measure joint laxity, graft elongations, isometry maps, and previous tunnel placement [20–23] (Fig. 23.2).

The surgical technique involves standard knee arthroscopy with three portals: a medial suprapatellar for water inflow, an antero-lateral for the arthroscope, and an antero-medial for instruments.

Fig. 23.2 The navigation system (BLU-IGS, Orthokey LLC, Lewes, DE, USA) consists of a commercial opto-electronic localizer and a customable acquisition software for kinematic analysis

Menisci and articular cartilage are evaluated and, when necessary, treated. The residual graft from the previous surgery is carefully debrided.

A small 1.5–2 cm skin incision is made over the tibia, just medial to the tibial tubercle. Then, in order to track bone movement during kinematic tests, two reference arrays are fixed, respectively, on the femur and tibia, with 3 mm surgical wires. The tibial reference array is fixed in the approach for tibial tunnel preparation and oriented distally with respect to the knee. The femoral array is inserted above the end of the lateral condyle, distally oriented with respect to the knee (Fig. 23.3). After fixing the femoral and tibial trackers, the surgeon performs an anatomical registration phase, through the percutaneous acquisition of anatomical landmarks: particularly the hip center (identified through pivoting) (Fig. 23.1a, b), femoral epicondyles, tibial malleoli and tibial plateau extremities. Furthermore, other points can be acquired arthroscopically in order to have a complete view of joint characteristics and surgical reconstruction: joint line, tibial plateau centers, and the internal and external exit holes of the previous tunnels. At this point, the system can already determine the placement of the previous tunnels and check for their isometry.

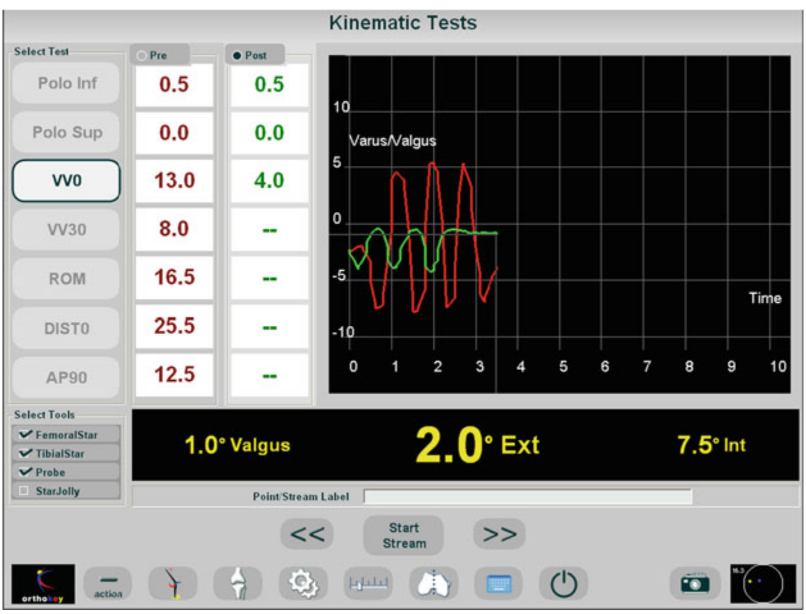

Fig. 23.3 Intraoperative setup

Before performing the ACL revision, a series of kinematic tests is performed in order to evaluate joint kinematics and laxities [20–24]. For revision ACL reconstruction, the tests are:

1. Passive range of motion (PROM).
2. Varus-valgus stress test (VV) at 0° (full leg extension) and 30° of flexion.
3. Internal-external rotation test (IE) at 30 and 90° of flexion.
4. Antero-posterior stress test (AP) at 30 and 90° of flexion.
5. Pivot-shift (PS) test.

The 6 degrees of freedom (DoF) of the knee joint are computed from the relative motion of the tibial frame with respect to the femoral one, to decompose instantaneous rotations and displacements. Knee laxities are also defined for each performed test.

The tibial and femoral tunnels are prepared right after this preoperative evaluation. The authors recommend the creation of just one tibial tunnel where both bundles of the graft are passed to avoid additional damage to the bone stock, while achieving a better press-fit of the two bundles. On the femoral side, one tunnel is required for the reconstruction of the postero-lateral bundle of the ACL, while the antero-medial bundle is reconstructed through an over-the-top passage of the graft, avoiding additional tunnel creation.

According to the technique [19], the knee is flexed to about 135° and a guide pin is drilled through the tibia at an angle of 55° to position it in the postero-medial part of the ACL footprint. For the femoral tunnel, the knee is repositioned a little less than 90° of flexion and the guide pin is inserted through the antero-medial portal on the medial wall of the lateral condyle, approximately 5 mm anterior to the over-the-top position. Then the knee is flexed to around 130°, and the guide pin is advanced until it passes the femoral cortex, just above the end of the lateral femoral condyle. The internal and external exit point of the guide pins on both tibia and femur are collected by the system (Fig. 23.4). Digitizing the diameter of the reamer, chosen by the surgeon to drill the tunnels, it is possible to check the isometry of the new tunnels and search for any possible overlapping with the previous ones.

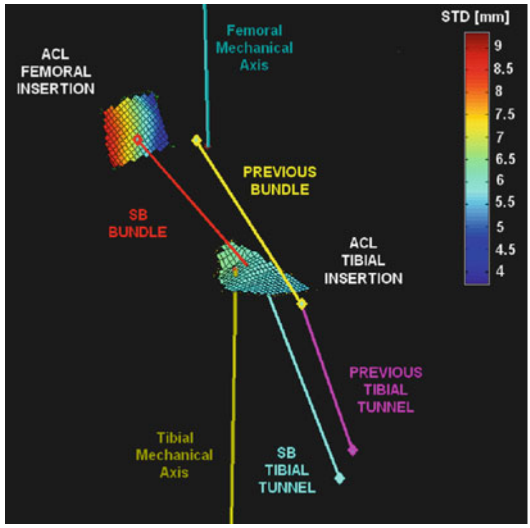

Fig. 23.4 Maps of isometry for ACL tibial and femoral insertions, with the corresponding previous graft placement and the position of the new postero-lateral bundle

If the placement of the tunnels is good, both bundles of the graft are passed through the tibial tunnel and then, while the antero-medial bundle is brought in the over-the-top position through the posterior capsule, the postero-lateral one is passed throughout the femoral tunnel.

Finally, after the fixation of the graft, the kinematic evaluation is repeated to check real-time the efficacy of the reconstruction and to search for any possible associated secondary laxity (Fig. 23.5).

Kinematic evaluation of intra-operative data is performed off-line with dedicated software [25, 26] designed for the study of diarthrodial joints. The 3D coordinates of the anatomical landmarks are used to compute the bone reference frames [27, 28]. Motion data, recorded during kinematic tests, are elaborated using Euler decomposition [20]. VV laxities are calculated along the axis identifying anterior-posterior direction on tibia. IE laxities are calculated along tibial mechanical axis. AP translations are calculated as the 3D displacement of the tibia reference frame centered in the most posterior point of ACL tibial insertion.

