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Joan Carles Monllau
Editors

The ACL-Deficient Knee

A Problem Solving Approach

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Foreword I

Twenty-five years have passed since we published the first edition of The Crucial Ligaments and a much expanded 2nd edition was published in 1994. Drs. Vicente Sanchis-Alfonso and Joan Carles Monllau now offer The ACL-Deficient Knee – A Problem Solving Approach. They support their text, and the work based on the fact that the ACL "is an injury that has not been completely solved" and that "problem resolution" is a more constructive and logical approach than "closed compartment" presentation. Indeed, they are absolutely correct.

The strengths of this new, fresh, and much needed contribution to the discipline of knee surgery are many. Foremost – an acknowledgement that "we are not there yet" – 50 % of primary repair ACL surgery patients develop osteoarthritis, and further in Section 3, the authors clearly address the formidable complications of our current surgery. The authors are to be complimented on the unique approach to this conundrum through the use of problem resolution rather than the traditional didactic compartments.

The editors have assembled an international panel of distinguished authors who present problem resolution in 3 sections and 33 chapters. In addition, the text comes with a collection of step by step surgical technique videos that will be accessed via an online link.

The organization and content of the chapters reflect the combined experience, seniority, and wisdom of the editors and the authors. This is evidence-based medicine at its best.

This text, The ACL-Deficient Knee, is noteworthy and needed. Every student of knee care and knee surgery will find new information, new principles, and will further enhance and advance our care of the knee.

The beneficiaries of this evidence-based text are the patients and those who will follow and will someday lead.

Colorado, USA John A. Feagin Jr. M.D.

Foreword II

Treatment ACL Injuries: Still an Unsolved Clinical Problem?

In 1955, I performed my very first ACL operation. Unfortunately, now 57 years later, we are not that much wiser when it comes to the ACL injuries than we were then. We still do not know which graft is the best one to use for an ACL reconstruction. We are still discussing whether we need a single or a double graft. We still do not agree on the rehabilitation and at what time we can allow the athletes to go back to sports. And worst of all, the results of the ACL reconstructions are not that much better (or not better at all) than they were in the 1970s in spite of arthroscopic technique and thousands of scientific studies.

In 1965–1966, the late Lennart Broström and myself performed our first patellar tendon reconstructions for old ACL injuries. Fortunately, we had not read Kenneth Jone's paper about ACL reconstruction with the patellar tendon (because his suggested technique is very "unanatomical"). Nor did we know about Brückner who was performing a similar procedure at the same time but published it in a small east-German journal, that we did not even know the existence of. The stimulus for Lennart Broström was to perform a similar operation in the knee as the technique he had developed for reconstruction of the anterior talofibular ligament of the ankle. Nor did we know about pivot shift. My first contact with pivot shift was at an AOSSM course in Snowmass, Aspen, Col., USA, in 1973 when Victor Frankel, M.D. demonstrated pivot shift on his own wife, who had sustained an ACL injury.

Should then all ACL injuries be treated surgically? No, professional athletes should be treated surgically. Leisure time athletes and nonathletes with pivot shift should be informed that if they give up sports, they can live well even with their unstable knee. If they want to continue with "pivoting sports," they need surgery. Unfortunately, ACL injuries are often combined with injuries to the joint lines. Some authors maintain that one gets these irrespective of treatment. For me, a reconstruction of the ACL in order to obtain a stable knee has been a way of preventing the pivot shifts that I have seen can destroy the joint lines.

Since 1965, I have performed many hundred ACL reconstructions. Due to my age, I have now given up surgery, but I am still following the discussions about ACL injuries and the treatment options. I am really surprised over that most orthopedic surgeons in my own country – Sweden – have abandoned the patellar tendon graft and gone over to use the hamstrings for ACL reconstructions. Since there are no real proofs that the hamstring tendons are any better than the patellar tendon, my feeling is that it is the industry that has persuaded the doctors to change from patellar tendon grafts to hamstring grafts. The surgical instruments used for a hamstring ACL reconstruction and for securing those grafts are much, much more expensive than the simple instruments you need for a patellar tendon reconstruction. Although I have been preaching the need for good randomized clinical trials since 30–40 years, there are very few good such studies performed. One good such study (that unfortunately is seldom quoted) is the Swedish study by Heijne and coworkers. They compared patellar tendon reconstructions with hamstring reconstructions in a "double" randomized study. Besides comparing the two different surgical techniques, they also randomized the patients to either aggressive rehabilitation (an early start of open chain exercises 4 weeks postoperatively) or a later start (12 weeks postoperatively). Everybody would probably guess that the hamstring reconstructions with early start of open chain would be the best group. It was not. The patellar tendon reconstructions with late start of open chain were the best ones. My feeling is that when the enthusiasm over the hamstring reconstructions has subsided in a couple of years' time, the patellar tendon reconstructions will come back again in Sweden. There are some types of sport where the hamstring grafts definitely should be avoided – downhill skiing for instance. All downhill skiing is done in internal rotation of the lower leg. As soon as a ski rotates outward, you fall. In skiers, one should therefore avoid using two internal rotators like the hamstrings for ACL reconstruction as Steadman and his group in Vail, Colorado, USA, has pointed out. It is possible that we will also find out that different sports need different grafts.

Since I have been so engaged in the history of ACL reconstructions, of course I also have some dreams for the future. I believe that in 10 years time we will not be discussing what graft we should use. When a child is born, we will take stem cells from the umbilical cord and let them grow under tension and under sterile conditions. They will then develop tendocytes and a "neoligament." I believe that all professional football players will have 2–3 sterile deep-frozen autologous tendon grafts in their deep freeze. We will implant one of these with arthroscopic technique and use growth factors to speed up the healing. Not every orthopedic surgeon will perform these operations; only a small group of very talented ACL surgeons will perform them. Their hands will be "instrumented" and a robot will perform the operations anywhere in the world. This has already been done for cardiac surgery and will become common also in orthopedics.

Finally, I hope that in the future, we will be able to promise ACL-injured athletes a 95 % chance of becoming normal after ACL surgery. Today, it is difficult to promise them more than a 70 % chance of becoming normal again. It is therefore my hope that this excellent book could change this.

Stockholm, Sweden Ejnar Eriksson M.D., Ph.D.

Preface

This book reflects our deep interest in knee pathology, particularly that of the anterior cruciate ligament (ACL), and emphasizes the great importance we give to the concept of subspecialization, which is the only way to confront the deterioration and mediocrity of our specialty, orthopedic surgery, and to provide our patients with better care. In line with the concept of subspecialization, this book necessarily required the participation of various authors.

We are aware of the fact that several monographs about ACL injuries have been published. Therefore, why are we going to publish a new book about the ACL-deficient knee? The answer is obvious, because it is a very frequent injury. The annual incidence of primary ACL reconstructions is 35 cases per 100,000 inhabitants. If we only consider a high-risk population (age group between 16 and 39 years old), the incidence goes up to 80 cases per 100,000 inhabitants. In the USA more than 100,000 ACL reconstructions per year are performed, and in Spain, more than 15,000. But the main reason we have decided to write this book is because it is an injury that has not been completely resolved, despite the good or excellent surgical treatment results, and if we measure them by return to elite sports, then it is almost 95 %. In fact, if surgical treatment results are measured by the capacity of surgery to prevent the development of osteoarthritis in the knee, we can be sure that the problem has not yet been resolved, since more than 50 % of patients with an isolated ACL tear that has been operated develop an osteoarthritis in a long-term follow-up. Therefore, until we are able to refine the surgical treatment, injury prevention should be the priority of our studies. Therefore, we are facing a very frequent injury that is far from being completely resolved.

In this book, we approach the ACL-deficient knee from a different perspective that is unlike the previous classical one. The common approach is the analysis of closed compartments, anatomy, biomechanics, physical findings, imaging techniques, surgical treatment, and rehabilitation. Our approach is completely the opposite. We are focused on problem analysis and problem solving, besides analyzing the possibility of prevention. Therefore, in each chapter, the biomechanics, anatomy, etc. that are relevant to the topic are reviewed. There are chapters where highly specialized surgical techniques are presented (v. gr. double-bundle reconstruction or meniscal transplant). These chapters are written by internationally renowned specialists who are pioneers in the topic analyzed. In this book, we will also address the characteristics of ACL tears in children. We are finding a growing number of injuries in children, due to the increase of sports at early ages.

In this book, we will deal will the ACL-deficient knee in three sections. In the first section, we will analyze the current status and real controversies that exist nowadays in the approach and treatment of the ACL-deficient knee. In the second section, we will present different case scenarios that a surgeon treating ACL injuries could encounter and how to solve each one of them (the problem and the solution). In the third section, the complications of the treatment will be analyzed, as well as how to prevent them and how to treat them (can we do better?). At the end of each chapter, future research, and the take home messages are summarized, with an evidence level of each recommendation whenever it is possible (evidence-based medicine). For this reason, at the beginning of the book, there is a reminder of the basic concepts of evidence-based medicine (How Can we Use Evidence-Based Medicine to Guide our Practice?). We should never forget the achievements of our surgical forefathers, and this is the reason why at the forefront of the book we evaluate the ACL-deficient knee from ancient history to the twenty-first century. Finally, another interesting aspect of this book is the collection of step by step surgical technique videos that will be accessed via an online link that will allow the knee specialist to perform the technique presented by the author.

This book is addressed to orthopedic surgeons specialized in knee surgery, specialists in sports medicine, rehabilitation specialist MDs, and physiotherapists. This book obviously does not attempt to replace the classical monographs, even so we believe it can complement them. We trust that the reader will find this work useful, and consequently, that it will be indirectly valuable for patients.

Spain Vicente Sanchis-Alfonso, M.D., Ph.D.
Spain Joan Carles Monllau, M.D., Ph.D.

Acknowledgments

We have had the privilege and honor to count on the participation of outstanding specialists who have lent prestige to this monograph. We thank all of them for their time, effort, dedication, kindness, as well as for the excellent quality of their contributing chapters. All have demonstrated generosity in sharing their great clinical experience in a clear and concise form. We are in debt to you all. Personally, and on behalf of those patients who will undoubtedly benefit from this work, thank you.

Last but not least, we are extremely grateful to both Springer-Verlag in London for the confidence shown in this project, and to Mr. Karthik Periyasamy and his production team from SPi Global (Chennai, India) for completing this project with excellence from the time the cover is opened until the final chapter is presented.

Vicente Sanchis-Alfonso, M.D., Ph.D.
Joan Carles Monllau, M.D., Ph.D.

Historical Aspects on Surgery for Anterior Cruciate Ligament Deficiency

Dedication:
I dedicate this work to the loving memory of my late mother Karin Christa and father Franz-Josef whose loss one cannot comprehend and who will be missed forever.

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Synopsis

Our understanding of the clinical implications and surgical remedies of injuries to the anterior cruciate ligament (ACL) has seen remarkable changes since Robert Adams observed the first confirmed case of an ACL rupture in 1837. High morbidity and mortality associated with surgery delayed efforts to repair the torn ligament until the end of the nineteenth century. Suture repair however yielded unpredictable results. The era of ligament reconstruction began with Grekov and Hey Groves in the early parts of the twentieth century, but their knowledge and achievements were not uniformly appreciated at the time. A period of startling ingenuity followed, which created an amazing variety of different surgical procedures often based more on surgical fashion than an indication that continued refinements were leading to improved results. It is hence not surprising that real inventors were forgotten, good ideas discarded, and untried surgical methods adopted with uncritical enthusiasm only to be set aside without further explanation. Over the past 100 years, surgeons experimented with a variety of different graft sources. Synthetic graft materials enjoyed temporary popularity in the misguided belief that they were stronger and more durable. Until the 1970s, ACL reconstructions were formidable procedures, often so complex and fraught with peril that they remained reserved for a chosen few. Advancements in arthroscopy techniques and instrumentation have improved surgical reliability and reproducibility and established ACL reconstruction as a procedure within the realm of most surgeons' ability.

Prologue

Writing a historic review bears the danger of creating an uninspiring list of chronological events which incite little enthusiasm with the reader. The author has hence made the conscious decision to focus on key events and circumstances over the past two millennia that have proven to be of significance in the progression of this particular field of surgery. Anyone who yearns for a more elaborate review of the historic events is referred to other publications [196]. The reader should bear in mind that information obtained through reviewing historical papers is mainly based on case reports and observational studies, with the great majority representing no more than a reflection of a surgeon's personal experience. Longer-term follow-up studies are scarce and controlled trials simply unavailable. This historic review of the surgical advances in the treatment of ACL deficiencies portrays how evolving knowledge combined with often controversial concepts and ideas has shaped our current understanding of ACL reconstruction.

From Ancient Greece to the 20th Century: The Age of Conservative Management

The history of the surgery for the anterior cruciate ligament (ACL)-deficient knee is also the history of the discovery of the ligament's function, the recognition of its injury pattern, and the development of reliable methods in assessing and diagnosing ACL injury. Although Hippocrates (460–370 BC) acknowledged the disabling signs associated with distortion of the knee, he was unaware of the underlying cause of such ailment [87]. We owe the discovery of the cruciate

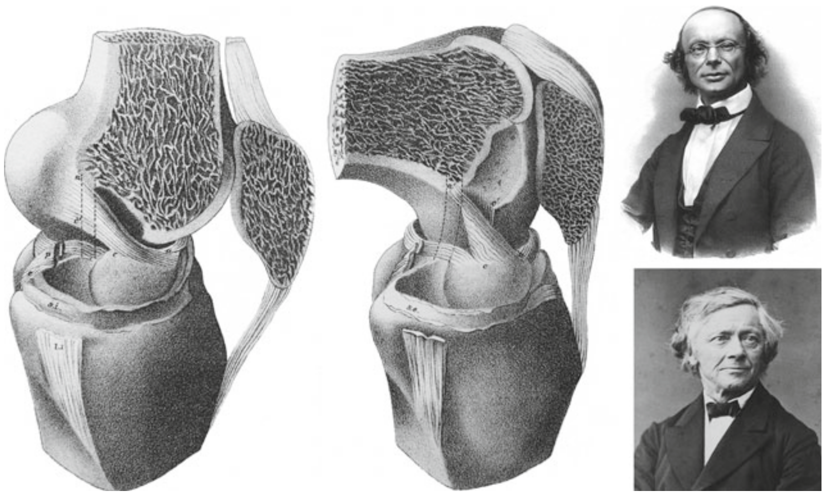


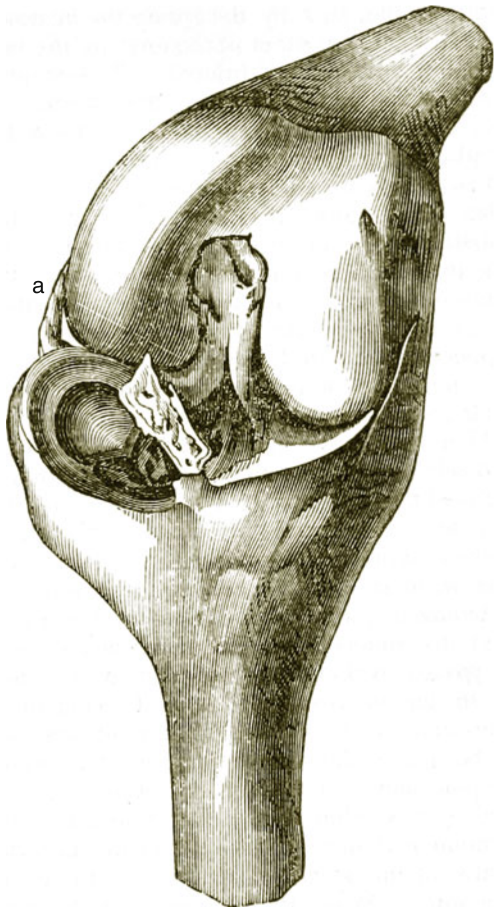
Fig. 1 Drawings taken from "Mechanik der menschlichen Gehwerkzeuge" published by the Weber brothers in 1836. These are this first illustrations to show the ACL to consist of two distinct fibre bundles with in dependant tension pattern. Wilhelm Weber (*top right*) was a Professor of Physics in Göttingen whilst his brother Eduard (*bottom right*) was Professor of Anatomy in Leipzig (Image of Eduard Weber courteous of Universitätsbibliothek Leipzig, Drawings with kin permission of Springer Science, Berlin [226])

ligaments and their name to Claudius Galen of Pergamon (131-201 BC) who devoted much of his life to the study of anatomy mostly though dissection of the deceased [68]. Over the following 2,000 years the ACL led a relatively uncharted existence. This changed in 1836 when Wilhelm (1804–1891) and Eduard Weber (1806–1871) published their treatise "Mechanik der menschlichen Gehwerkzeuge" which became a milestone in the description of anatomy and function of the cruciate ligaments [226]. The two brothers demonstrated that the ACL consists of two functionally independent fiber bundles with independent tension pattern, which are twisted during knee flexion (Fig. 1). They also realized that sectioning of the ACL resulted in abnormal forward movement of the tibia, thereby providing an early description of the anterior drawer sign. In 1858 the anatomist Karl Langer of Vienna (1819–1887) confirmed earlier findings made by the Weber brothers and provided an advanced description of the kinematic behavior pattern of the cruciate ligaments [127].

Clinicians of the eighteenth century began to raise awareness of the functional disabilities associated with distortion of the knee but failed to make the connection with rupture of the ACL. William Hey (1736–1818) described the sensation of the "pivot shift" when he observed that "The knee joint is not infrequently affected with an internal derangement of its component parts, and this sometimes in consequence of trifling accidents. The defect is, indeed, now and then removed as suddenly as it is produced, by the natural motions of the joint without surgical assistance" [84]. Sir Astley Cooper of London (1768–1841) called it a "partial luxation of the thigh-bone from the semilunar cartilages," while Joseph-François Malgaigne (1806–1865) considered the sudden subluxation of tibia on femur to be due to abnormal relaxation of the cruciate ligaments [2, 33]

Robert Adams of Dublin (1791–1875) first described the distressing signs of "giving way" in a patient as a "Sudden sense of weakness … followed by

Fig. 2 Robert Adams of Dublin provided the first record of a torn cruciate ligament (avulsion injury), which he observed in 1837 [2]



Anterior crucial ligament torn up with portion of tibia.

some effusion of synovial fluid into the joint" [2]. He also provided us with the first description of a proven ACL injury, although it is likely that many more such injuries had occurred before then, but failure to recognize clinical signs and the absence of reliable assessment tools prevented their discovery. In 1837 Adams observed the case of a drunken 25-year-old man who injured his knee wrestling and died 24 days later. Autopsy of the knee revealed that the knee had become septic and that the ACL had torn off the tibia with a portion of bone still attached to the ligament (Fig. 2). Adams did consider it "not improbable that in sprains of the knee joint, the interior of the articulation is occasionally injured; that the crucial ligaments are stretched; and that some of their fibres give way occasionally, breaking in their centres, or detached by their extremities from the bone."