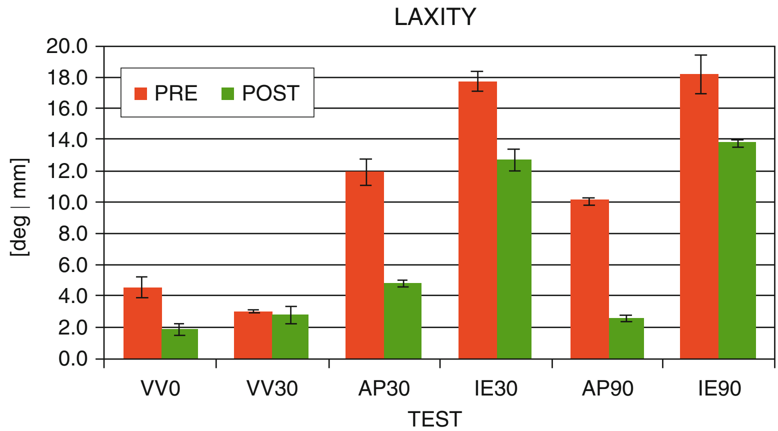

Fig. 23.5 Typical results of laxity reduction after ACL revision

Discussion

ACL revision surgery is a challenging operation and its results remain poor when compared with primary procedures. Many studies comparing navigated and conventional ACL reconstruction have proven that CAOS produces better tunnel placement, eliminates impingement, and reduces anisometry in cases of ACL reconstruction. This improvement is especially effective with relatively inexperienced surgeons, an important fact because more than 80 % of ACL surgery is performed by this group [17].

While all these advantages of CAOS are available for primary ACL reconstruction, they are especially important for ACL revision surgery [18]. Indeed, in revision surgery CAOS might be effective to improve its outcome and to detect causes for failure of the primary reconstruction. ACL reconstruction fails due to problems in technique, graft incorporation, and reinjury [13, 14, 17]. The majority of cases relate to technical errors; mal-positioning of the tibial and femoral tunnels forming the bulk of the problem. Almost all of the technical errors of ACL reconstruction are correctable using CAOS. Mal-positioned tunnels (the primary reason for graft failure), graft impingement, and anisometry are the three factors that can be avoided by navigation in revision surgery [13, 14, 17]. Several arthroscopic reference points, such as PCL or the posterior aspect of the anterior horn of lateral meniscus for placing the tibial tunnel, have been proposed. However, in the revision setting these landmarks are often distorted. Additionally, tunnel placement in revision ACL surgery is complicated by the existence of previous tunnels. This is particularly so when a preexisting tunnel is partially mal-positioned. CAOS allows for precise tunnel orientation via such compromised bone. Furthermore, tunneling can be simulated and altered to perfection without having to actually drill the bone. Similarly, graft impingement and anisometry can be simulated prior to tunnel placement in image-based CAOS. These factors can again be reconfirmed before final fixation of the graft with feedback obtained from the navigation system during pre-loading cycles.

Very few studies are available comparing navigated and conventional ACL revision surgery. Those that exist confirm the improvement in accuracy obtained with navigation. In a technical note, Nakagawa et al. presented their revision technique aided by a fluoroscopic-based navigation system [18]. They recommend the system to improve accuracy and repeatability of tibial tunnel positioning through an enhanced intra-operative visualization, but they did not demonstrate superiority of computer-assisted revision surgery over the conventional one. Interestingly, they suggested a possible role of fluoroscopic navigation in locating metal hardware that has been buried in overgrown bone [18]. Recently, Colombet et al. employed a navigation system to optimize the graft placement and to measure the laxity values in the setting of ACL revision [29]. They demonstrated that a lateral tenodesis in addition to a single anatomic antero-medial bundle ACL reconstruction with a hamstring tendon did not significantly affect anterior tibial translation. Its contribution in controlling the tibial rotation was effective only at 90° of flexion. Their paper is the only one documenting the use of navigation system to evaluate laxity values in the setting of ACL revision surgery. This feature of CAOS is very important in revision surgery because it enables the surgeon to check real time the result of the reconstruction, which might be impaired by the aforementioned factors, and to investigate possible associated injuries.

Moreover, CAOS may potentially allow the surgeon not only to study the effect of associated injuries on knee stability and function but also to customize the surgery for each patient [13, 14, 17]. The image-less-based navigation systems can document the change in motion produced by associated injuries like meniscus, PCL, and PLC. These, combined with the alterations due to ACL rupture, can guide customized procedures for the patient [15]. However, studies in primary ACL reconstruction have not been able to show a significant improvement in intra-operative evaluation or postoperative subjective outcome with the use of CAOS in ACL reconstruction.

Two important limitations of CAOS for ACL revision surgery are its susceptibility to error in anatomical variations and sensitivity to errors of registration [13, 14, 16]. Preexisting anatomical variations may not correspond to the anatomical or biomechanical models pre-loaded in the navigation system, leading to error. Registration of anatomy is also heavily dependent on the surgeon. However, future advancement with laser or ultrasound registration will hopefully overcome these current limitations with CAOS techniques [14]. Another possible limitation is the time required for the setup of the system. In our experience the setup requires an additional 15 min during the surgical procedure. However, especially in revision surgery, there may be a time savings relating to less trial placements of the guide pins and the ability to pre-check the new tunnel placement.

Lastly, a possible concern is the financial investment required by CAS. However, it is evident how improved accuracy could decrease the incidence of long- and short-term failure of the procedure. This is particularly important in revision surgery, due to the possible technical pitfalls previously mentioned. Thus, considering the costs of failure in terms of further revision required and loss of work or sports by the patients, the additional investment seems to be justifiable.

In the future, we expect further advances. The need to reduce the possible sources of error and to restore normal knee kinematics will lead to the development of new systems where the preoperative anatomical and functional data (acquired by high precision systems such as Dynamic RSA and MRI) will be integrated with intra-operative data, hopefully acquired by a noninvasive system. This methodology will help customize the procedure for the knee to reduce morbidity for the patient and costs for the health care system.

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24 Approach to the Multiply Revised ACL-Deficient Knee

Peter B. MacDonald, David A. Rhodes, Randy Mascarenhas, and Michael J. Stuart

Introduction

Patients with an ACL injury commonly present to the sports orthopaedic surgeon. In the United States alone, approximately 200,000 ACL ruptures and up to 175,000 reconstructions occur per year [1]. ACL graft failure presents a challenging scenario that is increasingly encountered in clinical practice. In an attempt to understand the risk factors for primary reconstruction failure and improve the outcomes of revision surgery, the Multicenter ACL Revision Study (MARS) was established in 2006. Over a 3-year period, 460 patients with ACL reconstruction failure were prospectively enrolled and subsequently underwent revision reconstruction. In their epidemiological report, over 11 % of the cohort had experienced multiple reconstruction failures [2]. Clinical decision-making and technical considerations for repeat revision ACL reconstruction are the focus of this chapter.

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Literature Review

Despite the increasing body of literature surrounding the topic of ACL revision surgery, repeat revision surgery has garnered little attention. As of this writing, there are only two known reports in the English language scientific literature.

Wirth and Peters, in 1998, first reported on their dilemma of treating patients with a history of multiple knee operations for instability [3]. In their series of 1,752 ACL reconstructions over the period of 1976–1996, they performed 228 surgical procedures (13 %), including revision ACL reconstruction, extra-articular stabilization, arthrolysis, osteotomy, synovectomy, meniscal surgery, and closed knee manipulation. A subset of 17 patients with multiple ACL revision procedures formed the basis of their report. The cohort included 15 women and two men who underwent an average of seven surgeries each. They attributed the causes of failure to be technical error (11), infection (4), and trauma (2). Consequences of the ACL reconstruction failure were reported as recurrent giving way of the knee, limited range of motion, pain, and effusion. A management algorithm was presented that centered on trying to solve the primary problem from the patients' perspective. The identified problem was then addressed with the "smallest possible procedure." Although nine of their patients were subjectively satisfied, 15 reported persistent instability, pain, or swelling. The authors concluded that the most important goal was to prevent a series of multiple

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operations that perpetuate a history of illness and poor outcomes for the patient.