In 1845 Amedeé Bonnet of Lyon (1809–1858) published his "Traité des maladies des articulations," describing some of the essential signs indicative of acute ACL rupture: "In patients who have not suffered a fracture, a snapping noise, haemarthrosis, and loss of function are characteristic of ligamentous injury in the knee" [17]. Bonnet advocated conservative management for ligamentous injuries and suggested application of cold packs in the acute stage [18]. Through his own experiments, he was aware of the detrimental effects of

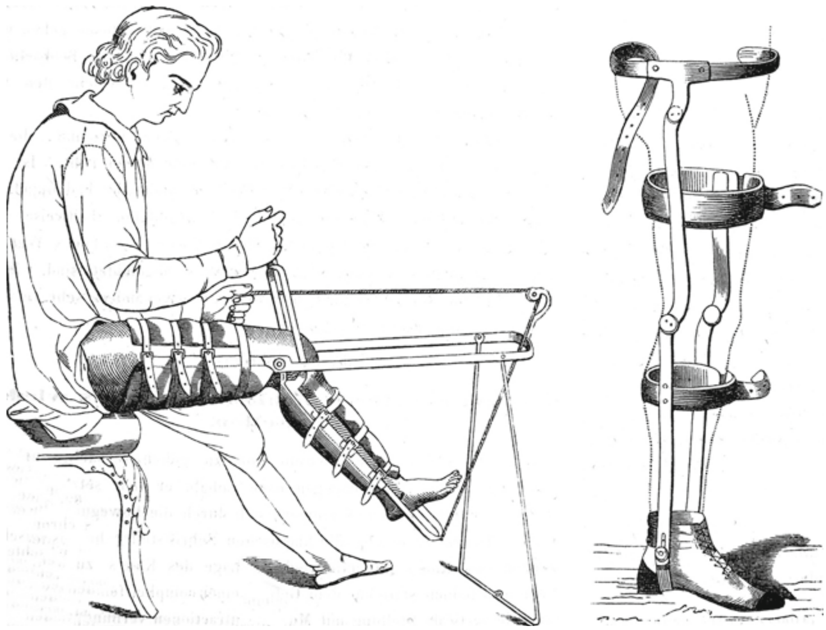


Fig. 3 Amedeé Bonnet's patient-operated movement apparatus to prevent stiffness following internal knee derangement (*left*). Knee brace to enable patients with chronic instability to remain ambulatory [18]

prolonged immobilization on articular cartilage and hence encouraged early motion exercises using a motion apparatus and sliding frames (Fig. 3). For patients who continued to suffer from instability, he suggested wearing of a long-leg hinged brace. Sadly, Bonnet's ideas and suggestions received little recognition beyond French borders.

In 1850 James Stark of Edinburgh (1811–1890) reported some of the disabling signs of ligament rupture he had observed as "… something gave way with a snap in the left knee; when raised, she found she had lost all command over the leg" [208]. He treated both of his patients conservatively, but despite 3 months of immobilization and a further 10 months using a semi-rigid brace, neither regained normal knee function.

Toward the end of the nineteenth century, clinicians started to perform cadaver experiments with zest to better understand the mechanism of ligament failure. It was soon recognized that the ACL most commonly tore off the femoral insertion unless it became avulsed with a fragment of bone off the tibia [18, 44, 90]. In 1876 Leopold Dittel of Vienna (1815–1898) published on the examination results of a number of knee specimens [44]. Although he noted that ACL tears can occur in isolation, he also recognized the common association between ACL injury, damage to medial collateral ligament, and medial meniscus, structures which Galeazzi later incorporated in his concept of the "central cruciate meniscal capsular complex" (Fig. 4). Erwin Payr (1861–1946) and Willis Campbell of Memphis (1880–1941) confirmed Dittel's findings through clinical observations [26, 179]. Although Campbell described this injury pattern "terrible triad," it was the term "unhappy triad" coined by Don O'Donoghue of Oklahoma (1901–1992) in 1950 which became a household name and synonymous with this injury pattern [172].

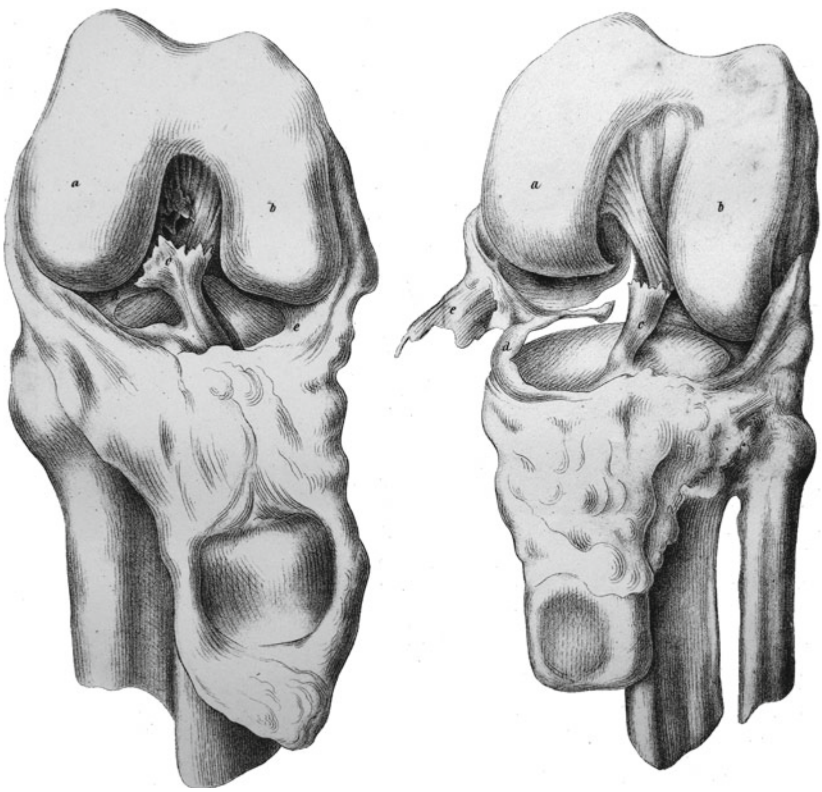


Fig. 4 Drawings of two knee specimens prepared by Leopold Dittel following his motion experiments published in 1876. The *right* image is depicting the common injury pattern of ACL, medial collateral ligament, and medial meniscus, later described by O'Donoghue as "unhappy triad". Letters on drawing refer to a=medial femoral condyle, b=lateral femoral condyle, c=ACL, d=medial meniscus, e=medial collateral ligament [44]

Albert Trillat later described the injury pattern of "pentade malheureuse interne" which included additional damage to PCL and lateral meniscus [218].

In 1875 Georgios Noulis of Athens (1849–1919) presented his thesis entitled "Entrose du genou" to the medical faculty of the University of Paris [168]. It contained the first detailed description of what today is known as the Lachman test, and was based on his observation that anterior displacement of the tibia was most noticeable when he positioned the leg near full extension. Stirling Ritchey rediscovered the value of Noulis's findings in 1960 [188]. The eponym was attributed to the test in 1976 by Joseph Torg in appreciation of his mentor John Lachman (1956–1989) [216]. Torg popularized its value in assessing ACL function by providing a biomechanical rationale regarding the test's improved diagnostic accuracy over the anterior drawer test. The latter had for a long time been considered the investigation of choice despite Palmer's and Lenggenhager's discovery that significant anterior subluxation cannot occur in isolated ACL tears without injury to external supporting structures [130, 177]. The test's value however was not called into question until evidence on its low sensitivity was revealed through investigations conducted by Jack Hughston of Columbus (1917–2004) and Sten-Otto Liljedahl of Stockholm (1923–1982). Both researchers were able to show that the test was positive in just 1/3 of patients with proven ACL deficiency [96, 131].

By the late 1870s, clinicians had gained a sound knowledge of the clinical signs and symptoms associated with injuries to the ACL which Paul Segond of Paris (1851–1912) summarized as "strong articular pain, frequent accompanying pop, rapid joint effusion and abnormal anterior-posterior movement of the knee on clinical examination" [199] He also described the so-called Segond fracture, which he rightly believed to be "… pathognomonic of torsion of the knee in internal rotation and slight flexion of the lower leg and which is associated with rupture of the anterior cruciate ligament."

In 1927 Bruno Pfab described in detail the blood supply to cruciates and menisci [182]. Our knowledge of the functional unit of ACL and PCL in safeguarding normal rolling and sliding motion of femur on tibia was further enhanced through the work of the anatomists Hermann von Meyer (1815–1892) and Hermann Zuppinger (1849–1912) of Zürich, Hans Straßer of Bern (1852–1927), and Rudolf Fick of Innsbruck (1866–1939) [58, 156, 210, 239]. In the following decades, further studies on the functional anatomy of the ACL confirmed its role as the primary anterior stabilizer and secondary rotatory stabilizer of the knee [1, 22, 167]. By the end of the twentieth century, the orthopedic community had thus acquired a sophisticated understanding of the functional behavior of the ACL and the detrimental effects associated with its deficiency.

Direct Ligament Repair

During the nineteenth century, conservative management remained treatment modality of choice as open surgery was considered grave and generally reserved for life-threatening conditions. The aim was to get the patient back to work, while little emphasis was placed on establishing normal function or a possible return to recreational activities. Patients were generally immobilized for several months, and although most patients showed acceptable stability, few regained their preoperative mobility. Even after the introduction of Lister's antiseptic method, surgeons showed reluctance in embracing surgery for a condition as obscure as ligament disruption. This era was described by Edgar Bick as a time "when the [knee] joint was considered a matter beyond the pale of the ordinary rules of surgery" [14].

In 1900 William Battle (1855–1936) published the successful result of an open ACL repair using silk sutures [12]. Arthur Mayo-Robson of Leeds (1853–1933), however, had performed a similar procedure in a 41-year-old miner 5 years earlier but did not publish his case until 1903 [150]. When reviewed 6 years later, the patient considered his leg "perfectly strong," and Mayo-Robson remarked, "He walks well without a limp and can run. No abnormal mobility whatever present. Extension to the straight line is perfectly free. Flexion is somewhat limited."

By 1913 Hubert Goetjes of Cologne was able to trace a total of 23 published cases of ACL rupture and added 7 of his own [74]. He presented a deep understanding of the effects of cruciate deficiencies and gave a comprehensive account of the ligament's function and biomechanics. Goetjes recommended direct repair of all acute and chronic cases affected by abnormal knee

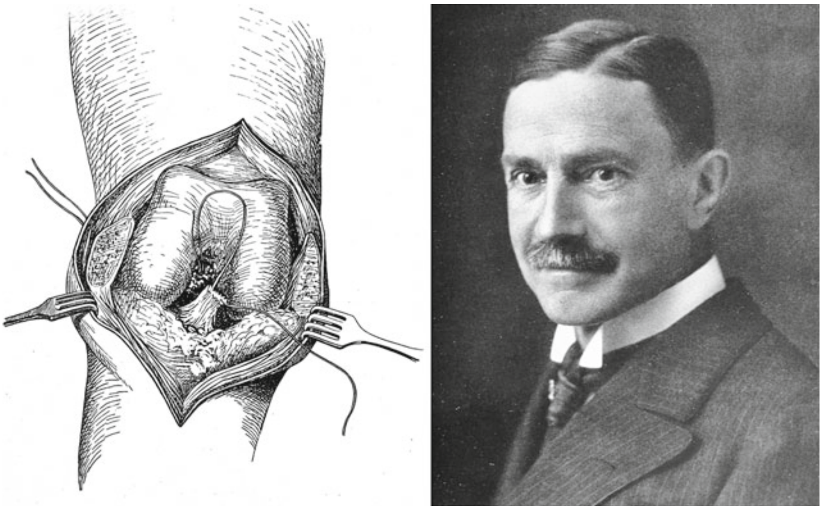


Fig. 5 ACL repair technique presented by Georg Perthes of Tübingen (*right*) in 1927 using a patella-splitting approach. The ligament remnant was reattached to the femur with a transcortical aluminum-bronze wire (With kind permission of Hüthig Jehle Rehn, Heidelberg [181])

function and became the first surgeon to suggest examination under anesthesia when the clinical diagnosis was uncertain.

The results of ACL repair however remained unpredictable. Robert Jones (1857–1933) expressed disbelief that suture repair would yield advantage over plaster immobilization when he remarked that "… stitching the ligaments is absolutely futile. Natural cicatricial tissue … is the only reliable means of repair" [108]. Jones's view was echoed by Ernest Hey Groves (1872–1944) who commented that "… in all my cases the ligaments have been so destroyed … that direct suture would have been utterly impossible" [85]. Critics of surgical intervention like Constantine McGuire also believed that repair did not yield any benefit other than a conversion from a state of instability to one of joint stiffness, created through prolonged immobilization [140].

Georg Perthes (1869–1927) offered an improved repair technique by connecting a wire loop to the ligament remnant which he secured via transfemoral drill holes (Fig. 5) [181]. He reported excellent results with up to 4 years of follow-up in three patients. Perthes thought it was wrong to consider ACL repair only once patients became affected by ongoing instability and expressed concern that "the level of knee laxity and associated symptoms of swelling and discomfort are likely to increase with time." He suggested examining patients as soon as pain and swelling had subsided and to repair all complete tears. Pfab provided further evidence on the suitability of this technique, when he observed complete reconstitution of the ACL following Perthes' repair in sheep [183]. In response to the often insufficient length of ligament remnants, Erwin Payr of Leipzig (1861–1946) designed a procedure that was essentially a partial ACL reconstruction [179]. A fascia loop was threaded through a semicircular tunnel, positioned at the femoral origin of the ACL, and sewn against the tibial ACL stump (Fig. 6).

In 1938 Ivar Palmer of Stockholm (1897–1985) published his treatise "On the Injuries to the Ligaments of the Knee Joint," a detailed study on anatomy,

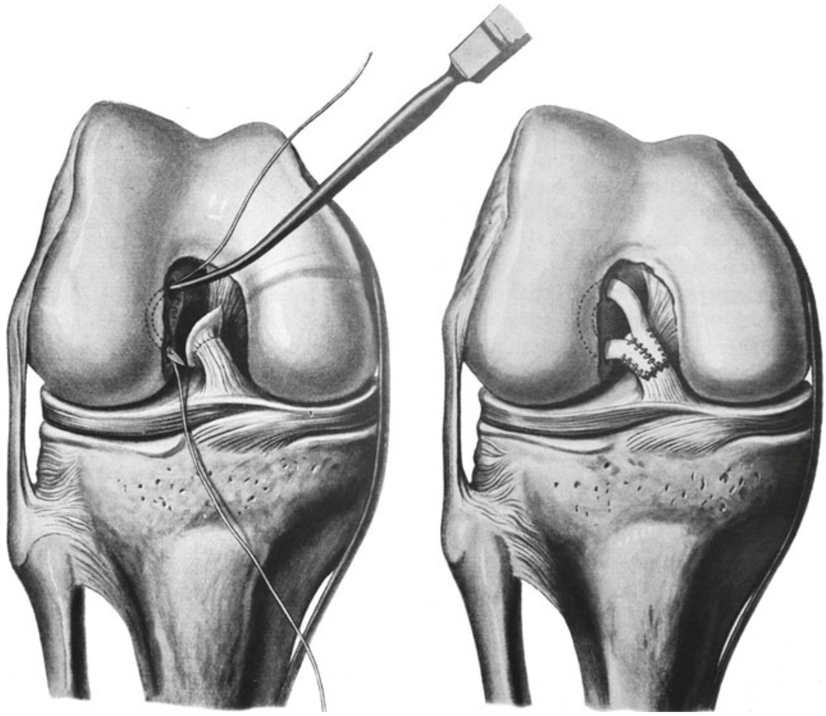


Fig. 6 Erwin Payr's technique published in 1927 to repair the proximally torn ACL with a fascia lata loop anchored against the lateral wall of the intercondylar notch (With kind permission of Springer Science, Berlin [179])

biomechanics, pathology, and treatment [177]. Like Perthes, he advocated that "the golden opportunity is the early operation … when it is generally possible to restore anatomic conditions." Palmer, a proponent of the Perthes' repair technique, also saw potential benefits in repairing both ACL bundles separately.

In the early 1950s, O'Donoghue, a key figure in orthopedic sports medicine, published his experience of treating 22 athletes, revealing that surgery within 10 days of injury offered the best chance of a complete recovery [172, 173]. In his view "the rate of success [of reconstruction] is not sufficiently high to warrant the attitude that acute ruptures of the anterior cruciate need not be repaired under the misapprehension that the ligament can be satisfactorily reconstructed at a later date if the patient has sufficient disability. On the other hand, after successful repair of an acute rupture I have no hesitation in recommending return to active athletics, including football." Through emphasizing the need for early intervention if return to sport activities is desirable, O'Donoghue gave ACL surgery an unexpected boost in the USA. In 1965 Liljedahl presented 18-month follow-up results of 33 patients who had undergone acute ACL repair with "all but three of their knees were completely stable and had a full range of motion" [131].

Suture repair continued to be practiced into the 1980s and was supported by good clinical results published by David MacIntosh and John Marshall [142, 145]. Both devised a variation on the Perthes' technique with sutures being passed behind the lateral femoral condyle in a so-called over-the-top repair. In 1976 John Feagin of New York presented his 5-year results of 32 army cadets who had undergone direct ACL repair [57]. Although initially 84 % did well and returned to sporting activities at 5 years, almost all patients suffered some instability and two-thirds experienced pain. Feagin concluded that “long-term follow-up evaluations do not justify the hope … that anatomic repositioning of the residual ligament would result in healing.” His views were shared by Werner Müller who believed that “success in these cases may well have been due to extensive adhesions among the intra-articular folds, greatly reducing joint play and restraining anterior translation while still permitting recovery of knee motion in flexion-extension” [163]. Superior results achieved with ligament reconstruction compared to ligament repair sealed the fate of primary suture repair, which was all but abandoned by the end of the twentieth century [46, 53].

Pioneers of ACL Reconstruction

Clinicians eventually realized that a number of patients with chronic knee laxity suffered ongoing and debilitating instability despite previous attempts of conservative or surgical management. Hey Groves expressed disenchantment with the standard of treatment of ACL injuries at the time when he wrote, “while the frequency and importance of this injury is becoming more widely known, there have not been any corresponding advances in the method of treatment … a rigid plaster or leather cast to be worn for a year, followed by a hinged apparatus represents the generally accepted method” [85]. In 1913 Paul Wagner wrote a thesis entitled “Isolierte Ruptur der Ligamenta Criuciata” in which he suggested the use of fascia to reconstruct the ACL when the ligament was so badly damaged that repair was impossible [222].

Erich Hesse, surgical assistant to Ivan Grekov of St Petersburg (1867–1934), reported in 1914 on a 40-year-old man who dislocated his knee and tore the ACL [82]. Grekov used a free fascia graft, routed through drill holes in the femur and stitched against the ligament remnants, achieving a knee that was functioning “exceptionally well with no side to side laxity.”

Although we know that Max zur Verth of Hamburg (1874–1941) replaced ACLs with proximally based fascia lata before 1917, details of his surgical technique and outcome remain unknown [89]. On 25th of April 1917, Hey Groves reconstructed his first ACL at Bristol General Hospital, using fascia, which he detached from Gerdy’s tubercle and “threaded through new canals bored in femur and tibia” [85]. Leaving the tendon attached to the muscle was believed to maintain the tendon’s blood supply and nutrition. Hey Groves was aware that proper knee joint function could only be reestablished if the reconstructed ligament graft is placed in the exact anatomic position of the original ACL “in contradistinction to a mere passage of new ligaments across the joint” [86]. He also recognized the importance of graft obliquity as “any new ligament which is used to replace them should be given this oblique direction, even in an exaggerated degree, because an anterior ligament will be efficient in preventing anterior tibial displacement in proportion to its obliquity.” It took however, more than 80 years before the mechanical principle behind the notion of graft obliquity to facilitate improved rotational stability received wider recognition [135, 198].

In 1918 Alwyn Smith of Cardiff (1884–1931), who reported on nine cases treated with the Hey Groves’ technique, criticized its incomplete nature “as it

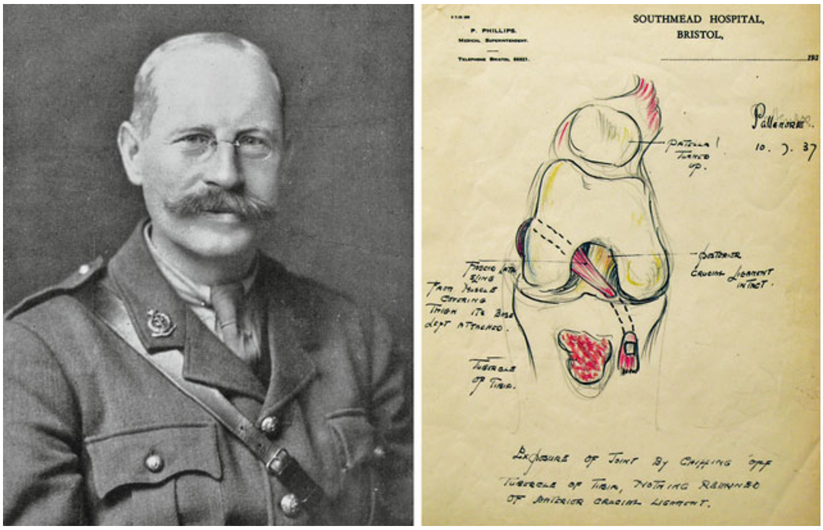


Fig. 7 Photograph of Ernest William Hey Groves taken in full uniform in 1916 (From (1941) *Br J Surg* 24:165–167, with kind permission of John Wiley & Sons, Hoboken). Original drawing by Hey Groves produced in 1937, depicting his revised ACL reconstruction technique (author's archive)

does not attempt to strengthen in any way the internal lateral ligament, so that the new fascial strip has to bear the entire strain of abduction of the knee as well as of anterior sliding and internal rotation" [207]. Smith obviously encountered a more complex injury pattern with involvement of the medial structures. In his technique, he described using distally based fascia routed through femoral and tibial tunnels and folded upward across the medial joint space to strengthen the MCL. Smith also described using massage and electrical stimulation to prevent quadriceps atrophy.

Hey Groves like Smith also switched to distally based fascia as he found that a proximally based graft only provided a limited length (Fig. 7) [86]. In 1919 he conveyed his experience of 14 cases, of which "None were made worse, 4 showed no benefit, 4 benefitted to some degree, 4 were cured and 2 were only operated 6 months ago [but] promise to be successful." Compared to his predecessors, Hey Groves recognized the association between ACL deficiency and anterolateral tibial subluxation when he commented that "In active exercise, when the foot is put forward and the weight of the body pressed on the leg, then the tibia slips forward; sometimes this forward slipping of the tibia occurs abruptly with a jerk ...." In 1972 Robert Galway and David MacIntosh of Toronto used this phenomenon to devise the "pivot-shift test", thus creating a sensitive assessment tool to identify ACL incompetence [70]. During the 1980s Roland Jakob of Berne refined the test by developing a reproducible grading system to classify type and degree of various laxities [*]. Donald Slocum, Ronald Losee, and Jack Hughston (jerk test) described alternative assessment methods to reproduce anterolateral subluxation, all of which essentially represented variations of

*Jakob RP, Stäubli HU, Deland JT. Grading the pivot shift. Objective tests with implications for treatment. J Bone Joint Surg. 1987;69[Br]:294–299.

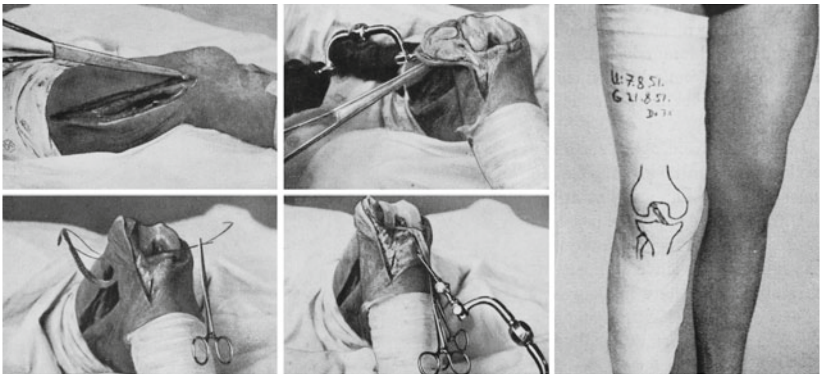


Fig. 8 Contemporaneous intraoperative photographs showing an ACL reconstruction procedure according to Hey Groves performed by Bernard Janik of Vienna in the early 1950s. These images highlight the extensive exposure needed to perform this surgery at the time (With kind permission of Walter De Gruyter, Berlin [102])

the pivot-shift phenomenon [97, 137, 206]. In 1981 Jakob introduced the "reverse pivot-shift test" to assess and diagnose posterolateral instability [**].

In 1927 Maurice Horan reported on a well-healed ligament in a knee which he excised 5 years following a Hey Groves reconstruction [91]. In 1938 Palmer was able to examine the knee of a patient who had died of a pulmonary embolus just 10 weeks after receiving a "Hey-Groves plasty" [177]. To Palmer's amazement, the graft had already become synovialized, and vessels and connective tissue had started to invade from the periphery. Max Lange of Munich (1899–1975), who had used Hey Groves' technique since the late 1930s, reviewed 50 of his cases in 1957 and observed excellent results in 82 % following early reconstruction and in 62 % when surgery was delayed [69, 125].

Despite the excellent work of these early pioneers, the debate over the following 50 years was less over primary repair versus reconstruction but whether any procedure should be performed at all [149]. The mood was captured by Timbrell Fisher (1888–1967) who believed that "operations should be reserved for cases who suffer grave functional disability, which persist in spite of increasing the power of the quadriceps, and other thigh muscles, or the wearing of a well-planned and accurately fitting mechanical support" [59].

Although ACL reconstruction was a formidable procedure (Fig. 8), proponents of surgery like Leroy Abbott of San Francisco (1890–1965) believed that "The application of a splint or plaster cast until such time as the lesion is judged to have healed satisfies the attendant, if not always the patient. Rest and fixation, although sound in principle … often prove disastrous in those patients in whom the supporting ligaments of the knee have been severely damaged" [1]. The 1930s also saw evidences emerge, as referred to by Hans Burckhardt of Essen (1879–1965), that the ACL-deficient knee is "exposed to gradual degeneration due to malfunctioning of its internal guiding system" [25].

[**] Jakob RP, Hassler H, Stäubli HU. Observations on rotatory instability of the lateral compartment of the knee. Experimental studies on the functional anatomy and the pathomechanism of the true and the reversed pivot shift sign. Acta Orthop Scand [Suppl]. 1981;191:1–32.

Choice of Graft Materials

Fascia Lata (Iliotibial tract)

Fascia remained a popular choice of graft for the best part of the twentieth century [36, 50, 98, 102, 187]. In 1927 Charles Eikenbary of Seattle (1877–1933) reported on using free fascia graft implanted through a medial parapatellar approach [50]. He thereby avoided complications associated with patellar tendon detachment or patellar division, which were still the standard methods to facilitate knee exposure at the time [85, 187, 207, 211].

First clinical results on the survival of free fascia grafts, which up to this point were believed to disintegrate as a result of being deprived of their blood supply, were provided in 1929 by Wilhelm Jaroschy of Prague (1886–1938) [103]. Heinz Simon, his assistant, later observed an increased incidence of degenerative changes in 3 out of 12 patients following ACL surgery but was uncertain whether this was related to the operation. Simon nevertheless demanded that tunnels are to be positioned at the ligaments' native attachment sites [202].

William Cubbins of Chicago became key promoters of the Hey Groves procedure in the USA [36, 37]. Few surpassed his enthusiasm when, in 1937 he and his colleagues exhumed the body of a deceased who had been buried for 3 weeks and on whom cruciate reconstructions had been performed a year earlier. Based on their clinical experience, they concluded that best results are obtained either through acute ligament repair or in the chronically unstable knee through ACL replacement.

In 1937 Frank Strickler of Louisville championed intra-articular reconstruction augmented with a lateral extra-articular substitution using a continuous loop of distally based fascia [211]. Tibial and femoral tunnel were positioned centrally within the joint, creating a vertically aligned graft, believed by Strickler to "work equally well in either rupture of the anterior or posterior cruciate ligament." In his experience, "about 6 months from the date of surgery, these patients have a good functioning, serviceable joint."

In 1940 Frederick Tees of Montreal offered a modification on the Hey Groves technique, by routing the graft via the tibia through the lateral femoral condyle before anchoring it against the fibular head [214]. Tees believed that reinforcing the lateral ligament would help to stabilise the joint, thereby introducing the idea of lateral extra-articular augmentation. In 1963 O'Donoghue suggested a similar variation, but instead of attaching the tendon to the fibula head, he folded it upward to repair the defect in the fascia [174]. In 1978 John Insall of New York (1930–2000) presented the "bone block ilio-tibial band transfer," a procedure based on Nicholas's and Minkoff's "iliotibial band pull-through" technique, first used at Lennox Hill Hospital in 1971 [98, 165]. Insall detached the central portion of the fascia lata with its osseous insertion from Gerdy's tubercle, rerouted the graft over the top of the femoral condyle into the joint and screwed the bone block to the tibial plateau. Insall was well aware that it would be "impossible to duplicate the original anatomy exactly with any form of graft," but his clinical results nevertheless showed that "although the results of the postoperative anterior drawer test are disappointing if one hopes to restore the knee to normal, the improvement in the patients' functional capacity is quite dramatic…and most of these patients were engaging in strenuous sports without brace protection."

Meniscus: The Misguided Sacrifice

The treatment of choice for a torn meniscus was its removal, and since it was known that meniscal tissue consisted of avascular fibrocartilage nourished by synovial fluid, it appealed as an almost ideal substitute for the ACL [224].

In 1917 zur Verth replaced the ACL of a sailor with the torn lateral meniscus, which he left attached posteriorly, and sutured against the ligament remnants [89]. Although meniscus never gained widespread popularity, it was nevertheless considered by many to be a suitable ACL replacement [32, 133, 166, 230]. Their opinion is reflected by Bengt Tillberg who, after having performed the surgery on 43 patients, concluded that "The use of a meniscus for the reconstruction of either cruciate ligament is considered to be simple, safe and effective" [215].

Max Lange had experimented with meniscal tissue graft in the early 1930s but remained critical upon its use. He upheld the view that meniscal tissue was "functionally unsuitable to replace a ligament" as it was primarily designed to withstand compression rather than tension and shear [125]. In histological studies, Lange was able to confirm cystic degeneration of meniscal implants and concluded that "a degenerative meniscus appears to be too poor to be considered for reconstruction, whilst a healthy meniscus would appear to be too good" [69, 125].

Knowledge of the importance of the meniscus, consequences of its removal, and reports on clinical failures gradually prompted a shift in opinion [93, 143, 224]. This was led by publications of Hughston in 1962 who recognized the contribution of the meniscus to knee stability and those of Peter Walker in 1975, who defined the role of the meniscus in the force transmission across the joint [94, 223]. By the end of the 1980s meniscus was finally abandoned as grafting material.

Extensor Retinaculum and Patellar Tendon

Mitchell Langworthy of Spokane/WA (1891–1929) is reported to have been the first surgeon to replace the ACL using part of the ligamentum patellae [50]. Langworthy never published on his method and suffered an untimely death when he became the victim of a bullet from an unhappy patient in his private practice in 1929.

In 1928 Ernst Gold presented the case of a 27-year-old lady, who had torn her ACL skiing 2 years earlier [75]. Gold achieved a good result by using a distally based strip of extensor retinaculum and patellar tendon, which he passed through a tibial tunnel, and secured against the PCL. In 1932 zur Verth reported on the treatment of chronic ACL-deficient knees with a pedicled section of patellar tendon [240]. Arnold Wittek of Graz (1871–1956) adopted the "zur Verth" technique and presented 16 successfully operated cases in 1935 [231].

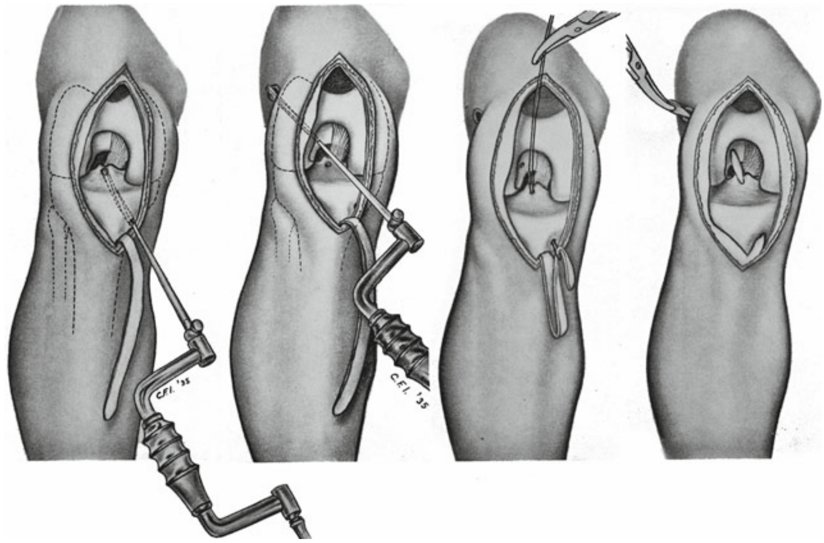


Fig. 9 Illustrations taken form Willis Campbell's publication on knee ligament repair published in 1936, showing the use of pedicled extensor retinaculum and patellar tendon in reconstructing the ACL (With kind permission of Elsevier, Philadelphia [26])

In 1936 Campbell, who coined the term "giving way" in summarizing the distressing signs of knee instability, described the use of pedicled extensor retinaculum containing "very strong tendinous tissue from the medial border of the quadriceps and patellar tendons" (Fig. 9) [26]. Campbell, like Smith, promoted combined reconstruction of ACL and MCL in cases of "unhappy triad" [27].

In 1963 Kenneth Jones of Little Rock suggested a reconstruction technique which he "considered simpler and more physiological than those previously described" [106]. He used the pedicled central third of the patellar tendon which he passed "beneath the fat pad" into the joint. To overcome problems of insufficient graft length, Jones "placed [the femoral tunnel] in the intercondylar notch just posterior to the margin of the articular cartilage." This resulted in an extremely nonanatomical graft position, contradicting his earlier claims and forcing Jones to concede that "Anatomical normalcy of the structure is, by the nature of the situation, beyond expectation." Two-year results were nevertheless promising, but when Jones reviewed 83 of his patients in 1980, almost 30 % were lacking confidence and suffered residual symptoms [107]. In the USA, the principle of ACL reconstruction with patella tendon became synonymous with the Jones procedure and known as such.

Modern biomechanical understandings and the principle of the "four-bar-linkage" have since revealed that anterior positioning of the femoral tunnel away from its native insertion would, as shown by Werner Müller, increase tension forces within the ligament graft in proportion with knee flexion (Fig. 10) [21, 153, 162].

In 1966 Helmut Brückner of Rostock described the use of the medial third of the patellar tendon [24]. To overcome problems of insufficient graft length, which had forced Jones to compromise on the femoral tunnel position, Brückner routed the tendon strip through a tibial tunnel, thereby essentially shortening the distance between graft attachment and entry into the joint. This allowed Brückner

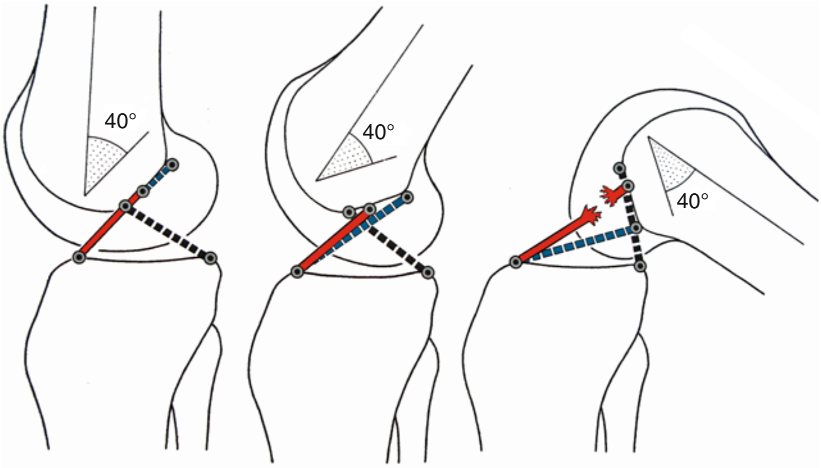


Fig. 10 Werner Müller's interpretation of the detrimental effect of malpositioning of the femoral tunnel, based on the "four-bar-linkage" model, first developed by Hermann Zuppinger of Zürich in 1904 and later refined by Straßer and Menschik (With kind permission of Springer, Berlin [162])

to position a blind-ending femoral tunnel close to the anatomic footprint. By 1969 he had performed 35 reconstructions, 90 % of which regained normal stability and 25 % experienced minor discomfort after strenuous activities [184]. The Brückner technique remained relatively unknown at first but received wider attention through Lennart Brostöm of Stockholm who modified Brückner's original procedure by pulling the proximal graft into a decorticated groove and securing it with transfemoral sutures [23]. Clinical results of 72 patients were published by Eriksson in 1976, 80 % of whom were stable at 1 year [55].

Critics of using the medial third of the patellar tendon argued that it would create changes in patellar kinematics resulting in patellar maltracking and subsequent degeneration [147, 229]. In 1974 Artmann and Wirth of Munich started to experiment with free bone-patellar tendon-bone graft (B-PT-B) taken from the central portion of the patellar tendon as it allowed for the femoral tunnel to be freely placed in its most anatomic position without being compromised by insufficient graft length [10]. Although Brückner had already reported on using a free graft in 1966 (Fig. 11), he initially reserved this technique for cases where the ipsilateral patellar tendon was compromised through previous surgery [24].