More recently, Wegrzyn and colleagues reported on ten consecutive patients who underwent repeat revision ACL reconstruction [4]. All patients had a history of two revision ACL reconstructions and were followed for a mean of 38 months after the second revision procedure. Their definition of ACL reconstruction failure included recurrent instability and/or pain with daily activities or sports participation and abnormal knee laxity on physical examination. Only one patient required a two-stage procedure for tibial tunnel enlargement. All reconstructions were performed using ipsilateral or contralateral patellar tendon or semitendinosis autograft. The surgeon reused eight femoral and seven tibial tunnels because they were appropriately positioned. At latest follow-up after the repeat revision, clinical outcomes were excellent or good (IKDC A and B) in seven of the ten patients. Two patients returned to the same sports activity level, four had a lower level of activity, and four discontinued sports participation. The overall mean side-to-side difference with KT-1000 arthrometer testing was 1.3 ± 1.9 mm and 2 patients had a 1+ Lachman on physical examination. Knee radiographs revealed degenerative change in six of the ten patients, all of whom had been treated with partial menisectomies in the involved compartment. However, no progression was noted in the interval from second revision to final follow-up. Finally, the cause of failure after the first revision was felt to be traumatic in 70 %, technical in 10 % (anterior femoral tunnel), and 20 % biological (no trauma and satisfactory tunnel positions).

Causes of Multiple ACL Reconstruction Failures

Failure of the multiple ACL-reconstructed knee shares many of the same causes of failure as primary and first revision reconstructions. A symptom-based evaluation process can be quite helpful in discovering the underlying reason for failure. Most patients will present complaining of recurrent giving-way episodes, pain, stiffness, or some combination thereof. While the technical, biomechanical, and patient-related risk factors for ACL reconstruction failure have been previously defined, we present a simple, systematic approach to determine potential subtle causes of failure so they may be addressed at the time of repeat revision surgery.

A thorough clinical examination and appropriate imaging studies are fundamental in determining the causes of failure and to formulate a surgical plan. The salient features of a detailed history include the mechanism of injury, sensation of knee shifting or giving-way, feeling a "pop," and the ability to return to play. In addition, patient recollection of skin bruising patterns may be helpful, such as the region of the proximal fibula which could signify a posterolateral corner injury. The patient's inability to return to their desired level of activity after surgery may provide clues to potential problems such as a technical error or inappropriate rehabilitation.

The medical record should also be scrutinized for information on the previous injuries and treatments. Prior operative reports and clinical notes may help to uncover technical errors, associated injuries, and intra-articular pathology, and objective recordings of pre- and postoperative rehabilitation.

A focused lower extremity physical examination begins with observation of limb alignment, varus or valgus thrust, surgical scars, and asymmetric muscle girth or tone. Active and passive bilateral knee range of motion is measured using a goniometer and a complete ligamentous examination must also be performed. ACL deficiency is identified with the Lachman test and dynamic subluxation tests including the pivot shift, modified pivot shift, and flexion rotation drawer tests. Arthrometric evaluation can also be used to determine if the ACL graft is functional. A 3 mm side-to-side difference and/or greater than 10 mm displacement on the injured knee is consistent with a ruptured graft [5]. Associated pathological laxity should be ruled out because unrecognized posterolateral and posteromedial injuries are recognized causes of ACL graft failure. PCL deficiency is identified with the posterior sag and drawer tests. Collateral ligament integrity is evaluated by varus and valgus stress testing at zero and 30° of flexion. Posterolateral instability is diagnosed with the dial test at both 30 and 90° of flexion. The dial test is positive when external tibial rotation is increased at least 15° when compared to the contralateral extremity. Increased rotation at 30° of knee flexion only is consistent with posterolateral injury. Increased rotation at both 30 and 90° of knee flexion is consistent with combined posterolateral and PCL injuries.

Appropriate imaging studies are essential to evaluate the multiply revised ACL knee. Standard radiographs include bilateral weight-bearing anteroposterior (AP), 40° flexion posteroanterior (PA), lateral in full extension, and patellar views. Arthrosis, tunnel position and/or expansion, and the location of any metallic hardware are all noted. Radiographic degenerative changes are important to recognize because the presence of arthritis may alter the decision-making and/or postoperative expectations of revision ligament reconstruction surgery. Tunnel malposition can usually be observed on plain radiographs. When viewing the lateral radiograph, the tibial articular surface is divided into four equal quadrants from anterior to posterior [6]. The tibial tunnel aperture should enter the joint in the posterior portion of the second quadrant. Likewise, Blumensaat's line is divided into four quadrants and the femoral tunnel should be noted in the most posterior quadrant. On the AP radiograph, the tibial tunnel aperture should be located in the midline of the plateau and the femoral tunnel entrance is observed on the lateral wall of the intercondylar notch. Tunnels should also be examined for expansion on the AP and lateral radiographs. More accurate measurement of tunnel expansion is possible with a CT scan with 3D reconstruction of the defects. Tunnel dimensions, geometric shape, and the presence of sclerotic bone can be identified. We have found that tunnel diameters greater than 16 mm necessitate a staged approach with tunnel bone grafting first followed by revision ligament reconstruction at 6–9 months (see Fig. 24.1a, b). Determining the type and position of all previous fixation devices is also important for preoperative planning. If hardware removal is anticipated for the revision reconstruction, the appropriate implant removal devices must be available and the resultant bone voids need to be addressed. CT scans and radiographs can be obtained after surgery to assess graft incorporation into the tunnels, which is identified by blurring of the bony tunnels and reactive sclerosis of the surrounding bone (see Fig. 24.2a, b). If the clinical exam suggests coronal plane instability as noted by a varus or valgus thrust during gait or a positive dial test, full-length standing (hip-knee-ankle) radiographs should be obtained to assess limb alignment. An abnormal lower

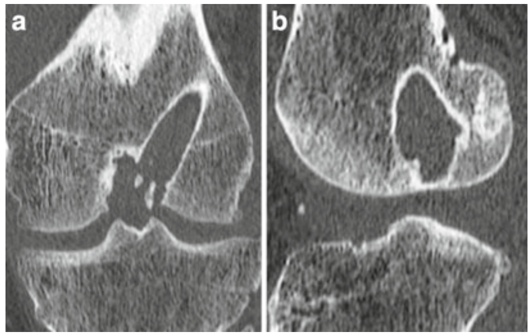

Fig. 24.1 Coronal (**a**) and sagittal (**b**) CT cuts indicating massive tunnel widening greater than 16 mm in a patient with multiple failed ACL reconstructions. A staged revision with bone grafting as the primary procedure followed by ACL reconstruction 6–9 months later is recommended

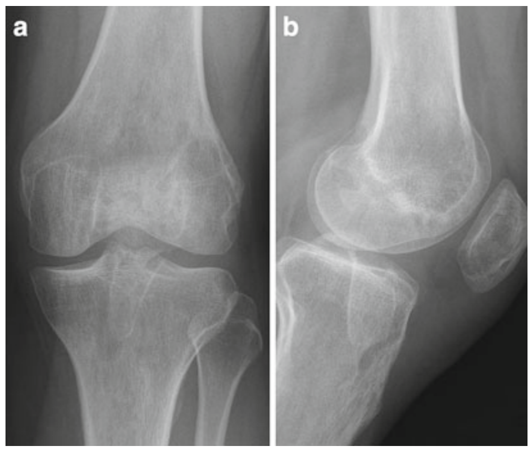

Fig. 24.2 AP (**a**) and lateral (**b**) radiographs obtained 6 months following bone grafting of femoral and tibial tunnels for massive tunnel expansion. Graft incorporation has occurred (and can be confirmed with CT), and ACL reconstruction can now proceed

extremity mechanical axis secondary to ligamentous instability or arthrosis can compromise graft integrity. Therefore, limb malalignment may need to be addressed via osteotomy and/or collateral reconstruction prior to or at the time of revision ACL reconstruction. Magnetic resonance imaging (MRI) is a very useful tool that provides information on graft status and associated ligamentous, chondral, and meniscal pathology. Artifact from metallic hardware may diminish MRI utility, however, and reliance on a thorough clinical examination and basic radiographic evaluation cannot be overstated.