William Clancy of Madison/WI, moved from pedicled medial third to free patellar tendon graft in the 1980s and became a major proponent of this technique in the USA [30, 31]. John Marshall and associates of New York chose a different approach with their "Quadriceps tendon substitution" technique published in 1979 [145]. They harvested the patellar ligament, the prepatellar expansion, and part of the quadriceps tendon as a single graft, passed through a tibial tunnel, and looped "over-the-top" of the lateral femoral condyle. In 1976 Kurt Franke presented his experience of 79 ACL injuries, most of which were treated with a free B-PT-B graft according to Brückner [62]. He followed his patients over an 8 year period, and despite 5 cases of graft rupture, the functional results were "highly satisfying", and the majority of patients went back to high-level sporting activities.

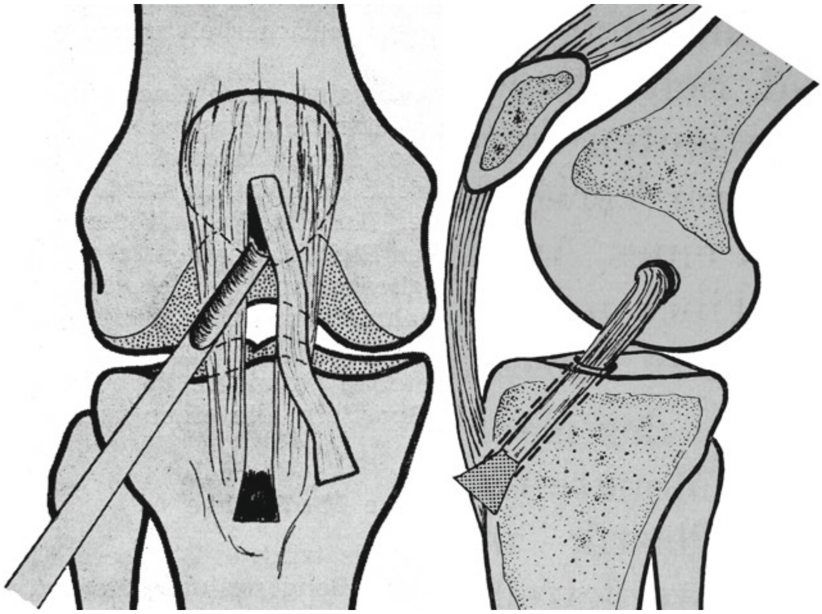


Fig. 11 ACL reconstruction with free central 1/3 patellar tendon graft and press-fit tibial fixation first described by Helmut Brückner in 1966 (With kind permission of Springer Science, Berlin [24])

Kenneth Lambert and the group of Noyes investigated potential benefits of vascularized tendon grafts in the 1980s, but clinical and experimental studies by Tomas Drobny of Zürich failed to show any advantage over free tissue grafts with regard to revascularization, tissue integration, and biomechanical properties (Drobny TK, 2012, personal communication) [45, 121, 178]. The merits of patellar tendon were further endorsed by Eriksson in Europe and Clancy and Shelbourne in the USA, and by the end of the 1990s, patellar tendon had become the most popular graft source in ACL surgery [30, 55, 200].

Quadriceps Tendon

Mindfulness of the potential morbidity associated with harvesting patellar tendon prompted some surgeons to experiment with alternative sources [3, 169, 194]. In 1976 Robert England of Jackson/WY reported on a patient who was scheduled for acute ACL repair, but upon arthrotomy, the ACL was found to be absent [54]. England elected to use a free quadriceps graft which he secured with transcortical sutures according to Perthes. Pleased with the patient's outcome, he repeated the procedure successfully in three further patients. Walter Blauth started using quadriceps tendon for chronic ACL deficiency in 1981 [16]. In the USA, John Fulkerson became the key promoter of quadriceps tendon which he considered to be superior to any other graft source [66]. Although quadriceps never gained the same level of popularity as patellar or hamstring tendon, it has nevertheless remained a suitable alternative in the revision setting or when other graft sources are compromised [42].

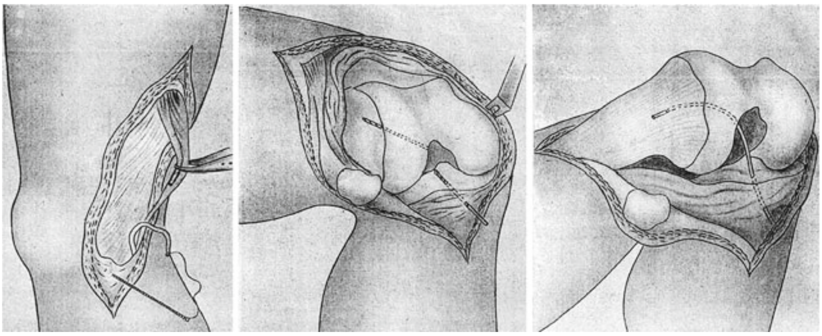


Fig. 12 In 1934 Riccardo Galeazzi of Milan presented his ACL reconstruction technique with an anatomically placed distally pedicled hamstring graft (semitendinosus) [67]

Hamstring Tendons

In 1927 Alexander Edwards of Glasgow suggested an operation he had performed on a cadaver whereby both cruciate ligaments were replaced with the proximally based hamstring tendons [48]. He was not concerned with anatomic reconstruction, since he used a single femoral tunnel drilled through the medial femoral condyle and two tibial tunnels placed in the anterior aspect of the tibial spines.

In 1934 Riccardo Galeazzi (1866–1952) pioneered anatomic ACL reconstruction with hamstrings, utilizing semitendinosus tendon which he left attached to the pes anerinus (Fig. 12) [67]. Patients were immobilized in a cast for 4 weeks and remained partially weight bearing for 6 weeks. All three patients in his series fared well but follow-up was short. Galeazzi's brilliant idea however remained unnoticed.

Harry Macey of Rochester/MI (1905–1951) presented a simplified version of the Galeazzi technique in 1939 but never reported on any clinical cases [139]. The knee was exposed via an S-shaped lateral parapatellar approach while the hamstring tendon was severed through a small stab incision at its musculotendinous junction thereby reducing surgical trauma.

In 1950 Kurt Lindemann of Heidelberg (1901–1966) developed the concept of "dynamic reconstruction" by attempting to take advantage of the stabilizing effect of the muscle-tendon unit, a principle first explored by Hey Groves in 1917 [132]. Lindemann utilized proximally based gracilis tendon, which he directed via an opening in the posterolateral capsule into a tibial tunnel (Fig. 13). At 2 years, all of his six patients had returned to work and maintained normal knee function.

In 1956 Robert Augustine of Madisonville/KY, unaware of Lindemann's publication, suggested an almost identical procedure using gracilis [11] He believed in the dynamic effect of the operation to "stabilise the tibial plateau on the femur in conjunction with the PCL when the hamstrings are contracted." DuToit of Pretoria used the Lindemann procedure extensively during the 1960s, and most of his patients returned to vigorous sporting activities [47]. In his opinion, the preservation of proprioceptors and attachment to active muscle would facilitate tension in the transferred graft to be maintained.

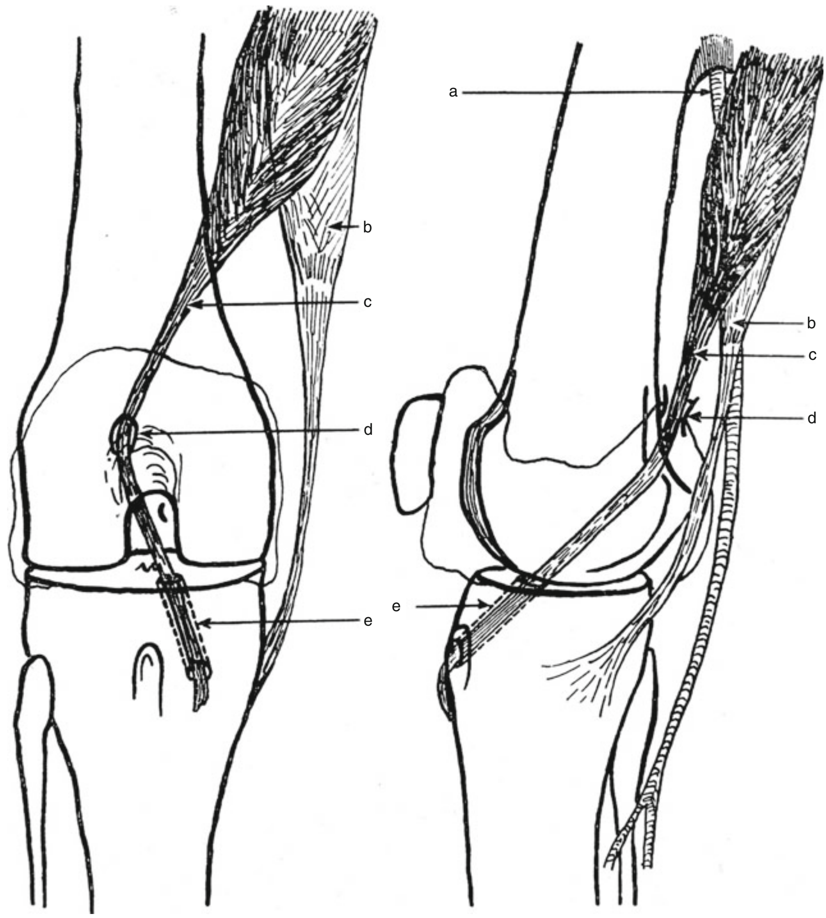


Fig. 13 Kurt Lindemann of Heidelberg introduced the concept of "dynamic ACL reconstruction" in 1950, believing that the gracilis muscle/tendon unit would actively stabilize an ACL-deficient knee. Letters on drawing refer to: a = politeal artery, b = original position of gracilis muscle, c = altered position of gracilis, d = entry point of tendon through posterior capsule, e = tibial canal. (With kind permission of Springer Science, Berlin [132])

Robert Merle d'Aubigné of Paris (1900–1989) adopted the principles of the Galeazzi/Macey technique in the 1950s using pedicled semitendinosus, while gracilis was passed through a transfemoral tunnel, to reinforce the MCL [155]. Max Lange, although satisfied with his results achieved with fascia, switched over to hamstrings in the mid-1960s as the operation "required less exposure and dissection therefore reducing surgical trauma." He also believed in the merits of medial capsular reefing for most chronic cases with significant laxity [125, 126]. The 1970s saw a renewed interest in pedicled hamstrings as graft source led by James McMaster of Pittsburgh and Kenneth Cho of Washington DC [29, 151].

James Horne and Chris Parsons of Toronto expressed concern about possible abrasion of the tendon graft at the femoral tunnel entry site and proposed for the graft to be positioned "over-the-top" of the lateral femoral condyle in a more "anatomical line" [92].

In 1973 Karl Viernstein (1920–2011) and Werner Keyl of Munich recruited both gracilis and semitendinosus tendon introducing the double-strand technique [219]. Brant Lipscomb of Nashville brought the concept of using both hamstrings to a wider audience in the early 1980s, but their technique soon became challenged by the introduction of the four-strand hamstring reconstruction offered by Marc Friedman of Los Angeles [64, 134]. Comparative studies eventually confirmed equivalence in terms of clinical outcome between hamstrings and other autologous graft sources [8, 88, 189].

Xenografts and Allografts

Allograft reconstruction of the ACL was an attractive proposition as it avoided the need of graft harvest and associated donor site morbidity. Although Eugene Bircher of Arau (1882–1956) and Italian Micheli successfully experimented with kangaroo tendon, xenografts remained a rare choice and never gained any real popularity [15, 158]. The use of human allografts was first reported by Konsei Shino in 1986 [201]. When he reviewed 31 of his patients after a minimum follow-up of 2 years, all but one had been able to return to full sporting activities. The use of allograft has since achieved widespread popularity particularly in the USA despite a temporary setback in the 1990s following fears of viral disease transmission [79, 160].

Synthetics: Hankering for the Ideal Graft

Themistocles Gluck of Berlin (1853–1940), pioneer of joint arthroplasty, successfully bridged tendon defects with plaited catgut in 1881 [72]. Fritz Lange of Munich (1864–1952), who had successfully used silk for the treatment of paralytic feet in 1895, first suggested silk as prosthetic ligaments to treat "wobbly knees" in 1903 [122]. In 1907 he reported on four cases of ACL deficiency, which he stabilized with extra-articularly placed "artificial ligaments made of silk" augmented with hamstring tendons (Fig. 14) [123]. The silk was slowly surrounded by fibrous tissue, and Lange praised the "wonderful ability of the silk to produce fibrous tissue under functional stress," a finding confirmed through histological investigations by Max Borst of Würzburg (1869–1946) a few years earlier [19]. Lange's grandson Max achieved clinical success by utilizing silk augmented with fascia in ACL reconstruction which he reported in 1932 [124]. Lange was mindful that joint stability could not be achieved by silk alone, which he saw merely as a scaffold providing initial strength while inducing a process of ligament healing and regrowth.

In 1913 Edred Corner of St Thomas in London (1873–1950) tried to replace a torn ACL with two interlaced loops of silver wire, but the wire broke after the patient started to mobilize [34]. Karl Ludloff of Frankfurt (1864–1945), used a strip of fascia wrapped around a thick central silk suture to replace the ACL in a 23-year-old farmer in 1927 [138]. He was meticulous in trying to place both tunnels at the center of the anatomical footprints of the

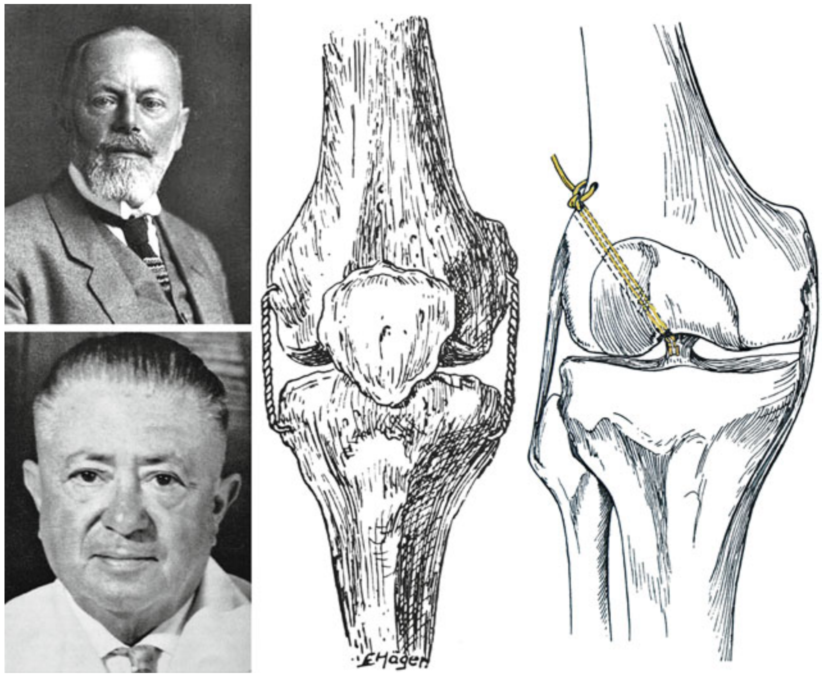


Fig. 14 In 1903 Fritz Lange (*top left*) started using silk sutures as extra-articular augmentation to treat chronic knee instabilities. His grandson Max (*bottom left*) introduced the technique of partial substitution/reconstruction of the torn ACL with "Hydrargyrumoxyzyanat-Seide" in the late 1920s. (From: Vulpius O, Stoffel A (1913) Orthopädische Operationslehre. Enke, Stuttgart [221])

ACL and kept tunnel diameters small enough to obtain a tight-fitting graft. Ludloff refrained from any form of graft fixation as he believed that the graft should be allowed to establish equilibrium of tension. He encouraged early mobilization, and the patient was walking on the 25th day. When reviewed at 5 months, he had resumed his duties as a farmer and presented minimal loss of flexion and a negative anterior draw.

The second half of the twentieth century saw a myriad of different synthetic ligament graft materials appear. In 1949 Rüther reported disappointing results following the implantation of a synthetic ACL made of Supramid®, a polyamide derivative [193]. Olav Rostrup started using Teflon® and Dacron® grafts in 1959 [191]. He saw synthetics primarily as augmentation devices to support fascia or tendon and felt that the synthetics used are "not the ideal material" and hence did "not recommend its wide-scale or indiscriminate use." In 1973 Proplast®, a porous Teflon® graft claiming to offer enhanced fibrogenic properties, became one of the first synthetic graft materials to receive FDA approval, but clinical performance was disappointing [233].

Richard Wilk and John Richmond of Boston reviewed 50 patients with Dacron® ligament grafts in 1993 and recorded a significant deterioration in ligament failure rate from 20 % at 2 years to 37.5 % at 5 years [227]. Equally devastating results were reported from Sweden by Wolfgang Maletius and Jan Gillquist. In their 9 year results they recorded 44% of graft failures, whilst only

14% of patients maintained acceptable stability [144]. The Stryker Inc. finally discontinued the Dacron® ligament device in 1994. David Jenkins of Cardiff experimented with flexible carbon fiber in the 1980s [105]. Carbon was thought to act as a temporary scaffold, encouraging the ingrowth of fibroblastic tissue and collagen production. Clinical results however were overshadowed by foreign body reaction and tissue staining through carbon fragmentation [192].

In the late 1970s, Jack Kennedy of London/ON (1917–1983) introduced the LAD®, a ligament augmentation device made of polypropylene [111]. Kennedy developed the concept of "load sharing," which arose from observations that biological grafts are affected by temporary degeneration and loss of strength before being fully incorporated. The LAD® was hoped to protect the biological graft during this vulnerable phase [113]. Lars Engebretsen of Oslo conducted a large randomized controlled study in the 1980s to assess the merits of the LAD® compared to acute repair and reconstruction [53]. He enrolled 150 patients into the three treatment arms and produced follow-up results of up to 16 years. Both acute repair and repair with the LAD® provided for failure rates of up to 30 % which discouraged the authors from recommending the use of this ligament augmentation device [46].

Various other synthetic ligament grafts, including Gore-Tex®, PDS®, Eulit®, and Polyflex®, were introduced during the same period [101]. Awareness of the potential biological and biomechanical shortcomings of using a single type of synthetic material also prompted attempts to combine materials of favorable characteristics like it was done with the ABC (Activated Biological Composite) ligament. Clinical long-term performance of most of these materials, however, was characterized by fatigue failure as in vivo functional stresses exceed their biomechanical properties [186]. Reports on complications like chronic synovitis, osteolysis, foreign body reaction, and poor incorporation into host bone finally sealed the fate of synthetics, a trend Ejnar Eriksson had already anticipated in 1976 by stating that synthetics are "like shoestrings, they eventually break" [56, 203, 232].

Extra-articular Procedures: Treating Functional Disabilities

Even before intra-articular reconstructions were attempted, surgeons had already started to experiment with simplified extra-articular procedures designed to control patients' disabilities [71, 123]. The rationale behind such efforts was encapsulated by Henry Milch of New York (1895–1964) when he expressed the notion that "a torn ACL left little if any disability whilst the medial or tibial collateral ligament is of the utmost importance in the stability of the knee" [159].