Indications and Contraindications

Repeat revision ACL reconstruction presents unique challenges to the orthopaedic surgeon. Patient needs and expectations must be balanced with the risks, potential complications, and the guarded prognosis associated with the multioperated knee. Consideration must be given to the patient's chief complaint and the specific goals of the surgical procedures. As stated previously, most patients will present complaining of recurrent instability, pain, stiffness, or some combination thereof. The available revision ACL literature suggests that the greatest chance for a positive outcome results from revision surgery performed for recurrent instability [7–15]. An anatomically placed and appropriately tensioned graft in a patient who has participated in a focused rehabilitation program will reliably restore translational and rotational stability. However, it is important to note that the correlation between objective laxity and subjective outcomes is not linear [7, 15] and the problems associated with pain and stiffness may not be solved by a revision ligament reconstruction. When pain is the chief patient concern and the preoperative evaluation uncovers extensive meniscal or chondral pathology, revision surgery should be discouraged despite the presence of objective laxity. Conversely, if pain is associated with recurrent giving-way episodes and no other significant cause is identified, revision reconstruction may be entertained. Likewise, unless graft placement is nonanatomic, loss of motion should be addressed by physiotherapy or non-reconstructive surgery such as arthroscopic debridement.

Preoperative Planning

The two most important questions to answer when planning for revision ACL surgery are: (1) is there a need for concomitant procedures? and (2) should these procedures be staged? Associated instability patterns resulting from collateral ligament and/or PCL deficiencies may need to be addressed at the time of the revision ACL reconstruction. Likewise, malalignment correction with an osteotomy may also be required. Meniscal and articular cartilage procedures should also be incorporated into the operative plan. The need for staging is dependent upon the presence of massive tunnel expansion and/or malposition that precludes proper tunnel placement without bone grafting prior to revision surgery. The most common scenario is a femoral tunnel that was placed too anterior, too vertical, or a combination of both. This can be addressed in the vast majority of cases by either drilling an entirely new femoral tunnel or creating a blended tunnel (with or without bone grafting). Another option is to utilize the existing femoral tunnel while adding a second femoral tunnel in order to employ a double-bundle reconstruction in an attempt to improve rotational stability.

Other important factors to consider before surgery include the source of the previous graft, as well as the type and location of hardware. Revision ACL reconstruction graft options depend on which grafts were used in the previous surgical procedures. These options include autograft (ipsilateral or contralateral patellar tendon, hamstring, and quadriceps tendons) and allograft (patellar, Achilles, tibialis anterior, quadriceps tendons). We consider autograft tissue if the prior procedure utilized allograft and prefer allograft tissue if the prior procedures utilized autograft. Allograft has the advantages of no donor site morbidity and decreased operative time. Additionally, allogeneic tissue with bone blocks also allows for filling of the preexisting bone tunnels.

Surgical Technique

The patient is placed supine on the operating table. A spinal anesthetic or a general anesthetic is administered in addition to a femoral nerve block. Routine prophylactic antibiotics are given intravenously. The patient is positioned on the table to allow for maximal knee flexion during surgery and a lateral post helps facilitate valgus stress.

A thorough examination of both knees is performed under anesthesia before prepping the leg. It is important to assess the integrity of the ACL as well as the collateral ligaments, PCL, and posterolateral corner by varus/valgus stress testing in full extension and 30° of flexion, the posterior sag and drawer tests, and posterolateral drawer and dial tests (external rotation at 30 and 90° of flexion).

After sterile prep and drape, a standard diagnostic knee arthroscopy is performed to assess the previous ACL graft, menisci, articular cartilage, and PCL. Remnants of the previous graft are removed, the posterior and distal margins on the medial wall of the lateral femoral condyle are identified and a notchplasty is performed if necessary to prevent graft impingement. The notchplasty may also help to facilitate removal of existing hardware if necessary and to aid in the placement of new tunnels if needed. The previous tibial tunnel entrance is identified and the hardware is removed if necessary. If the tunnel location is acceptable, a guidewire is placed through the existing tibial tunnel. Based on preoperative evaluation of imaging and the intra-operative findings, decisions are made on tunnel position and diameter, the need for bone grafting, and the type of fixation to be used.

Staged Revision ACL Reconstruction

While most revision ACL reconstructions can be performed with bone grafting as necessary at the time of the revision operation, massive tunnel expansion (16 mm or greater) may require a two-stage approach with hardware removal and bone grafting performed as the initial procedure (see Fig. 24.1a, b). Femoral tunnel malposition may also necessitate a two-stage revision if previous tunnel placement interferes with the placement of the new tunnel. Other required procedures such as osteotomy, articular cartilage, or meniscal surgery can also be completed during this first stage. Revision ACL reconstruction is then performed after the bone graft is incorporated, typically 6–9 months later (see Fig. 24.2a, b).

After all hardware and soft tissue remnants have been removed from the femoral and tibial tunnels, a guidewire is placed in each tunnel to allow compaction reaming. If necessary, tunnels can be grafted with cancellous autograft or allograft, bone dowels, or bone substitutes. When grafting the tibial tunnel, an instrument should be used to cover the tunnel exit site in the joint with graft placed through the entrance site on the anterior tibia. Graft can then be packed against the instrument using a bone tamp.

Primary Revision ACL Reconstruction

Revision ACL tunnels are reamed with a new aperture and new trajectory if previous tunnels were poorly placed in a nonanatomic location. If tunnel position is acceptable with only mild widening, the same tunnel aperture and trajectory can be used. If moderate widening is present, then a new trajectory should be employed. If the aperture and trajectory of a new tunnel communicate with the existing tunnel, then a blended tunnel will occur and either bone grafting, large allograft bone blocks on the graft, or stacked interference screws may be needed to fill the defect. The guidewire can either be placed through an existing tibial tunnel or placed in a new position using an ACL guide. Reaming is then performed over the guidewire with an impaction reamer.

A similar process is then performed for the femoral tunnel. If a new tunnel is required, the presence of a previous tunnel may make placement of a guidewire difficult. In this case, allograft can be used as structural support to fill the defect. An appropriately sized bone graft cylinder is created from the allograft (for example, femoral head) by drilling a center hole and

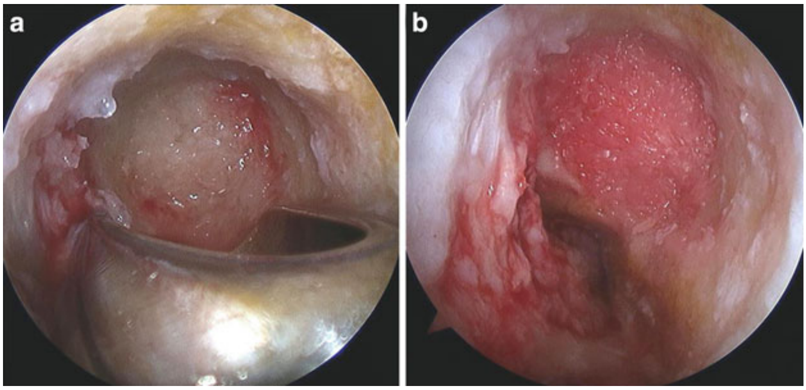

Fig. 24.3 (**a**) Allograft bone block impacted in place and (**b**) visualized arthroscopically to provide adequate filling of a femoral tunnel defect