The first account of an extra-articular procedure was published in 1907 by Fritz Lange who successfully placed silk sutures across the joint space in an attempt to treat disabling knee laxity (Fig. 14) [123]. Encouraging results of free tendon transfer by Kirschner and Davis persuaded Knut Giertz of Stockholm (1876–1950) in 1913 to attempt stabilising the knee of a 13-year-old girl who had lost her cruciates as a result of septic arthritis [41, 71, 114]. He augmented both collateral ligaments with sections of fascia, and the child regained good function albeit with slight restrictions in motion.

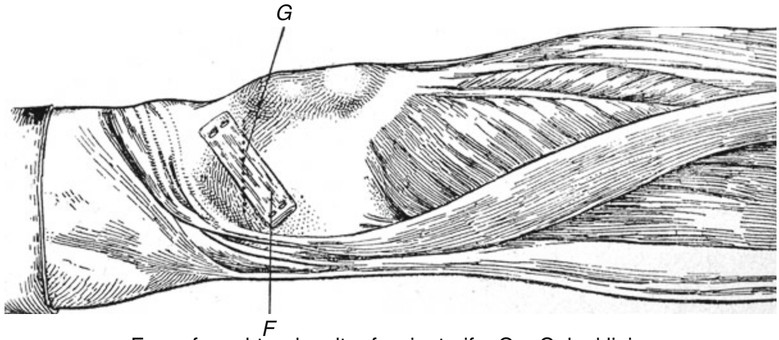


Fig. 15 Extra-articular stabilization with obliquely placed fascia strip across the medial joint space according to Hermann Matti of Bern (With kind permission of Springer Science, Berlin [148])

In 1918 Hermann Matti of Bern (1879–1941) published his paper entitled "Replacement of the torn anterior cruciate with extra-articular free fascia graft," where he describes the application of an obliquely placed doubled-up fascia strip across the medial joint space (Fig. 15) [148]. A number of similar procedures focusing on strengthening of the MCL and anteromedial capsule were introduced over the following 20 years [13, 20, 149]. In 1947 Emil Hauser of Chicago (1897–1981) proposed placing pedicled strips of patellar and quadriceps tendon in a crisscross fashion onto the anteromedial capsule to treat ACL or PCL deficiencies [80]. In 1957 Merle d'Aubigné advocated his "plastie osteo-ligamentaire," an opening wedge tibial osteotomy positioned above the distal MCL attachment for the treatment of ligament laxities [155].

In 1963 Arthur of Cape Town (1907–1989) conveyed, "If we consider that the cruciate ligaments act as check-straps which prevent anteroposterior movement of the tibia on the femur and that resulting instability after rupture of these ligaments is due to the absence of these check-straps, then the only logical course of treatment is anatomic replacement. On the other hand, if the cruciate ligaments are guide ropes which keep the tibia in its normal helicoid track on the medial condyle of the femur, it is possible to replace this function by extra-articular tendon transplant" [81]. Helfet made a case for the latter, and his views were echoed by Arthur Ellison (1926–2010), who in comparing the knee with a wheel believed that "it is easier to control rotation of a wheel at its rim than at its hub" [52]. The debate hence gradually moved away from focusing primarily on restoring anatomy by ways of reconstructing damaged ligament structures toward a treatment approach that tried to address functional disabilities.

The concept that instability was caused by abnormal rotation about the long axis of the tibia was introduced by Donald Slocum and Robert Larson of Eugene/OR in 1968, citing as the usual cause, an injury to the medial capsular ligament complex [204]. The clinical picture became known as "anterior medial rotatory instability" and sparked the development of a myriad of extra-articular procedures most notably the "pes anserinus transfer" and the

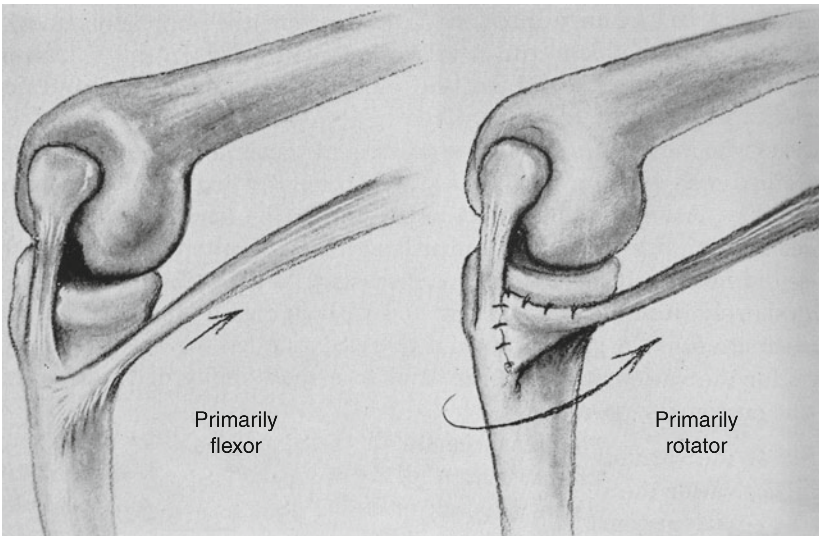


Fig. 16 "Pes anserinus transplantation" introduced in 1968 by Donald Slocum and Roger Larson of Eugene for the treatment of anteromedial rotatory instability [205]

"five-in-one repair" (Fig. 16) [95, 164, 175, 205]. Slocum and Larson's discovery however was not new. In 1893 Johann Hönigschmied of Klagenfurt had already reported on the propensity of increased external rotation following medial capsular injuries he had created in cadaver experiments [90]. In 1928 Hans Tretter of Graz expressed a similar opinion when he concluded that "The condition of the capsular structure is vitally important in limiting the degree of rotatory knee movements" [217]. In 1953 Felix Merke of Bale suggested capsular reefing as a sole procedure for ACL deficiency to control tibial rotation, while Max Lange recommended it as an augmentation to "further improve the results of ACL reconstruction" [125, 154].

Anatomical and clinical studies by Kennedy and Fowler and the establishment of the "pivot shift phenomenon" as pathognomonic for ACL deficiency, prompted Hughston to incorporate these findings into his "anterior lateral rotatory instability," or ALRI, theory [70, 97, 110, 112]. Despite its linguistic complexity, ALRI simply described the clinical appearance of an isolated ACL injury. It became a buzz word in orthopaedic circles in the 1970s, and a proficient examiner was held in high esteem when he produced a decisive pivot shift.

Marcel Lemaire of Paris (1918–2006) recognised the physical disability associated with the pivot shift. He subsequently created his "transposition musculo-aponéurotiques"; a laterally based extra-articular procedure utilizing a pedicled fascia strip reinforced with nylon and secured against the lateral epicondyle (Fig. 17) [128]. He later dropped the nylon stent, using a loop of fascia routed through a bony tunnel and folded back onto Gerdy's tubercle [129]. In 1975 he reviewed 328 of his patients, rating 87 % as having a good result [129]. Lemaire was aware that, although his procedure was ill equipped to effectively reduce anterior drawer, it controlled elements of rotational laxity and abolished the pivot shift, which in clinical practice appeared sufficient to allow patients to resume sporting activities.

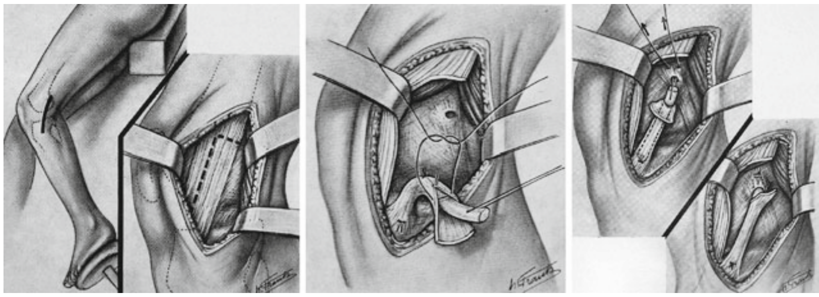


Fig. 17 "Transposition musculo-aponéurotiques" by Marcel Lemaire of Paris first presented in 1967. The procedure was designed to reduce disabling symptoms associated with tibial subluxation [128]

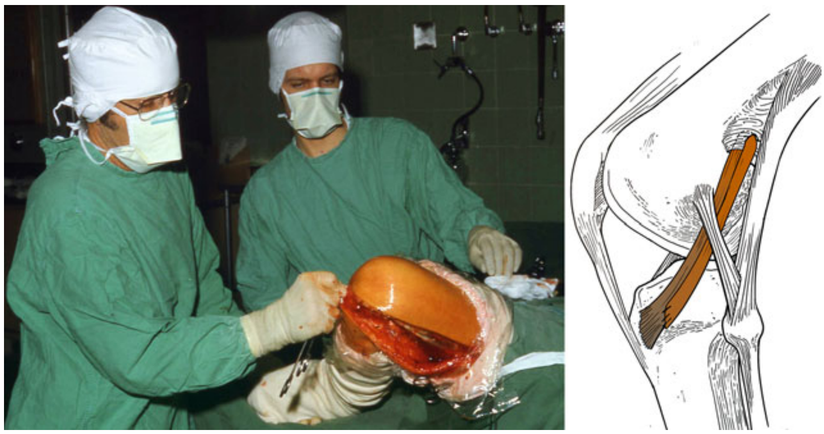


Fig. 18 David MacIntosh of Toronto (*far left*) performing his "lateral substitution reconstruction" in the early 1970s (Photograph courtesy of David Dandy, Cambridge)

In 1971 MacIntosh and Galway devised the "lateral substitution reconstruction," which became known as the "MacIntosh tenodesis" (Fig. 18) [70, 141]. Compared to Lemaire's revised technique, the tendon loop was placed beneath the LCL and routed through the intermuscular septum. In cases of significant laxity, MacIntosh suggested a combined reconstruction with a pedicled fascia sling placed "over-the-top" of the condyle, into the intercondylar notch and through the tibial tunnel to exit at Gerdy's tubercle, a procedure not dissimilar to Hey Groves' earlier technique. A variety of other substitution procedures designed to control anterolateral subluxation, notably those of Trillat (1972), Ellison (1975), and Losee (1978), became popular around the same time [51, 52, 137, 217].

By the 1980s, clinicians had created a classification of all variations of knee instabilities, appropriate tests to define them, and a plethora of surgical remedies to treat them [43, 100, 162]. Critics of the notion of rotatory laxities like David Dandy of Cambridge believed that with regard to the pivot shift phenomenon, "undue emphasis was being placed on tibial rotation, as the concept did not fit the facts." The introduction of a system of rotatory, straight, and combined instabilities administered in Dandy's view "a coupe de grăce to Slocum and Larson's original simple idea [and resulted in] a jungle of jargon and biomechanics that helps only those who profess to understand it" [39] (Dandy DJ, 2011, personal communication).

Although most extra-articular procedures diminished or obliterated pivot shift and Lachman manoeuvres in the short term, repairs gradually stretched out and led to unsatisfactory results [61, 112, 225]. In a landmark paper, Kennedy reported in 1978 on 52 patients following extra-articuar stabilization with only 47 % achieving good to excellent outcome [112]. Similar results were observed by Warren and Marshall, who concluded that "as a general rule, extra-articular surgery without attention to the cruciate ligaments will often result in failure" [225]. By the late 1990s, surgeons began to realize that efforts to stabilize an ACL-deficient knee had to involve the central pivot, and attention turned again toward the reconstitution of the anatomy [7, 8, 30, 169, 212, 237].

Double-Bundle Reconstruction: Replicating the Native ACL

Ludloff was aware of the complex tension pattern within the ACL and suggested in 1927 that "reconstitution to relatively normal function would require the new cruciate ligament to consist of two separate bundles" [138]. Palmer had already performed double-bundle ACL repairs in the 1930s, claiming good results, but his technique failed to find wider acceptance [177].

Viernstein and Keyl pioneered double-bundle ACL reconstruction with a distally based semitendinosus and gracilis graft in 1973 [219]. According to their technique, both tendons were routed via a single tibial tunnel into two separate femoral tunnels and sutured together at the exit (Fig. 19). By placing the femoral tunnels within the anatomic footprints of the native ACL, the graft appeared to emulate the twisting of the native ACL bundles during flexion. Up to this point, traditional single-bundle reconstruction techniques had aimed to replace the anteromedial bundle, thereby predominately restoring anteroposterior laxity. With the addition of a posterolateral bundle, Viernstein and Keyl were hoping to address any remaining elements of rotational laxity.

In the early 1980s Werner Müller introduced his "anatometric" double-bundle reconstruction for which he used free patellar tendon graft [162, 163]. The graft emerged from a single tibial tunnel and was divided proximally. The posterolateral leg, which incorporated the bone block, was placed intraosseously, while the anteromedial leg was lowered into a trough in the "over-the-top" position, thereby bringing it closer to its anatomical origin (Fig. 20) (Müller W, 2012, personal communication). Blauth started using free double-bundle quadriceps graft in 1981, dividing the proximal tendon into two strands, with one placed transfemorally and the other "over-the-top." By 1984 he had performed the procedure on 53 patients with good overall results [16].

In 1983 William Mott of Jackson/WY published his "Semitendinosus Anatomic Reconstruction," creating double tunnels in both tibia and femur through which he placed a free semitendinosus graft [161]. In 1990 Jean-Louis Meystre of Lausanne reported 77 % good to excellent results with his technique

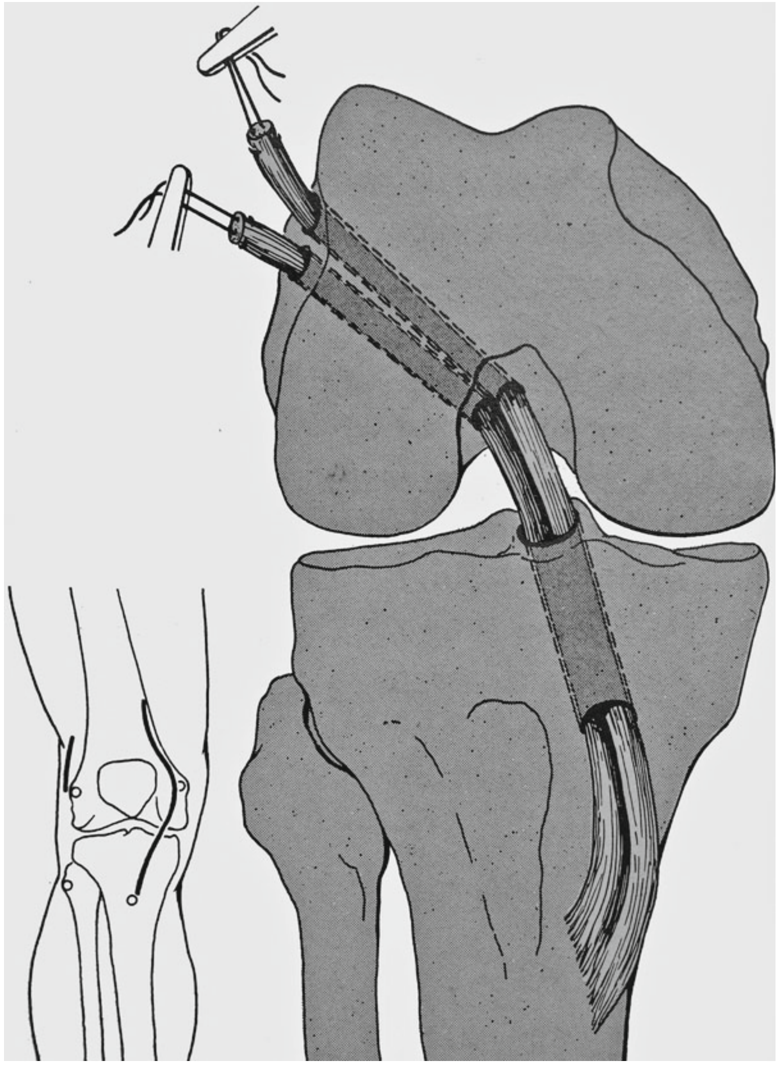


Fig. 19 Illustration of the first double-bundle ACL reconstruction as performed by Karl Viernstein (1920–2011) and Werner Keyl of Munich in 1973. The procedure required an open two incision technique with a medial para-patellar approach (left) (With kind permission of Urban & Fischer, Munich [219])

of semitendinosus double tibial and single femoral tunnel reconstruction [157]. Bradley Edwards and associates compared single bundle with three different double-bundle techniques in vitro which revealed that the most physiological graft conditions are obtained when using dual tibial/dual femoral tunnels [49]. More recently, selective bundle reconstruction in cases of partial ACL ruptures has been performed [170].

In 1997 the group of Freddie Fu of Pittsburgh highlighted significant variations in force distribution between the two ACL bundles, prompting the investigators to suggest that reconstruction principles would have to focus on the role of both bundles if in situ forces of the native ACL are to be reproduced (Fu FH, 2011, personal communication) [195]. The same investigators

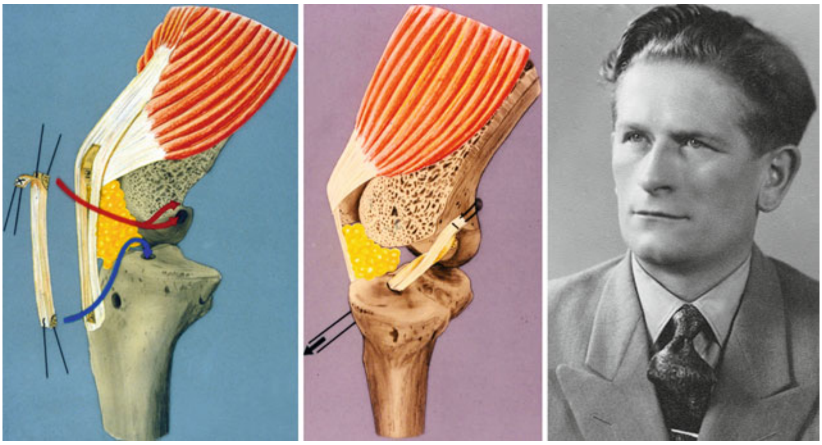


Fig. 20 Werner Müller of Bale (*right*) devised his "anatometric" double-bundle reconstruction in the early 1980s. Division of the proximal aspect allowed the graft to better cover the femoral footprint of the ACL, with the AM bundle being placed "over-the-top" in a 4-mm trough (Illustrations adapted from and courtesy of Tomas Drobney, Zürich)

indicated in an in vitro study that double-bundle reconstruction has the ability to more closely resemble physiological knee kinematics with respect to translation and rotation [234]. More recently, the groups of Kondo and Aglietti observed improved levels of stability and function with double compared to single-bundle reconstruction [4, 115]. It is hoped that such improvements may translate into a reduction in the prevalence of osteoarthritis, but whether proposed benefits will outweigh the increased surgical complexity and trauma associated with this technique remains unclear to this day [73].

The Concept of Isometry and the Variations Thereof

In 1911 Rudolf Fick described in detail the tension pattern of the two ACL bundles, with the "upper medial bundle" being tightest in extension and the "lower lateral bundle" tightest in flexion [58]. His discovery that some ACL fibres are tensioned at all times was later misconstrued to support the idea of graft isometry.