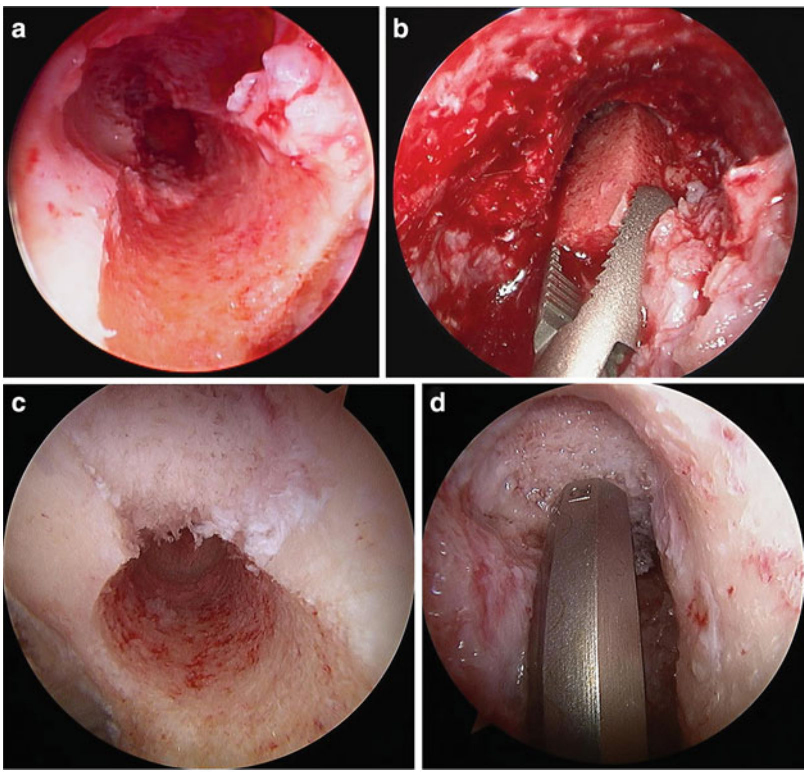

Fig. 24.4 (**a**) Moderate femoral tunnel expansion is viewed arthroscopically. (**b**) A patella allograft bone dowel is placed into the bone defect and then (**c**) impacted, (**d**) revealing adequate fill of the expanded tunnel

inserting a guidewire. The allograft cylinder with the guidewire is then impacted into the existing bone tunnel using a mallet (see Fig. 24.3a, b). This allows for easier placement of a new guide-wire. Another technique employs patellar allograft bone dowels impacted into the original tunnel defect (see Fig. 24.4a–d). A guidewire is then placed in the chosen position using a 7 mm offset guide and a 10 mm cannulated reamer is utilized to ream a new tunnel. After passage of the graft, fixation is achieved with a cannulated interference screw.

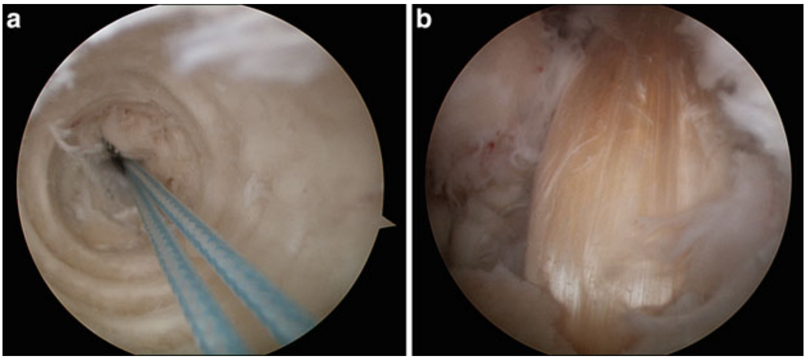

Fig. 24.5 Following compaction reaming for the (**a**) revision femoral tunnel, (**b**) a tibialis anterior allograft is passed and visualized

If an anatomic femoral tunnel cannot be drilled arthroscopically, a two-incision technique can be used. An accessory incision over the distal lateral femoral condyle is used to place a guidewire from the posterolateral femoral condyle into the intercondylar notch. The new femoral tunnel is then drilled from the outside in and allows for direct graft fixation on the lateral femoral cortex.

After the anatomic femoral and tibial tunnels are placed, the revision ACL graft is inserted and securely fixed (see Fig. 24.5a, b). In the multiple revision setting, dual fixation on the femoral side may be desirable, consisting of a suspension loop/cortical button and an interference screw. Large interference screws or multiple interference screws can also be used to provide secure fixation when the allograft bone plug does not provide complete fill of the defect. On the tibial side, we recommend interference screw fixation and backing up with a soft tissue button or suture anchor, if needed (see Fig. 24.6). Tibial tunnel widening can be addressed by using the same techniques employed on the femoral side. The graft is then tensioned and the knee is cycled to remove any creep.

The graft is visualized throughout knee range of motion to ensure that there is no impingement on the graft in the femoral notch. The Lachman and pivot shift tests are then repeated to ensure that they have normalized with placement of the new graft. The wounds are closed and a sterile, compressive dressing is applied.

Post-operative Rehabilitation

If an isolated, repeat revision ACL reconstruction was performed, patients are allowed to weight-bear as tolerated with crutches. If bone grafting or other reconstructions were performed in the same setting, patients are allowed only partial weight bearing for the first 4–6 weeks after surgery. A rehabilitation brace is required if associated collateral ligament surgery was performed. Quad sets, straight leg raises and ankle pumps along with knee range of motion from 0 to 90° are begun immediately post-operatively. Stationary cycling is feasible when knee range of motion has reached 90° and the brace is discontinued at 6 weeks following surgery. Jogging and sports/activity-specific rehabilitation are started at 3–4 months post-operatively and return to athletics or strenuous activity is not allowed until at least 9 months, provided that the knee is stable on physical exam and exhibits at least 80 % quadriceps strength and 90 % hamstring strength when compared to the nonoperative leg. Radiographs are performed to monitor tunnel bone graft incorporation. A CT scan or an MRI may be obtained for clinical reasons as needed.

Pearls

1. Establish a preoperative plan following a review of all medical records and operative reports, a thorough history and physical exam, and careful scrutiny of radiographs, CT scan, and MRI.

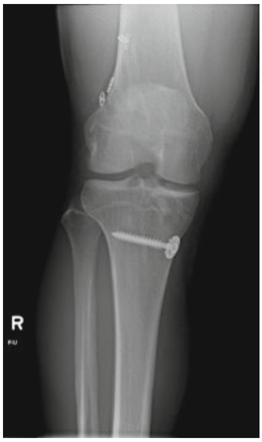

Fig. 24.6 AP knee radiograph following a third ACL revision reconstruction. Quadriceps tendon autograft has been used with interference screw fixation for the tibial bone block and soft tissue button suspension loop fixation on the femur. Previous femoral fixation hardware has been left in place due to the placement of a new femoral tunnel

2. Use preoperative imaging to assess tunnel widening to help decide whether a one- or two-stage procedure is required.
3. Assess the existing tunnel positions before and during surgery to determine if the existing tunnels are acceptable or if new/blended tunnels are required.
4. Be prepared to fill bone defects with bone graft or additional screws and then provide back-up fixation as necessary.

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25 Outcomes of Revision ACL

Bryan A. Warme and Russell F. Warren

Introduction

Revision anterior cruciate ligament reconstruction (RACLR) is a relatively uncommon, but increasingly important, orthopedic procedure. The frequency of RACLR has increased over the last few decades and with an increasing emphasis in our culture on sports participation and fitness, the number of both primary and revision ACL reconstructions is likely to continue to go up in the future (Fig. 25.1) [1, 2]. It is likely that most general orthopedic surgeons coming out of training today will see patients in their clinic with failed primary anterior cruciate ligament reconstructions (PACLR). It will be imperative that these physicians are able to handle the cases effectively, or discuss the relevant issues surrounding the condition and refer the patients on to a capable surgeon. While the results of RACLR are generally considered to be inferior to PACLR, the overall body of literature is sparse [3–8]. The majority of literature consists of retrospective case series studies with relatively small subject numbers done at single institutions over the last 2 decades.

As with any other orthopedic procedure, revision surgery is technically more challenging, takes longer to perform, and is often associated with more complications and worse outcomes. With specific regard to revision ACL surgery, there are many variables that have been proposed to contribute to poorer outcomes of RACLR compared to PACLR:

- Increased number of instability episodes
- Residual contractures or motion deficits
- Increased technical difficulty with dissection and graft harvest due to scar tissue
- Increased chronicity of ACL deficiency
- Increased incidence and severity of concomitant meniscus injury
- Increased laxity in secondary stabilizers
- Increased incidence and severity of concomitant articular cartilage injury
- Increased patient age and comorbidities
- Increased technical difficulty with proper tunnel placement
- Increased technical difficulty with graft fixation
- Limited autograft options
- Staged procedures
- Decreased bone stock available for graft fixation

These potential variables, coupled with the fact that RACLR is much less common than PACLR, contribute to the difficulty in performing highly powered and well-designed research studies of RACLR outcomes. Such studies will be

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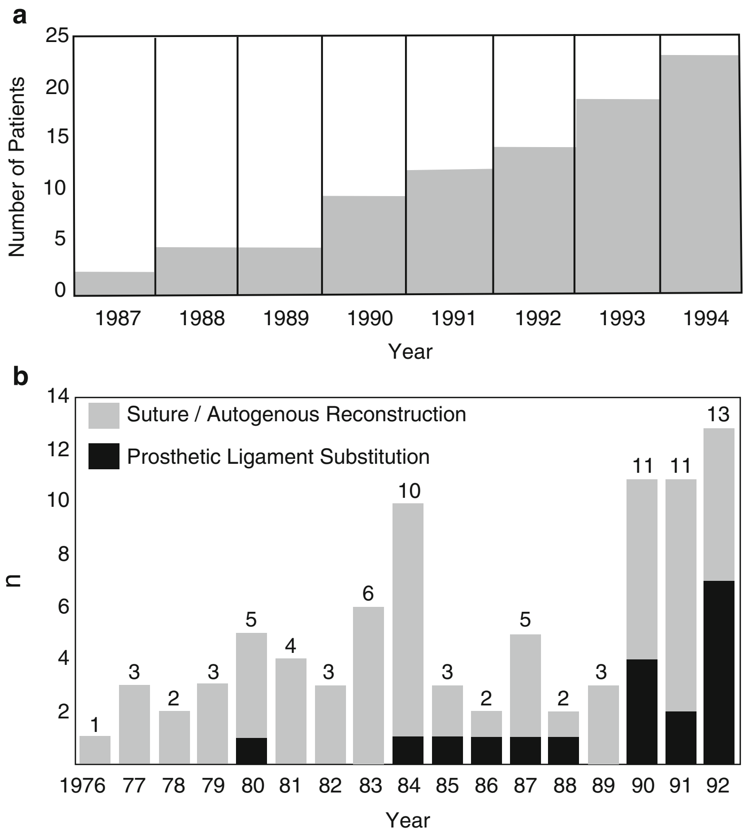

Fig. 25.1 Trend of increasing numbers of Revision ACL Reconstructions as reflected by single institutions in Miami (**a**) and Germany (**b**). (**a**) Reprinted with permission from Uribe JW, Hechtman KS, Zvijac JE, Tjin-A-Tsoi EW. Revision anterior cruciate ligament surgery: experience from Miami. Clin Orthop Relat Res. 1996;(325):91–9. (**b**) Reprinted with permission from Wirth CJ, Kohn D. Revision anterior cruciate ligament surgery: experience from Germany. Clin Orthop Relat Res. 1996;(325):110–5

important to identifying key variables and improving outcomes of revision surgery going forward. The current body of literature consists of a few dozen publications whose design, evaluation methodology, and surgical techniques are so variable that a meta-analysis on the subject is challenging to complete. As it stands today, it remains difficult to accurately predict how a patient will do after RACLR, which patients should anticipate a return to sports or activity at their pre-injury level, and which patients are likely to go on to develop arthritis or need more surgery. Other important topics that likely affect outcomes in RACLR that have yet to be definitively investigated include graft selection, surgical techniques, and the exact impact of concomitant articular or meniscal injury.

Outcome Measures

There are several outcome measures commonly used when assessing ACL surgery, analyzing both subjective and objective data. While these measures easily translate to the revision setting, there are no universally accepted set of outcome measures used in RACLR data collection that would easily facilitate comparative research or even a meta-analysis. Subjective outcome measures that have been validated and widely used for ligament knee assessment include the Lysholm knee score, the Tegner activity score, the International Knee Documentation Committee (IKDC) subjective score and the Marx Activity Scale. [9–16]. The Lysholm scale was introduced in 1982, consists of eight

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

	Less than one time in a month	One time in a month	One time in a week	2 or 3 times in a week	4 or more times in a week
Running: running while playing a sport or jogging					
Cutting: changing directions while running					
Decelerating: coming to a quick stop while running					
Pivoting: turning your body with your foot planted while playing a sport; For example: skiing, skating, kicking, throwing, hitting a ball (golf, tennis, squash), etc.					

Fig. 25.2 Marx Activity Scale. Reprinted from: Marx RG, Stump TJ, Jones EC, Wickiewicz TL, Warren RF. Am J Sports Med. 2001;29(2):213–8; with permission of Sage

questions, and evaluates knee instability [12]. It is physician administered, does not include a physical examination, and focuses on the patient's perception of function in both activities of daily living and sporting activity. The Tegner scale was published in 1985 and uses 11 assessments to help predict return to activity or sport [13]. Together, the Lysholm and Tegner scores complement patient perception of function and activity level. Figure 25.2 shows the Marx Activity Scale. It was introduced in 2001 and is different from other activity scales because it focuses on the patient's functional level, and is not sport-specific [16]. Furthermore, it focuses on activities that are difficult for someone with pathologic conditions of the knee [16]. The IKDC system was introduced in 1987 by physicians from both the USA and Europe [14]. It was developed secondary to concerns that other scoring systems used numerical values to reflect data that was not quantifiable [14]. The current modified form now has four sections: subjective assessment, symptoms, range of movement, and stability. The IKDC is now more widely used in conditions of knee disability other than instability, including assessment of articular cartilage [10, 11, 17, 18].

Objective outcomes commonly used to evaluate ACL surgery include the IKDC objective score, ability to return to play (or activity level), KT-1000 and KT-2000 (MEDmetric, San Diego, CA) measurements, radiographic analysis of tunnel placement and for signs of arthritis, and need for additional surgery. The IKDC activity level is scaled 0–4 as follows: Level 0 = unable to perform activities due to knee pain, swelling, or instability; Level 1 = light activities such as walking, housework, or yard work; Level 2 = moderate activities such as moderate physical work, running, or jogging; Level 3 = strenuous activities such as heavy physical work, skiing, or tennis; and Level 4 = very strenuous activities such as jumping or pivoting as in basketball or soccer. The KT-1000 and KT-2000 arthrometers have provided quantitative information on laxity in the AP direction, such as observed during the Lachman or Anterior Drawer exam maneuvers. However, no such clinical device or arthrometer has been developed and widely put into clinical practice to provide quantitative information for rotational laxity, such as during the Pivot Shift exam. There is growing evidence that the Pivot Shift and rotational stability may better predict long-term surgical outcome than assessments of translation in the sagittal plane [19, 20].

Outcomes of RACLR

Tables 25.1 and 25.2 summarize the subjective (Table 25.1) and objective (Table 25.2) results of selected RACLR studies performed over the last 20 years. The earliest reports on RACLR outcomes were published together in *Clinical Orthopedics and Related Research* in 1996 and described institutional results of RACLR from Miami, Pittsburgh, Cincinnati and one international group from Germany [1, 2, 8, 21]. This group of papers drew attention to the increasing need for revision surgery and the fact that RACLR is technically challenging with many variables affecting outcomes. These reports also indicated that the results of RACLR are likely inferior and less predictable than primary reconstructions. Importantly, these papers increased awareness of the peculiarities of RACLR and led to other institutions reporting their respective results.