The functional complexity of the motion controlled by the cruciate ligaments indicated that a ligament could not be placed at liberty within the joint. Alfred Menschik of Vienna used Zuppinger's concept of a "four-bar linkage" to develop a mechanical system based on mathematical principles in which he tried to explain that the spatial arrangement between ACL to PCL represents an inextricable relationship which works in a kind of "stepless transmission" [153, 239]. This created the biomechanical basis of graft isometry, a concept centred on the notion that the ideal ACL graft is isometric, either in parts or in the mechanical summation of its parts, thus showing little or no change in distance of linear separation during flexion and extension [35, 120, 171]. Isometric placement of the ACL inferred that a full range of knee motion should be achievable without causing irrevocable ligament elongation.

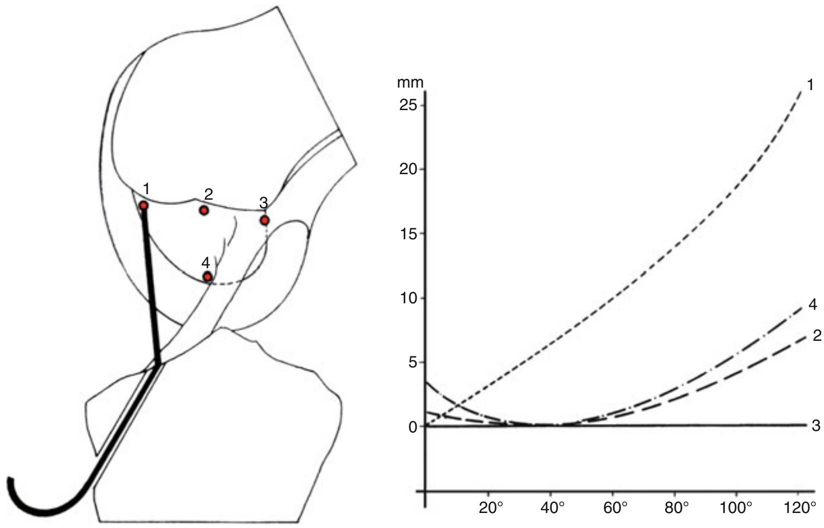


Fig. 21 Experimental study on the definition of isometric attachment points of the ACL by Artmann and Wirth in 1974. Changes in distance between tibial attachment and various points on the lateral wall of the intercondylar notch (*left*) are demonstrated on the *right* (With kind permission of Springer Science, Berlin [9])

Reproducing the ACL bundles and their tension pattern with a single tubular graft composed of parallel fibers posed difficulties, and surgeons were generally unsure where to best place tibial and femoral tunnels within the ligament's functionally important fan-shaped footprints. DJ Cowan of London believed that "from the multiplicity of its actions it would be difficult to produce a new ligament of the complexity of the normal anatomical arrangement of the anterior cruciate ligament" [35]. Surgical orientation was usually accomplished through bony landmarks like the lateral intercondylar ridge located immediately anterior to the femoral attachment of the ACL. It was described as the "resident's ridge" by Clancy since it is commonly mistaken for the "over-the-top" position by inexperienced surgeon in training [65, 104].

In an experimental study performed in 1974, Artmann and Wirth were able to define isometric points within the ACL origins (Fig. 21) [9]. This required the femoral tunnel to be placed within the posterosuperior portion of the anatomic footprint, close to the "over-the-top" position, while location of the tibial tunnel appeared far less critical. Based on these results, Artmann und Wirth concluded that reconstruction of the ACL should aim to replace the anteromedial bundle as it is the more isometric of the two, a finding later confirmed by other investigators [152, 171, 180].

The surgical precision required to achieve these goals demanded better instrumentation. The first specific femoral drill guide was presented by Palmer in 1938, incorporating the basic features of most modern aiming devices [55, 83, 120, 177]. In 1987 Dale Daniel (1939–1995) and Richard Watkins of San Diego developed the tension Isometer® to define points of equidistance for isometric graft placement [40]. The clinical application of isometers was at best difficult and hence became superseded by offset guides providing more reliable and reproducible tunnel positioning [60, 197].

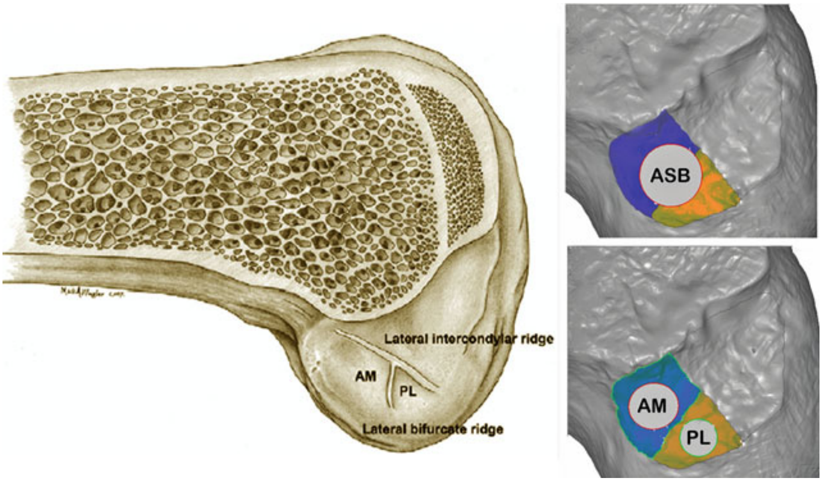


Fig. 22 "Anatomic double-bundle concept" according to Fu and associates based on the anatomic insertion sites of the native ACL (*left*). Three-dimensional laser scan image indicating best graft placement for anatomic single-bundle (*ASB*) or double-bundle (AM & PL) reconstruction (With kind permission of Elsevier, Philadelphia; laser images adapted from and courtesy of Carola van Eck, Pittsburgh [65])

Pierre Chambat of Lyon observed that the majority of ACL fibers are positioned posterior to their isometric points. He believed that these fibers should not be ignored as they display "favourable non-isometry," contributing to the rotational stability of the knee near extension [28]. In 1988 Friederich and O'Brien conceived the notion of "functional isometry" in recognition that "only a limited number of fibres can directly interconnect isometric points" [63]. According to Müller, these fibers are the first to become taut and "supported by [non-isometric] tissue fibres that become tense when the laws of biomechanics demand a greater fibre potential to supply the necessary mechanical strength" [163] (Müller W, 2012, personal communication). He believed isometry to be "too narrow and rigid a concept," and conceived the paradigm of "anatometry," thereby defining a workable compromise between isometric and anatomic graft placement.

By the 1990s, the wider surgical community began to appreciate that the concept of graft isometry was an elusive one, which if achievable, would create unphysiological conditions [6, 63, 119]. Traditional reconstruction techniques were unable to fully restore normal knee kinematics and were hence thought to be responsible for the relatively disappointing clinical results and the high prevalence of arthritis long term [109, 136, 213, 234]. Wirth and Artmann, who had assessed knee joint kinematics before and after ACL reconstruction in 1973, stressed the importance to precisely reproduce the anatomic origin and insertion when placing the graft if abnormal rolling and gliding motions are to be avoided [228].

Not surprisingly, the beginning of the twenty-first century has seen the reemergence of the philosophy of anatomic ACL reconstruction, aiming at the functional restoration of native ACL dimensions, fiber arrangements, and insertion sites, a concept Palmer, Ludloff, Wirth and Hughston had already

Fig. 23 First arthroscopically assisted ACL reconstruction performed by David Dandy in 1980 using a composite carbon fiber graft (Photographs courtesy of David Dandy, Cambridge)

championed in previous decades. Kazunori Yasuda and Freddie Fu recently created the "anatomic double bundle concept" which seeks replication of the native ACL anatomy by placing tunnels at the center of the ligament's native femoral and tibial insertion sites, independent of whether single or double-bundle reconstruction techniques are used (Fig. 22) [235, 236, 238]. Biomechanically, anatomic single- or double-bundle graft placement promises to provide improved rotational control when compared with nonanatomic reconstruction techniques [116].

Arthroscopically Assisted ACL Reconstruction: This Final Frontier

Prior to the advent of operative arthroscopy, Frederick Tees of Montreal (1940) and Willy König of Hannover (1950) had already performed transarticular reconstruction of the ACL without opening of the joint, either by relying on anatomical landmarks or on radiographic control for tunnel positioning [117, 214]. Arthroscopy to assess for internal knee derangements was first suggested by Danish clinician Severin Nordentoft in 1912 and Swiss surgeon Bircher in 1922 but did not gain wider appeal until the pioneering work of Robert Jackson of Toronto (1932–2010) [99]. On the 24th of April 1980, David Dandy performed the first arthroscopically assisted ACL reconstruction at Newmarket General Hospital in England using a carbon fiber prosthesis augmented with a MacIntosh tenodesis (Fig. 23) [38] (Dandy DJ, 2011, personal communication). Although Dandy reported good results with this technique at 1 year, he believed this to be due to the extra-articular reconstruction rather than the carbon fiber ACL graft, which in his experience often disintegrated over time (Dandy DJ, 2011, personal communication).

In those early days, arthroscopic ACL reconstruction was still relatively complex and challenging as neither sophisticated instrumentation nor camera and monitor units were available. Initially, the procedure required a two-incision technique, one to facilitate graft harvest and tibial tunnel preparation and another to position a "rear-entry-guide" for "out-side-in" drilling of the femoral tunnel [39]. The introduction of arthroscopic drill and offset guides in the early 1990s allowed for simplification of femoral tunnel preparation, making a posterolateral incision unnecessary [197]. In 1988 Friedman performed the first arthroscopically assisted reconstruction with a four-strand hamstring graft and was followed by Tom Rosenberg of Salt Lake City who, in 1994, pioneered arthroscopic double-bundle ACL reconstruction [64, 190]. By the turn of the century, the technique of arthroscopically assisted ACL reconstruction had become firmly established as the "gold-standard" and a procedure within the realm of most surgeons' ability [78].

Graft Fixation: The Weakest Link

Traditionally, most grafts were either sutured against periosteum or secured with transosseous wires or suture material. Hey Groves used ivory nails to secure his fascia grafts against the tibial bone in the 1920s and 1930s (Fig. 7) [85, 86]. Wittek first employed intra-articular screws for graft fixation in 1927, while Simon reported using a nickel nail in 1931 [202, 230]. Fred Albee of New York (1876–1945) believed that graft fixation was the main mode of failure and in 1943 suggested the use of bone wedges to create an interference fit between tendon and tunnel [5]. Augustine promoted aluminum "boat nails" for extra-articular fixation of hamstrings in the late 1950s [11]. In 1966 Brückner reported the use of patellar tendon graft harvested with a triangular bone block from the tuberosity which he press fitted into the tibial tunnel thereby avoiding additional fixation material [24]. Hans Pässler of Heidelberg later adopted a fixation-free technique for soft tissue grafts by knotting the ends [176]. Jones secured the proximal bone block of his patellar tendon graft by means of a Kirschner wire "drilled across the femoral tunnel and into the opposite femoral condyle" [107]. This technique received wider attention with the Transfix® device for the suspension of hamstrings designed by Donald Grafton and Eugene Wolf in 1998 [77].

Aperture fixation with AO screws was originally described by Kenneth Lambert of Jackson/WY in 1983. With this technique he was able to achieve an "interference fit, whereby it [the screw] actually engages both the side of the bone block and the screw hole in a more or less cogwheel fashion" [121]. Like Albee before him, Masahiro Kurosaka believed that the "mechanically weak link of the reconstructed graft is located at the fixation site." He designed the first designated "interference screw" in 1987, which gave rise to the development of a plethora of ligament fixation devices [118, 146]. The 1990s also saw the introduction of biodegradable implants [209]. In 1992 Leo Pinzcewski and Gregory Roger of Sydney introduced the RCI® screw, the first "soft" threaded interference screw, suitable for the use of both soft tissue and bone-tendon graft fixation [185]. In 1994 Ben Graf, Tom Rosenberg and Joseph Sklar introduced the Endobutton®, a universal ligament suspension device that anchors itself against the femoral cortex at the tunnel exit [76]. Despite concerns about disadvantages of suspensory compared to interference/aperture fixation, clinical results between the various fixation methods have not differed significantly [146].

Epilogue

The number of injuries to the ACL has risen exponentially, since the days when only a fall from a horse could send its rider into early retirement due to an unstable knee. High-speed travel and an ever increasing enthusiasm for sports are to be blamed for this development. From a healthy skepticism toward surgery in the nineteenth century to an ever increasing plethora of operative solutions, simplified by a myriad of surgical aids and implements, we have come a long way. The treatment of the ACL-deficient knee has seen many changes since Adams described the first clinical case of an ACL rupture 175 years ago. Arthroscopic ACL reconstruction has since become a standard procedure for almost every knee surgeon, but are we in danger of becoming complacent? It is essential that all of us continually review our own results and carefully assess the values and merits of new techniques and technologies in order to offer the best treatment to our patients. In all of this, we should not forget the old truism in Jack Hughston's advice that "no knee is so bad that it cannot be made worse by surgery."

It is intriguing to review the pioneering work of Hey Groves, Smith, and Palmer as it anticipated many of the modern ideas on graft obliquity and anatomic reconstruction. Many advancing ideas have been dismissed, or forgotten only to be rediscovered, often without extending credit to the original inventors. We should hence not lose sight of the achievements of our surgical forefathers and be encouraged to become familiarized with the historical developments as it may assist us in the pursuit of, what Ivar Palmer called, "the restoration of the physiological joint".

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Evidence-Based Medicine: How Can We Use It to Guide Our Practice?

Why Is Evidence-Based Medicine Needed?

In the last decades, the production of scientific biomedical articles has grown exponentially. Nowadays, we have around 25,000 medical journals that publish more than 2,000,000 articles per year, around 2,000 per day. However, their methodological quality is highly variable, generating contradictory results.

The practice of medicine has always been based on clinical experience and reasoning based on physiopathologic knowledge. To obtain information regarding the best treatment, the doctor referred to the opinion of experts, to his/her own experience, or to physiopathological arguments about the disease. At the beginning of the 1990s, a group of epidemiologists and clinicians from the McMaster University in Canada headed by G. Guyatt admitted the limitations of this type of practice and established the postulates of evidence-based medical practice (EBM) [6]: (1) Clinical experience and the development of a clinical instinct are necessary as well as crucial for a competent doctor, but are not enough. We have to exercise caution when attributing value to information that has not been obtained and evaluated in a systematic fashion because there is a high risk it can lead us to error, (2) physiopathological mechanism knowledge is necessary but not sufficient to guide in clinical practice, and (3) understanding certain principles, methods, and rules of scientific verification is necessary to correctly interpret the literature about causality, diagnostic tests, treatment strategies, and prognosis.

EBM is a strategy which implies that the decisions about patient care are made, adjusting all the valid and relevant information, integrating it with clinical experience and with the patient's preferences. In recent years, much has been said about the "paradigm change" that appearance of EBM has meant. EBM is only the integration of the scientific method to obtain the best clinical information to deal with a specific clinical case. EBM is a self-directed process based on problem-based learning. To help the physician in this process, EBM established four steps: (1) Convert our information needs in questions to be answered, (2) find the best evidence about the specific

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Table 1 Make a list with the most important terms that describe the problem, interventions, and outcomes

P	I	C	O
Problem of interest	Intervention which is considered	Comparison with placebo or other intervention	Outcome of clinical interest
ACL repair OR ACL Arthroscopy OR ACL reconstruction	Low weight heparin OR Enoxiparin OR Dalteparin OR Nadroparin	Placebo	Deep vein thrombosis OR Pulmonary embolism

Connect the synonyms with OR and the different components of the question with AND. A good search should not have more than three connectors, and sometimes the C box may be left empty

question, (3) evaluate critically the validity and usefulness of that evidence, and (4) apply the obtained result in our clinical practice.

In this chapter, we offer a short summary of the steps that can help the readers understand and integrate the contents of this book in their ordinary clinical practice.

How to Ask Effective Questions?

In our daily clinical practice, we frequently have doubts about how to diagnose or to treat a specific patient. The first step to solve the uncertainty that a case can generate is to correctly identify the problem we are trying to solve. The following search for information will be much easier if we learn an effective strategy to identify the problem. We do this by asking ourselves a correct clinical question that can be answered.

Clinical questions can be divided into general and specific ones. General questions normally have an initial interrogative adverb: what, how, when, and where? They are the most frequent questions when we begin our professional practice. When we become more expert, our information needs are more specific, and we tend to ask more specific questions than general ones. However, the need for general questions never disappears in spite of our growing clinical experience on a subject.

Specific questions have a double advantage over general ones. On one hand, they assist the mental process of delimiting the clinical problem, and on the other hand, are more susceptible to an efficient answer search in different databases and evidence-based resources.

When facing a clinical problem, it is very useful to ask a specific question with four components summarized in the acronym **PICO** (**P**roblem, **I**ntervention, **C**omparison, and **O**utcome) (Table 1). Elaborating a question with this system requires thinking and understanding the thought process the experienced doctor implicitly does every day.

- *Problem.* The problem to be solved has to be defined in a precise manner, but only using the information relevant to define patterns. Even if each patient is unique, diseases and, therefore, patients can be classified in patterns. Common sense, previous knowledge, and experience will guide us in describing the problem and highlighting its most relevant aspects.

- *Intervention*. The treatment, diagnostic test, or risk factor that we are considering must be carefully defined according to the type of information we need.
- *Comparison*. In the information search about a treatment, we must compare the intervention with a placebo or with another standard treatment that is common for that condition. If it is a question about a diagnosis, the comparison must be with another test that can be considered a "gold standard."
- *Outcome*. Here we will state clearly the relevant variable that we want to obtain or modify. We have to observe the final variables that are clinically important.

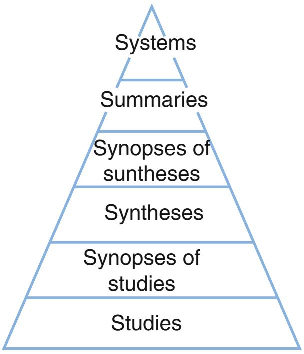
The specific questions usually come up when we are with a particular patient and are mostly to be questions about diagnosis or treatment. The PICO format can also be used to ask questions about prognosis, etiology, prevention, and financial analyses.

How and Where to Search for the Evidence?

Every day, new knowledge in medicine appears and requires a daily effort to keep updated. This knowledge is found in articles published in medical journals and constitutes the foundation on which the medical knowledge is built. The amount of medical articles in Medline is 12 million from 1966 to 2012 and growing. Approximately 8,000 every week and 400,000 articles every year are published in 5,000 biomedical journals. Obviously, it is impossible to stay updated reading all the articles, even only of one specialty. However, it is traditionally the first information search, and it can sometimes be difficult and extenuating because of its immense size and because most of what is published has a poor methodological quality. The search system PubMed is a project developed by the National Center for Biotechnology Information (NCBI) and the National Library of Medicine (NLM). We will briefly describe a simple search strategy to help us find the information we need.