At Miami, Uribe et al. reported their results on 54 patients undergoing RACLR with an average follow-up of 32 months. All revisions in their series were successful in objectively improving stability based on preoperative and postoperative KT-1000 measurements. Interestingly, they noted that autogenous grafts provided better stability than allografts, based on KT-1000 measurements of 2.2 (autograft) and 3.3 (allograft). Additionally,

Table 25.1 Subjective ACL revision outcome results from selected studies

Authors	Year of publication	Number of cases	Mean time to follow up (years)	Mean IKDC	Mean Lysholm	Mean Tegner
Uribe et al. [2]	1996	54	2.5	–	83	5.5
Johnson et al. [8]	1996	25	2.3	–	–	–
Wirth et al. [1]	1996	87	8	–	68	–
Grossman et al. [24]	2005	29	5.6	84.8	86.6	5.2
Battaglia et al. [5]	2007	63	6.1	73.6	–	–
Diamanto-poulos et al. [7]	2008	107	6.1	–	88.5	6.3
Reinhardt et al. [25]	2011	21	3	–	89	–

Table 25.2 Objective ACL revision outcome results from selected studies

Authors	IKDC	KT side-to-side difference	Return to play	X-ray arthritis	Further surgery
Uribe et al. [2]	–	Mean = 2.8 mm Autografts: 2.2 mm Allografts 3.3 mm	54 %	19 % progressive changes	–
Johnson et al. [8]	A/B: 12 % C: 52 % D: 36 %	≤3 mm: 20 % >3 to ≤5 mm: 44 % >5 mm: 36 %	68 %	–	–
Wirth et al. [1]	–	–	–	Fairbank grade 0: 36 % I: 55 % II: 7 % III–IV: 2 %	–
Grossman et al. [24]	A: 58 % B: 28 % C: 14 %	Mean = 2.78 mm Autografts: 1.33 mm Allografts 3.21 mm	80 % (4/5)	44 % "mild" or "moderate" in medial compartment	3 %
Battaglia et al. [5]	–	Mean = 3.9 mm <3 mm: 51 %	59 %	25 %	25 %
Diamanto-poulos et al. [7]	A: 16 % B: 42 % C: 35 % D: 7 %	≤3 mm: 85 % >3 to ≤5 mm: 8 % >5 mm: 7 %	–	Jaeger Wirth classification I: 31 % II: 33 % III: 15 % IV: 2 %	–
Reinhardt et al. [25]	–	"Symmetric": 62 % ≤5 mm: 33 % >5 mm: 5 %	52 %	–	10 %

they noted no ill effects of harvesting the contralateral patella tendon for their source of autograft. Ultimately, 54 % of their patients returned to their previous activity level, and articular cartilage degeneration portended significantly poorer subjective results [2]. Uribe et al. also noted in their study that the number of RACLR performed per year increased in a step wise fashion from 1987 to 1994, emphasizing the need for more research to improve outcomes of revision surgeries (Fig. 25.1a) [2].

Also in 1996, Johnson et al. reported their 28-month follow-up results on a series of 25 patients who underwent RACLR at Pittsburgh [8]. In contrast to the Miami group, they used fresh frozen allograft for all revisions. They also noted that all patients had improved anteroposterior stability and an overall improvement of their functional status compared to the pre-revision state. Importantly, however, like the Miami group, they noted a decrease in return to sporting activity: 84 % of patients in their series participated in sports more than one time per week before reinjury, compared with 68 % after revision surgery [8].

Noyes and Barber-Westin also reported in 1996 the Cincinnati experience with RACLR [21]. Their study included 65 allograft revisions and 20 autograft revisions, followed for an average of 42 and 27 months, respectively. KT arthrometer measurements demonstrated less than 3 mm of displacement for 53 % of the allograft revisions and 67 % of the autograft revisions. Overall failure rates of their revision surgeries were 33 % for the allograft group and 27 % for the autograft group.

Wirth and Kohn provided an international perspective on RACLR in 1996 by reporting their experience at the Hanover Medical School in Germany from 1976 to 1992 [1]. Their series included 87 revision surgeries with an average follow-up of 96 months. An important trend noted in their publication was the increasing incidence of revision ACL surgery at their institution from 1976 to 1992 (Fig. 25.1b). They noted that Lysholm scores were significantly inferior after revision (68 ± 12) compared with scores after PACLR (83 ± 14) and that only 60 % of their patients were satisfied with their respective results at final follow-up. They noted that in their experience, “the disappointed patient [whose PACLR has failed] will seek help from a different hospital” for RACLR, and that this contributes to the difficulty in both performing the surgery and investigating causes of failures in both the primary and revision settings.

Based on these four early institution-based series from 1996, it is difficult to make definitive conclusions regarding RACLR outcomes or provide research-based recommendations. From the Cincinnati and Miami reports, there seems to be a suggestion that autografts may outperform allografts in the revision setting, but the Pittsburgh group noted an improvement in the function of all their patients, all of whom received fresh frozen allograft reconstructions.

Graft choice as it relates to outcome is still a topic of debate and an area of research interest today as it was in 1996. Some published studies support using autograft over allograft [2, 21], while some have shown no difference [5]. Revision ACL autograft choices include the quadriceps tendon, the patella tendon, and one or more of the medial hamstrings. The Bone-Patella Tendon-Bone (BTB) graft is a popular graft choice for both primary and revision ACL surgery. In the revision setting, reharvesting a previously harvested BTB autograft from the ipsilateral knee has been shown to be possible [22]. However, when compared to contralateral BTB autograft harvest for RACLR, the reharvested BTB resulted in lower functional scores and more complications [23]. A meta-analysis has yet to be performed on all the available literature to help establish a definitive answer to this question.

Since 1996, several more studies have looked at outcomes of RACLR. One of the largest series currently available through a PubMed search is a German study published in 2008 with 107 revision cases that had an average mean follow-up of 72.9 months [7]. Diamantopoulos et al. used strictly autografts for their revisions and evaluated the revisions with the Lysholm score, the Tegner system, the IKDC, the KT-1000, and by radiography. Like the previously mentioned studies, they found significant improvement in both patient satisfaction and stability after revision. However,

Chronicity of Instability and Radiographic Arthritic Changes		
Mean Unstable Period, mo	**Patients Without Arthritic Changes**	**Patients With Arthritic Changes**
Injury to primary reconstruction	11.7	28.4
Reinjury to revision	13.7	33.0
Total time with unstable knee	22.3[a]	55.9[a]
[a]The difference between the groups was statistically significant.		

Fig. 25.3 Predictors of outcome: chronicity of instability. Reprinted From: Battaglia MJ II, Cordasco FA, Hannafin JA, Rodeo SA, O'Brien SJ, Altchek DW, Cavanaugh J, Wickiewicz TL, Warren RF. Am J Sports Med. 2007;35(12):2057–66; with permission of Sage

radiographic evaluation revealed 33 patients (31 %) had findings of degenerative arthritis at final follow-up. Aside from improved stability and the ability to return to sport or activity level, the development of arthritis after ACL reconstruction is an important outcome measure to consider. While ACL surgery is generally considered to be able to predictably restore knee stability, arthritis can be an eventual sequela of ACL injury despite a "successful" reconstruction that provides stability and allows return to sports and activity. This is especially true in the revision setting when the ACL-deficient knee has been exposed to a longer period of instability and more episodes of pivoting or extreme translational events [5].