Search in PubMed. Once the clinical question in the PICO format is established, we must find the keywords to define each of the elements of the question. It is useful to look for synonyms using a thesaurus MeSH. We write the keywords and synonyms separated by the boolean connector OR for each of the components in the PICO question. We perform an independent search for each of the components of the question, and the results are grouped in a new search using the boolean connector AND. In most cases, it will give a good number of citations that can be easily reviewed in order to find the best ones to answer our question. If the number of results is too high, we can limit the search extension using limits by study type or other available filters.

Table 2 The 6S model [5]



Systems: Computerized decision support

Summaries: Clinical Practice Guidelines, Evidence based textbooks

Synopses of Syntheses: Abstracts of Systematic Reviews

Syntheses: Systematic Reviews

Synopses: Abstract of highquality studies

Studies: Original Journal articles

Despite Medline's popularity to find specific medical information, it is not very useful because of the time it consumes and the skills it requires regarding critical reading to distinguish between what has value and what does not have. To facilitate this task, several pre-appraised resource databases have appeared, selecting only those studies with high methodological quality. They are also frequently updated, so the evidence provided is perfectly valid. To establish a hierarchy of these sources, Haynes developed the "4S" model that has evolved to the "6S" model [5, 10] (Table 2). In the ground floor, we can find the original *studies* and their *synopses* (short descriptions of some individual studies, such as those found in evidence-based journals). In next levels, there are *syntheses* (systematic reviews like the Cochrane's reviews) and the *summaries of syntheses*. Above them, *summaries* that integrate the best available evidence of previous studies to develop clinical practice guidelines (e.g., Clinical Evidence, National Guidelines Clearinghouse) and, at the summit of the model, the *systems*, in which patient´s individual characteristics are automatically matched with the best updated evidence, the clinician may thus manage it by using informatics decision support systems. When using model 6S, the search begins at the highest possible level. The use of pre-appraised resources increases the probability of searching through updated, high quality, and efficient evidence.

Types of Studies

Case series. The evolution of a group of patients is shown after a certain treatment without comparing it to a control group. This type of design is more likely to have a bias that tends to magnify the effect of the intervention. It can be useful for the initial evaluation of a new treatment in order to verify its safety.

Cross-sectional study. It measures the prevalence of risk factors or outcomes in a group of patients at a point in time. This design can only demonstrate association but not causality. However, a cross-sectional study is cheap and easy to perform and is often the initial approach in a clinical investigation. For example, a study that evaluates patients with anterior knee pain after an ACL reconstruction, with the intention of identifying the risk factors involved in the development of this complication.

Case–control study. The groups to be compared are established based on the final result, meaning the disease or symptom is present or not. Once the effect has been observed, the presence of risk factors or intervention factors is analyzed for each group. This type of design is the most common in the medical literature, although it is subject to bias that tends to magnify the effect of the intervention or the risk factor. However, it has the advantage of being cheap and not too time-consuming. It can also analyze multiple risk factors in one condition. For example, a study performed in a sample of patients with ACL reconstruction that compares those who have anterior knee pain with those who do not retrospectively analyzes the risk factors in each group (graft, lack of extension, etc.).

Cohort study. The groups to be compared are identified depending on the presence of a risk factor or if they have undergone an intervention. At this moment in time, the final result is unknown, and both groups are observed for a period of time to learn about the phenomenon that we are studying. This type of study is normally prospective, but it is possible to have a retrospective cohort if the final result has been reached, and it has been researched by analyzing medical files of samples where the event has already occurred. Cohort studies are superior to case–control studies since they are less likely to be biased. However, they are more expensive to perform, and some cases may be lost during follow-up. For example, a study that compares knee rotational stability in a group of patients with single-bundle ACL graft reconstruction with a group with double-bundle ACL reconstruction without a randomized allocation.

Randomized clinical trial. It is an experiment where subjects are assigned to one group or another randomly. In one group, the therapeutic intervention is performed, and the other group receives placebo or the usual treatment. To assign randomly allows each of the groups to be similar, the only difference being receiving or not receiving the studied variable. It is the ideal design type to learn about the effects of the treatment because it is more strict and less likely to be biased. It is considered the gold standard to learn about the effect of a therapeutic intervention. However, it is expensive and difficult to perform. Sometimes it is difficult to perform because of ethical limitations, especially regarding surgical interventions. The conclusions of a randomized clinical trial are very reliable (good internal validity), but sometimes their generalization to other patients is difficult (external validity) because they have strict inclusion criteria and because of how rigid the intervention is. For example, a group of patients with an ACL injury is randomized to receive either a single-bundle ACL reconstruction or a double-bundle ACL reconstruction.

Systematic review. It is a study where all the previous studies about a specific medical intervention have been systematically gathered. The search and gathering of the studies must follow a very strict methodology so that no study is missed. The studies included must follow certain quality criteria previously stated by the researchers. A *meta-analysis* is a statistical analysis that combines and integrates the results of several independent studies from a systematic review, therefore obtaining a large sample of patients. The quality of a systematic review and its meta-analysis depends on the type of studies included. When these studies are randomized clinical trials, the conclusions of the meta-analyses are of the highest level of evidence.

Level of Evidence

The goal of medical research is to learn about the truth; therefore, we must aim for precise and valid measurements. The elements that threaten our measurements are the random error and the systematic error. *Random error* is inevitable and part of the nature of any human activity because of its variability. Reducing random error is known as accuracy and can be achieved by increasing the sample studied. *Systematic error* is produced directly by the study's own characteristics. The absence of a systematic error is known as *validity*. The certainty of the results is known as *internal validity*. *External validity* is when the results can be generalized and applied to other patients outside the study. Obviously, internal validity is necessary for a study to have external validity. Internal validity of a medical study is threatened by systematic error that is called *bias*. They cause an incorrect estimate of the associations between exposure and disease. The most important biases are selection bias, information bias, and those caused by confusion factors. *Selection bias* is a systematic error caused during the recruitment and follow-up of the studied subjects. It is a frequent problem in case–control studies and retrospective cohort studies where the final event of interest has already occurred. The selection of the control group and the experimental group can be influenced by external noncontrolled factors that can make both groups noncomparable. *Randomizing* the selection for both groups is the technique used to minimize this type of bias. *Information bias* is a systematic error in the measurement of the studied variables. This distortion in the measurement can cause an erroneous classification of the subject at the beginning of the study or during follow-up because of an error in the measurement of the results. *Confounding factor bias* happens when an association between a variable and an event is observed in a study, and this association is not real; it is caused by an unevaluated third factor, which acts as a confounding factor. All studies can be influenced by confusing factors, and randomizing tends to reduce this confusion effect by distributing any possible confounding factors equally in both groups. Information and selection biases cannot be overcome by data analyses; however, a confounding bias can be controlled by using regression techniques. Depending on the presence of more or less systematic errors in the design study, a level of evidence has been established. There are different classifications developed by different institutions, all very similar (Table 3).

How to Critically Evaluate Evidence?

The third step in the practice of EBM is critically evaluating the articles we have found, with which we want to answer a specific clinical question. We should analyze three aspects of the study: its validity, its importance, and its applicability. The *validity* of the study refers to the trustworthiness or how close to the truth the results are. It will depend on the type of study and how it was developed. The *importance* refers to the magnitude of the findings and if these are important in the course of the disease. There are different ways to quantify these changes that can help or confuse us when making a decision.

Table 3 Levels of evidence and grades of recommendation

	Treatment	Prognosis	Diagnosis
Level I	High-quality randomized controlled trial	High-quality inception cohort	High quality prospective cohort with adequate gold standard
	Systematic review of Level-I randomized controlled trials	Systematic review of Level-I studies	Systematic review 2 of Level-I studies
Level II	Lesser-quality randomized controlled trial	Retrospective cohort	Retrospective cohort with adequate gold standard
	Prospective cohort study	Untreated controls from a randomized controlled trial	Systematic review of Level-II studies
	Systematic review of Level-II studies	Systematic review of Level-II studies	
	Outcome research		
Level III	Case–control study		Non consecutive cohort (without proper "gold" standard)
	Systematic review of Level-III studies		Systematic review 2 of Level-III studies
Level IV	Case series	Case series	Case–control study
			Poor reference standard
Level V	Expert opinion based on physiology, bench research or "first principles"	Expert opinion based on physiology, bench research or "first principles"	Expert opinion based on physiology, bench research or "first principles"

Grade A	Consistent level 1 studies	Body of evidence can be trusted to guide practice
Grade B	Consistent level 2 or 3 studies *or* extrapolations from Level 1 studies	Body of evidence can be trusted to guide practice in most situations
Grade C	Level 4 studies *or* extrapolations from level 2 or 3 studies	There is some support for recommendation but care should be taken in its application
Grade D	Level 5 evidence *or* troublingly inconsistent or inconclusive studies of any level	Evidence is weak and recommendation must be applied with caution

Adapted from Oxford Centre for Evidence-Based Medicine (www.CEBM.net)

Lastly, *applicability* refers to the capacity of using the results for our patients after establishing clinically relevant benefits as well as risks. For this task, different strategies have been designed to help us to critically evaluate articles [16] (Table 4).

Evaluating Validity of an Article About a Treatment

Has the Question of the Study Been Clearly Defined?

First of all, we must identify the goal of the study. Besides making sure it will respond to our specific information needs, it will indicate the validity of the obtained results. If a lot of data are collected with no specific criteria, we may

Table 4 Checklist to evaluate the validity, importance, and applicability of a trial

Appraising validity of the study
Primary criteria
Was the objective of the study clearly defined?
Was the assignment of patients to treatment randomized?
Was the allocation of patients concealed?
Was the followup of patients complete?
Were all patients analyzed in the groups to which they were initially randomized?
Secondary criteria
Were patients, clinicians and reviewers kept blind to treatment?
Were the groups similar at the beginning of the study?
Apart of the intervention, were the groups treated equally?
Appraising importance of the study
What is the magnitude of the treatment effect?
How precise was the estimate of the treatment effect?
Appraising appliability of the study
Are the patients covered by the trial similar enough to your population?
Were all clinically important outcomes considered?
Are the benefits worth the harms and costs?

Adapted from www.caspinternational.org)

find significant differences in some of them which do not depend on the intervention but on the sample variability itself. Also on occasion, the authors find that their study does not provide positive results when all the subjects in the sample are analyzed. They do however find small differences analyzing smaller subgroups of the sample without having calculated the strength of the study for these smaller groups. This phenomenon should make us question the validity of the study because the result variable itself has variability within a certain range under the law of chance if it is not correctly controlled.

Have the Compared Groups Been Formed Randomly?

Randomizing is the best process to make both compared groups more similar. This way, any differences observed in the results will be because of the intervention, and not because of the presence of other prognostic factors (known or unknown). As we mentioned previously, the results of a study are compromised by confounding factors that frequently cannot be identified. Random assignment, for example, by flipping a coin, to form an intervention group and a control group lets chance equally balance the existence of prognostic factors in both groups. If one prognostic factor was predominant in one of the groups (e.g., the seriousness of a disease), the effects of treatment could be exaggerated, canceled, or even counteract the real effects of the treatment. Generally in clinical studies, when randomizing is not used in the compared groups, the effects of the intervention tend to be magnified [8, 9, 17].

Frequently, studies select patients in succession as they come to the office. If we send the first patient to a group (where the coin indicated) and the second patient to the other group, and so on, we will obtain two groups with the same number of subjects, and we will mistakenly think we are randomizing well. In this case, researchers know to which group each patient will be assigned; this causes bias in patient selection. This selection bias is prevented by *allocation concealment*.

We should pay attention to some details that can help us make sure that the allocation is correct. Initially we would think that a random allocation could distribute all patients evenly in both groups; however, this does not always happen because of the laws of chance. If we flip a coin 50 times, the odds of getting heads or tails 25 times each is only 11 %. If we flip it 60 times, the odds of getting 30 and 30 is 10.3 %, for 80 times it would be 8.9 %. It is amazing to find in the literature so many studies with small samples (under 100 patients) in which simple random allocation has assigned the same number of patients in each group. This should make us be suspicious of improper allocation concealment. Those randomized trials that do not preserve allocation concealment tend to overestimate the treatment effect up to 40 % compared to those with adequate randomization [17]. Therefore, if we see a very large effect in a RCT without allocation concealment, we can suspect that the results are reflecting a biased allocation rather than the real treatment effect.

Complete Follow-Up and Intention to Treat Analysis

All the studies have losses to a variable degree. A *sensitivity analysis* is useful to find out if these losses invalidate the result of the study. This consists of assuming the losses in the treated group have not gone well and losses in the control group have gone well. If this does not change the result, those losses can be accepted.

On other occasions, some patients assigned to one group do not receive the allotted treatment for different reasons (the patients withdraw, it is not possible to apply the treatment, or he/she changes to the control group). Even if it seems to the contrary, patients should be evaluated depending on what arm they have been assigned, and not on the real treatment received. This is known as the *intention to treat analysis*; it causes less bias than an analysis by treated cases, which tends to magnify the effect of the intervention [19].

Has the Blind Design Been Followed with Regard to Patients, Clinicians, and Researchers?

Ideally, patients, clinicians, and researchers should not know what group each patient belongs to. The fact that each one of them knows what treatment was received can alter the perception of the obtained result; this is information bias. The impact of the blinding on the validity of a study is less than what randomization has, but it can be important if the final result measures subjective criteria like pain and disability. Non-blind studies tend to magnify the effect of the intervention in almost a third of this effect, both in general medical studies [8, 17] and in orthopedic surgery [15].

The technique with which the received treatment is hidden is called *masking*, and therefore, the group the subject belongs to cannot be identified. On certain occasions, it is not possible to mask a treatment, especially in studies that include surgical procedures or physical therapy, because of technical and ethical reasons. Single blind is when one of the participants, patients, or investigators does not know the treatment received. Double blind refers to the masking of both patients and clinicians, and triple blind when the evaluator is also blinded, as well as the patients and the clinicians who perform the treatment.

For the patient, this masking of the received treatment helps reduce the effect of placebo when the results are evaluated. The placebo effect is caused by the patient expectation or because of suggestion. All the medical interventions (pharmacological, surgical, or physical therapy) can have a placebo effect, but this effect is particularly strong with surgical procedures.

Regarding researchers, the masking also enables both groups to receive the same treatment throughout the entire study because the clinicians in charge cannot tell what group the patient belongs to. Researchers might feel tempted to closely follow the patients who receive the treatment researched, for example, closely following side effects or a special interest in a positive result.

In the trials about surgical techniques, on some occasions, the patient can be blinded. However, it is obviously impossible to blind the surgeon; in these cases, it is recommendable that the researcher be a different person [13, 14]. If a surgeon asks the patient about the result of the operation, the patient tends to say he/she is better than he/she really is because he/she wants to please his/her surgeon, plus the surgeon tends to perceive the results as better than they really are. This cognitive dissonance is another phenomenon that makes the surgeon's opinion not be very reliable [7, 11]. It is a principle established in experimental psychology that says that if one states firmly that something is true (e.g., a treatment that you have always performed), then cognitive shortcuts take place to evaluate the experience with ones beliefs. If you use one particular operating procedure, you will end up believing that what you do every day really works.

In the orthopedic literature, correct masking of at least one of the relevant actors (patient, clinician, or researchers) only takes place in less that half of the studies [3].

The concept of masking and allocation concealment may appear to be the same initially, but they are not. Masking refers to not knowing what group the subject belongs to once he/she has been included in that group, in order to avoid the information bias. Allocation concealment however tries to reduce selection bias, and it can always be performed, while masking is not always possible.

Evaluating the Importance of the Results

Once we have decided that the study is trustworthy, we can determine if it is worthwhile to continue reading to know the importance of the results. The importance is determined by the *magnitude* and by the *accuracy* of the results.

What Is the Magnitude of the Results?

Sometimes results are shown in continuous variables like the degree of pain or the degree of disability measured by a scale. The comparison is showed as mean differences. However, clinical studies usually show their results as binary variables (healing or not, infection or not, union or pseudoarthrosis, tumor recurrence or not) and can be presented in different ways.

Let us see an example: You are going to operate on a 32-year-old male with a closed patella fracture. You are worried about the infection risk, and you want to reduce the chance of infection by giving him an antibiotic. You find an article that evaluated the effectiveness of antibiotic prophylaxis with ceftriaxone in the surgical treatment of lower limb closed fractures [2]. The study seems valid because it is a double-blind randomized clinical trial in a large sample (2,195 patients: 1,105 ceftriaxone and 1,090 placebo), followed for 120 days, with a small amount of withdrawals and intention to treat analysis. After follow-up, 36 patients (3.6 %) in the ceftriaxone group had a superficial or deep infection compared with 79 patients (8.3 %) in the control group ($p<0.001$).

- *Relative risk (RR)* is the quotient between the risk in the treated group and the risk in the control group. In our example, the RR would be 3.6 %/8.3 % = 0.47, meaning the risk of infection is reduced in those who receive the antibiotic compared with those who receive placebo because the quotient is under 1. The relative risk can be more intuitively seen using the quotient between the larger and smaller RR, 8.3 %/3.6 % = 2.3. The risk without antibiotic is 2.3 times higher than with it.
- *Absolute risk reduction (ARR)* is the simple difference between the risk in the control group and in the treated group. In our example, 8.3 % – 3,6 % = 4,7 % or 0.047. Meaning, out of 100 patients with treatment, almost five infections will be prevented. ARR gives smaller figures, which is why it is less used since it gives clinicians the impression of smaller effect.
- *Relative risk reduction (RRR)* is the quotient between the absolute risk reduction (risk without treatment – risk with treatment) and risk without treatment. In our example, RRR is 4.7 %/8.3 % = 0.57 or 57 %, meaning that an absolute risk reduction of 4.7 % represents a reduction of 57 % with regard to not receiving treatment. The RRR is the most normal way of presenting results because the figures are high and it gives results in relative terms. By doing this, we lose the reference of the base risk without treatment which can lead us to overestimating the real clinical impact.
- *Number needed to treat (NNT)* is the number of patients who should receive the treatment so that one of them will obtain a benefit (or prevent an adverse event). It is calculated as the inverse of the ARR. In our example, NNT is 1/0.047 = 21. We need to treat 21 patients in order to prevent infection in one of them. The lower the NNT value is, the bigger the treatment effect is. This way of expressing the magnitude of the treatment's effect is more useful for the clinician because it enables him/her to compare the magnitude of the beneficial effect with its adverse effects.

Most of the studies express results in relative reduction risk because they give the impression of a bigger effect, and naturally, this is the way the pharmaceutical industry presents their results in order to impress the doctors. However, RRR cannot differentiate the effects of the treatment when it is calculated in patients with different prevalence of the adverse outcome. Let us suppose that ceftriaxone also produces a RRR of 57 % in infections in arthroscopic surgery. The risk of infection in knee arthroscopy is very low, where a study found three infections in 2,261 arthroscopies without antibiotic [1]; therefore, 3/2,261 = 0.0014 or 0.14 %. We can calculate its ARR by knowing the RRR and the risk without treatment (RRR = ARR/risk without treatment). Therefore, 0.57 = ARR/0.0014 and ARR = 0.57 × 0.0014 = 0.0008. Now we can calculate NNT = 1/0.0008 = 1,250. So we can see that although the RRR is 57 %, we have to treat 1,250 patients in order to avoid one of them being infected. The figure of NNT gives a better picture of the real impact of a treatment in clinical practice and may also help to evaluate the benefits and harms by quantifying them. It would be preferable for the studies to present their dichotomic results in NNT or at least show the data that will allow us to calculate it.