Another study that noted a high incidence of radiographic arthritis after RACLR was performed at the Hospital for Special Surgery by Battaglia et al. [5]. They noted a 25 % rate of radiographic arthritis (16/63 patients) and found it was associated with duration of instability after primary failure (Fig. 25.3) [5]. Similar to the German study by Diamantopoulos [7], this study had a relatively longer mean follow-up (72.7 months) than the other previously mentioned investigations. These two mid-term follow-up studies would suggest a trend toward an increased rate in of development of arthritis in knees that have endured two distinct ACL injuries and reconstructions. Return to sports in Battaglia's series occurred in 59 % (37/63 patients), and 16 patients (25 %) required repeat revision surgery. These results led to their conclusion that "patients who undergo revision anterior cruciate ligament surgery should be counseled as to the expected outcome and cautioned that this procedure represents a salvage situation and may not allow them to return to their desired levels of function" [5].

Interestingly, Grossman et al. [24] noted in their series of 29 RACLR that those patients who went on to have radiographic arthritis and joint space narrowing correlated to those patients who had significant articular lesions or a large part of the meniscus removed. This study too had a relatively longer follow-up (mean 67 months) than others currently available through a PubMed search. A decrease in thigh strength of approximately 12–18 % was also noted at follow-up compared to the contralateral thigh. Despite these findings, all 29 patients in their series reported they would have surgery again [24]. While it is clear that ACL deficiency and, more generally, knee instability, can contribute to the development of arthritis, specific details of this cause–effect relationship remain largely unknown. Going forward, long-term studies with 10+ years of follow-up would help better establish the relationship of RACLR and eventual arthritis.

One specific patient population where the outcome of RACLR and the possible onset of arthritis has significant long-term impact on quality of life is in the young athlete who has nearly a full lifetime left. The consequences of failure in this patient population are especially high as career options and life-long activity level can be affected. Reinhardt et al. reviewed 21 cases of RACLR in patients who had undergone PACLR between the ages of 12 and 17, and then revision surgeries before the age of 18 [25]. All of their revisions were performed as transosseus reconstructions in a single stage and the minimum

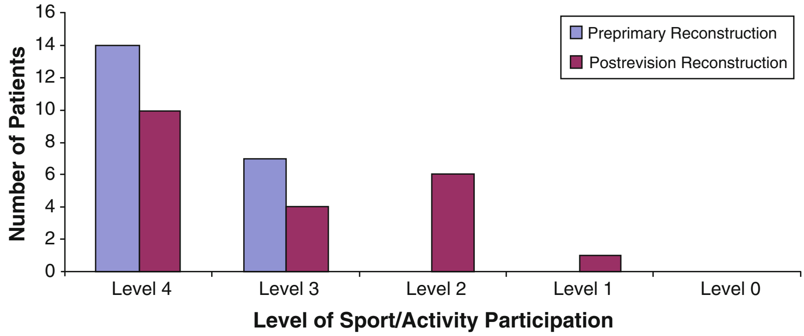

Fig. 25.4 Return to play in young athletes. This graph shows the levels of sport/activity participation before primary ACL reconstruction and at last follow-up after revision ACL reconstruction. Level 4 corresponds to the most strenuous activity level. Reprinted from: Clin Orthop Relat Res, Revision ACL reconstruction in skeletally mature athletes younger than 18 years. 2011;470(3) with permission from Springer Science+Business Media

follow-up was 24 months with a mean follow-up of 36 months. In their series, they found that only 52 % of patients were able to return to their prior level of activity or sport (Fig. 25.4). However, knee stability was restored in both the sagittal plane (19/21 patients had negative or IA Lachman) and rotationally (20/21 had a negative pivot shift) [25]. These results stress the importance of avoiding failure in the PACLR setting.

How to Council Patients with Failed ACL Reconstructions

Stability: Because each case of failed primary reconstruction is unique, each patient will have distinct variables that will affect ultimate stability. However, based on the currently available literature, we believe it is fair to say most cases of symptomatic instability can generally be improved with RACLR. The decision to use autograft or allograft and the specific type of graft should be made mutually between the operating physician and the informed patient and based on case-specific factors.

Return to play: There are no meta-analyses to help answer this question. It is likely more difficult to return to sport/activity after revision reconstruction than the primary reconstruction. As in stability, there are so many variables that ultimately impact the ability to return to sports, no consensus statement can be made. It is possible that concomitant injuries to the knee such as the cumulative articular cartilage damage, tears and degeneration of the menisci, and injury to secondary stabilizers play as large, or larger, a role in ultimately determining post-revision activity than does the function of the revised reconstruction. In a few of the series available to date, the return to play at the preinjury level or one level below the preinjury level was in the 50–60 % range.

Arthritis risk: There is growing evidence that the future development of arthritis is affected by both the chronicity of ACL deficiency and the number of instability episodes. Clearly, other factors play important roles in the development of arthritis, most notably the extent of chondral damage. Alignment, condition of the menisci, and function of the secondary stabilizers all ultimately contribute to the progression to arthritis. The available evidence would suggest that there may be a higher risk of future arthritis in the knee that requires revision reconstruction as compared to the knee undergoing PACLR.

Authors' Recommendations for Surgeons

As stated many times, no revision ACL is the same, and as such, planning and performing RACLR should be tailored to the specific patient on a case-by-case basis. With regard to graft selection, we favor autograft over allograft if an appropriate donor site is available. At our institution we typically do not reharvest the BTB autograft. Ipsilateral Quadriceps tendon, contralateral BTB, or hamstrings are our typical autograft choices. In cases where large bone defects greater than 20 mm exist in the tunnels, allografts with bone blocks (BTB, quadriceps, or Achilles allografts) can often be fashioned to fill large tunnels on one or both sides of the joint. If possible and appropriate, we favor single-staged RACLR over two-staged approaches. We have found that it can sometimes take a year or more to go through a two-staged surgery and rehabilitation process and as such, to decrease the chronicity of the process on the patient's life, we attempt single-staged surgeries when appropriate. If insufficient bone stock exists, we will have success with placing plugs or dowels in the preexisting tunnels and then completing the RACLR in the single procedure. If the tibial tunnel is too far posterior, it will require grafting and often a two-stage procedure. With regard to surgical technique, we often use the anteromedial portal to drill the new femoral tunnel. We believe this allows for better flexibility in achieving the desired starting point while also allowing the surgeon to diverge from, or bypass altogether, the previous femoral tunnel.

Conclusions and Future Directions

With a growing worldwide population and a continued emphasis on participation in sports in many cultures, RACLRs will likely become a more common operation in the future. Although outcomes research of RACLR has increased in the last 2 decades, there remains a great need to perform more thorough and powerful studies. To date, most of the published literature reflects level IV case series evidence from single institutions. Because RACLR is uncommon, the numbers of patients in these investigations are relatively small and often lack the power to provide definitive conclusions and recommendations. Patient demographics, limited autograft options, limb alignment, preexisting arthritis, concomitant meniscus injury, articular cartilage damage, previous tunnel malposition, or widening are just a few of the variables that make research in this arena challenging. These and other factors all impact the success of RACLR and no single RACLR case is the same.

The development and widespread implementation of a universally accepted arthrometer of rotational stability will help push the field of RACLR research forward. This information, coupled with data from translational stability afforded by KT measurements, will help provide quantitative information on global knee stability following revision reconstruction.

To help address the need for better RACLR research, the Multicenter ACL Revision Study (MARS) Group was recently formed. The MARS Group is a specialty society-organized multicenter study group constructed to accumulate substantially more subjects to allow for analysis of the many variables associated with RACLR outcomes [26]. As of April 2009, the cohort included 87 surgeons and had accumulated 460 patients, easily the biggest subject group to date. The ultimate goal of this project is to identify clinically useful predictors of outcomes to help assist with surgical decision-making and ultimately improve the success of RACLRs. The conclusions and recommendations from this group's studies will be key to progressing the field forward in the years to come.

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