How Accurate Are the Results?

Clinical studies collect results from a sample that represents part of the patients with that condition. The results are close to the "real value" that would be obtained if all the population had been studied. In our previous example, each estimation (RRR, ARR, NNT) is close to the "real value"; however, if we repeated this study with other patients, we would get similar results, but not identical. We would prefer to know the whole population's "real value" than the mean value obtained. Since studying the whole population is not possible, we can try to find in what interval this "real value" is with a certain probability. The *confidence interval (CI)* is a range or interval in which the population's "real value" will be with a generally established probability of 95 %. This means that if we repeat the study 100 times, the result would be within the CI range 95 times. The CI gives more information than the *p value* because it evaluates the accuracy with which the result has been estimated. The narrower the CI is, the more accurate it is. If it is large, it provides little information since the "real value" can be situated at any point. The $p < 0.05$ corresponds with a CI range in which the 0 is not included (when evaluating the differences in the mean of the absolute risks or NNT since 0 means there are no differences in the comparison of values). When evaluating relative risks, if the differences are significant, the CI will not include the value 1 (because 1 means that there is no increased or reduced risk).

The statistic significance (represented by the p value) tells us if we can be sure (normally with a probability of 95 %) that both compared groups are different. It tells us the probability that the obtained result is not due to chance. But it does not inform us about the magnitude of the differences between both groups. As clinicians what we need is to reduce our uncertainty by knowing if the effect of the intervention is relevant for our patient, and here is where the CI can help. For example, in the study we reviewed, we saw that the preoperative antibiotic significantly reduced the infection rate with a RRR of 57 % with a CI between 36 and 70 % and a NNT of 21 with a CI between 15 and 39. We can see that the range of the CIs do not include 0, and therefore, the differences are significant. We can also see that the high end of the CI of the NNT is 39 and should decide if this value is clinically relevant. If we accept it as clinically relevant, we can be sure that it will be useful to give our patients antibiotics. If we decide this high end is too high or is clinically irrelevant, the study will not help us much even if it does show significant differences.

On the contrary, a study that has given negative results (without significant differences) can also be useful if we look at its CI. For example, if for a condition in which there is no valid treatment, we find a study comparing an intervention with placebo that shows no significant differences, we could consider the IC. If the IC includes the 0 close to the lower value of the IC (for instance IC −0.5 to 25), we could decide to use that intervention because the "real value" of the intervention is within the IC.

Can the Results Be Applied to Our Patients?

Clinical trials are performed in a selected population with certain inclusion and exclusion criteria, which is why we should be cautious when generalizing the results. Clinical trials show the mean effects of the treatment in that population, but this effect can vary in other populations if the characteristics are different. We must therefore check to see if the characteristics of our patients match those of the studied population, and if they do, then we can confidently apply the results.

Sometimes our patients will show signs that can make us suspect a higher or lower risk than the mean risks of the patients included in the study. Even so, the study can still be useful. An important advantage of the NNT is that it enables us to estimate the benefit of a treatment in a particular individual patient. We should remember that the relative risk reduction (RRR) = absolute risk reduction (ARR)/risk in the control group (RCG), so the ARR = RRR × RCG. Since NNT = 1/ARR, we can replace NNT = 1/RRR × RCG. In a study, the RCG is the patient expected event rate (PEER). If our patient is like the average patient in the study, his/her PEER will be the same as the RCG of the study, and we can make calculations for our patient. For example, in the antibiotic prophylaxis study, the RCG = 0.083, and when using the antibiotic, we obtained a RRR of 0.57. Our patient with the patella fracture seems to have the same infection risk as the mean risk of the patients in the study; therefore, NNT = 1/RRR × PEER = 1/0,57 × 0.083 = 21, which is the same NNT value as the one in the study. But if our patient shows some sign that makes us suspect he has a higher or lower base risk, we can apply the results of the study using our PEER estimate. So, if our patient had diabetes or was elderly or immunosuppressed, the infection risk would increase the PEER to let us say 0.15 (this value can be found in other studies that quantify the risk factors). This way, our patient would have an NNT = 1/RRR × PEER = 1/0.57 × 0.15 = 9, and we could observe a greater impact of the treatment in our patient because he had greater risk for infection.

Have All the Clinically Important Results Been Taken Into Account?

Statistically Significant and Clinically Relevant

An important aspect for the applicability of the published results is to consider that statistically significant is not always the same as clinical importance. The term "statistically significant" has invaded the medical literature and is perceived as a quality label for the results. A p value <0.05 indicates that the results have not been by chance. For example, a trial that compares the clinical results of ACL reconstruction using conventional single bundle or double bundle [12]. They reported significant differences ($p = 0.025$) in the Lysholm score with a better function when using double bundle (Lysholm 90.9) than when using single bundle (Lysholm 93.0). Even if the difference is significant, a 2.1 improvement in the Lysholm score does not seem too clinically important for the patient and may not compensate for the costs and associated risks. In another example a study evaluated the analgesic effect of a continuous pump of local anesthetic after shoulder arthroscopy [4]. They reported significant differences ($p = 0.003$) with less pain in those who received the infiltration with a difference of 0.6 (95 % CI 0.2, 1) in the visual analogue pain scale from 0 to 10 cm. Even if the difference is significant, a 0.6 cm improvement is pain doesn't seem too clinically relevant for the patient.

Surrogate Results and Clinically Relevant Results

In our final choice, what we really need to know is if a treatment improves those results that are important for the patients. Frequently, clinical trials have as a final variable result that we think can be relevant for the patient, but that by themselves are not. For example, a trial that compares the ACL reconstruction using anatomic double bundle with the traditional anatomic single bundle can show better rotational stability with double bundle, but something clinically important for the patient's outcome would be to reduce a future osteoarthritis. It is possible that a better control of rotational stability would have a correlation with reducing future osteoarthritis; however, through this study, we cannot know for sure if the double bundle prevents osteoarthritis of the knee in the long term. To base a decision on what is called intermediate results is the same as basing our decisions on physiopathological arguments.

Do the Benefits of the Treatment Outweigh the Costs and Possible Adverse Effects?

Lastly, the final choice has to be made, integrating the balance between benefits, risks, and costs. We have seen tools that allow us to quantify these parameters to limit uncertainty and to facilitate the choice. It is our clinical judgment and experience that each case will integrate the information from studies to offer our patients the best evidence available. Clearly, patients should actively participate in the decision-making process, taking into account their preferences and values.

Currently, cost is an important part of the medical care. Therefore, it is our responsibility to practice cost-effective medicine. However, we must note that cost-effectiveness should not be confused with cost savings. A quality cost-effectiveness analysis (CEA) should be performed under the recommendations of the Panel on Cost-effectiveness in Health and Medicine [18]. According to them, a CEA should be based on the long-term outcome of the procedure, instead of on the short-term outcome. Following our previous example of double-bundle (DB) ACL reconstruction versus single-bundle (SB) ACL reconstruction, it is clear that the DB technique significantly increases the cost of ACL reconstruction at short-term, and we could conclude that erroneously that DB is not cost-effective. In theory, the ultimately potential advantage of DB ACL reconstruction is to reduce the incidence of knee osteoarthritis at long-term, decreasing long-term health costs and increasing quality of life. However, the long-term effectiveness and outcomes of anatomic DB ACL reconstruction have not been determined to date and therefore would be inappropriate to draw conclusions about cost-effectiveness of DB ACL reconstruction.

Take Home Messages

- Evidence-based medicine is an approach in clinical decision-making that combines physicians' training and experience with the best scientific evidence available while considering the patients values and preferences.
- EBM offers a number of tools and strategies that may help clinicians find, evaluate, and apply the best research evidence for the patients' care. It is eminently practical and patient centered. The best way to learn EBM methodology is by practicing it in our daily clinical setting.

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Part III Complications After ACL Reconstruction: Can We Do Better? – Prevention and Treatment

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Part I

Current Status and Controversies in the ACL-Deficient Knee Problem

What Have We Learned from the Kaiser Permanente Anterior Cruciate Ligament Reconstruction Registry (KP ACLRR)?

1

Elizabeth W. Paxton, Maria C.S. Inacio, Gregory B. Maletis, Jamie L. Desmond, and Tadashi T. Funahashi

Contents

1.1 Background

Patient registries are defined as "organized systems that use observational study methods to collect uniform data (clinical and other) to evaluate specified outcomes for a population defined by a particular disease, condition, or exposure, and that serves one or more predetermined scientific, clinical, or policy purposes" [8]. While randomized clinical trials (RCTs) provide a high level of scientific evidence, patient registries provide a unique opportunity to study devices and outcomes in a real-world environment when RCTs are not feasible, practical, or ethical. Registries are ideal when longitudinal follow-up is necessary, when large sample sizes are required to detect rare events, and when examining outcomes in patients with various comorbidities and in different practice settings [8].

The importance of registries in implant surveillance and outcome improvement has been demonstrated by national total joint arthroplasty registries in Sweden [14], Norway [13], Finland [6], Australia [10], New Zealand [15], and England and Wales [1]. While national total joint arthroplasty registries have been in existence since the 1970s, anterior cruciate ligament reconstruction (ACLR) registries were initiated in the mid-2000s. Within Scandinavia and Finland, there are several ACLR registries [9]. These registries provide a critical role in addressing clinical questions that require large cohort studies, identifying risk factors associated with ACLR outcomes, identifying early procedure and implant

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failures, and improving treatment and ACLR outcomes through feedback to surgeons and hospitals [5].

Within the United States, ACLR treatment and outcomes have been evaluated in case series, prospective studies, and large administrative databases [4, 7, 17, 19]. Although these studies provide important information on ACLR treatment and outcomes, registries provide additional value by monitoring implants, evaluating techniques and treatment in a community-based setting, identifying prognostic factors associated with outcomes, and generating feedback to physicians and hospitals on best clinical practices.

Recognizing the benefits of ACLR registries, Kaiser Permanente (KP) developed and implemented an ACLR registry to track and monitor ACLR procedures and outcomes within our integrated health-care system. KP serves 8.9 million members in nine US states and the District of Columbia. The KP ACLRR, started in 2005, was designed to (1) monitor the safety of ACLR graft and implants, (2) define the population undergoing ACLR, (3) identify patient risk factors associated with complications and failures of this procedure, and (4) provide feedback to surgeons and hospitals on clinical best practices. This chapter highlights the methodology and key learnings from our ACLR registry.

1.2 The Kaiser Permanente Anterior Cruciate Ligament Reconstruction Registry (KP ACLRR)

The KP ACLRR was piloted in 2005 and fully implemented in 2006. The registry was developed using standardized chart documentation and by leveraging existing administrative databases and our integrated electronic health record system (EHR). Standardized forms are completed by our surgeons and staff at the point of care. These registry forms include information on the patient, surgical approach, concurrent pathology, procedures for meniscal and cartilage injury, type of graft used, and type of implant used for graft fixation. Registry forms are also supplemented with additional data from our EHR, claims, and other administrative files. Using these other data sources, complications (surgical site infections, thromboembolic events, revisions, reoperations, and contralateral knee procedures) and population attrition (death and membership termination) are closely monitored. In addition, comorbid conditions (diabetes, smoking status) and anthropometric measurements (weight, height) are obtained. All registry outcomes are validated through chart review according to specific guidelines [21] or internally developed protocols. In addition to collecting patient, implant, and surgical information, the ACLRR also obtains patient-reported outcomes using the Knee Injury and Osteoarthritis Outcome Score (KOOS). Data are collected preoperatively and at 1, 2, and 5 years postoperatively from three locations. See Fig. 1.1 for the registry structure and Fig. 1.2 for the registry form.

The KP ACLRR currently has 16,000 procedures registered with greater than 85 % participation from 42 medical centers. Over 200 surgeons voluntarily participate in the registry. The registry has been critical to our organization by identifying patients during implant recalls and notifications, assessing implant failures, identifying complications and failures, and providing feedback to our physicians. The registry has also allowed us to conduct a variety of research projects in a real-world setting.

1.3 KP ACLRR Contributions (2005–2011)

1.3.1 Assistance During Recalls and Advisories

Since its implementation, the KP ACLRR has assisted participating surgeons in rapidly identifying patients during three recalls. While none were class 1 recalls (the highest level of seriousness and urgency), there was one class 2 recall, one class 3 recall, and one company-issued recall. In 2007, the FDA issued a class 2 recall on Smith and Nephew's Calaxo Bioabsorbable Screw following reports of pain, swelling, fluid buildup,

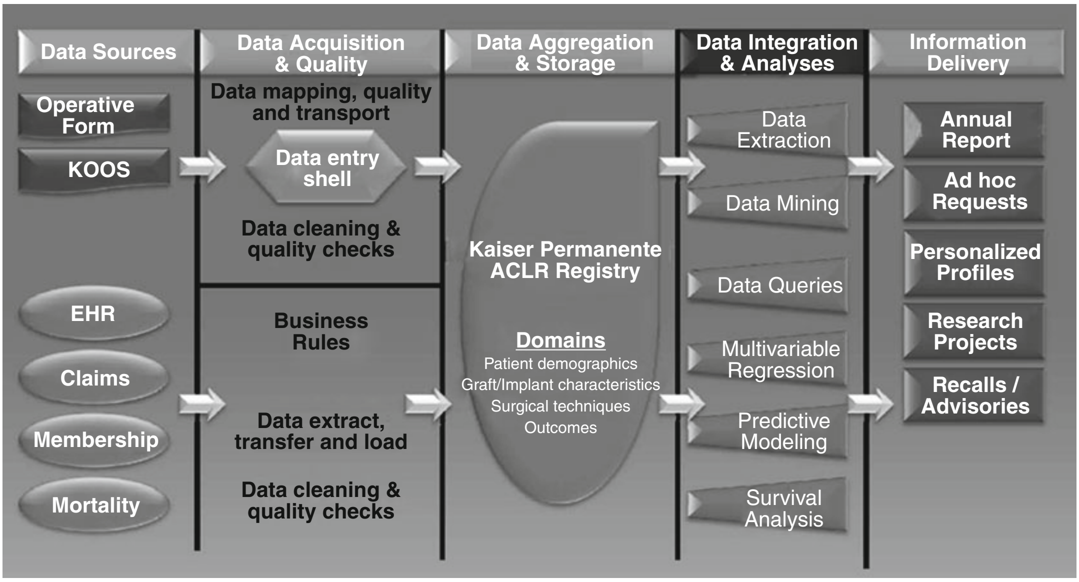

Fig. 1.1 Anterior Cruciate Ligament Reconstruction Registry structure

and screw fragmentation. In 2006, the FDA issued a class 3 recall of Muskoskeletal Transplant Foundation's human tissues after one of its facilities tested positive for Chryseobacterium meningosepticum. Finally, in 2008, Smith and Nephew issued a recall of its SoftSilk 1.5 screws due to incorrect labeling of these products. During each of these recalls, the implant tracking component of the KP ACLRR allowed for rapid identification and notification of all affected patients. By identifying, notifying, and monitoring these recalled devices, the KP ACLRR has demonstrated the importance of registries in enhancing patient safety.

1.3.2 Characterization of the Population Undergoing ACLR and Utilization Patterns

The KP ACLR registry plays an important role in characterizing patients and identifying utilization patterns. Annual reports, which include descriptive analyses of the population enrolled in the KP ACLRR, are provided to the participating surgeons and other stakeholders within KP. The registered cohort now has a median follow-up time of 1.5 years (ranging from 0 to 6 years). Six percent of the registry cases are revision ACL surgeries. With a median age of 25 years old, females make up 36 % of the primary ACLRs in our registry. The other 64 % of the registered cohort is composed of males, whose median age is 29 years old. An epidemiological study conducted by the registry found that between 2001 and 2005, an increasing incidence of ACLR in males 14–17, 26–29, and 40–49 years of age was observed. We found similar increases in females 14–21, with the most dramatic increase in the 14–17 year olds [3]. Overall, 14–17 year olds account for the highest percentage of females undergoing primary ACLR. Males undergoing ACLR are more evenly distributed throughout age groups (Fig. 1.3).

Meniscal injuries are a common finding at the time of ACLR, with greater than 60 % of patients noted to have some type of meniscal injury at surgery. Data from February 1, 2005–September 30, 2011 showed that 21 % of patients had isolated medial meniscal tears, 24 % had isolated lateral tears, and 16 % had both medial and lateral meniscal tears. A menisectomy was performed in 57 % of cases, and a repair was performed in 28 %. Repairs were most commonly performed

KAISER PERMANENTE®

ACLR REGISTRY
OPERATIVE FORM
Registry Form #1SC

NAME: ____________________

MRN: ____________________

Imprint Area

CIRCULATING NURSE PLEASE COMPLETE SHADED PORTION

SURGEON | DOB / /

OPERATIVE DATE (MM/DD/YY) / / | OPERATIVE SITE ☐LEFT ☐RIGHT | GENDER ☐MALE ☐FEMALE

PLEASE CHECK YOUR LOCATION:
☐AV ☐BP ☐DOW ☐FON
☐KC ☐LA ☐OC ☐PC
☐RIV ☐SB ☐SD ☐WH ☐WLA

INJURY DATE (MM/DD/YY): / /

Occupational Health Services/Workers comp *(please check)*: ☐

Activities that lead to injury: ☐ Baseball ☐ Basketball ☐ Cycle ☐ Dance ☐ Fall ☐ Football ☐ Gymnastics ☐ Hockey ☐ Martial Arts ☐ Motor Vehicle Accident ☐ Racket sports ☐ Running/Hiking/Walking ☐ Skateboard ☐ Skiing ☐ Snowboarding ☐ Soccer ☐ Volleyball ☐ Water Sports ☐ Work ☐ Other:________________

Diagnosis:
☐Medial meniscus ☐Lateral meniscus
☐ACL ☐PCL
☐MCL ☐PLRI
☐Other:______________ ☐Cartilage injury

X-ray findings:

Medial joint space	☐None	☐Mild	☐Moderate	☐Severe
Lateral joint space	☐None	☐Mild	☐Moderate	☐Severe
PF joint space	☐None	☐Mild	☐Moderate	☐Severe
Anterior joint space	☐None	☐Mild	☐Moderate	☐Severe
Posterior joint space	☐None	☐Mild	☐Moderate	☐Severe

Is this a revision of prior ligament surgery: ☐No ☐Yes
Index knee prior meniscus/ cartilage surgery: ☐No ☐Yes- if yes, what procedure:
☐ACL ☐Meniscus repair ☐Meniscus transplant ☐Microfacture/drilling ☐Osteochondral autograft
☐Osteochondral allograft ☐Partial or total menisectomy abrasion ☐Other: ______________________
Contralateral knee normal: ☐Yes ☐No – if no, please describe:__________________________

☐ **Cartilage injuries** *(see grade box, describe only the highest grade lesion)*

Location:	**Size** (mm)**:**	**Grade:**	**WBA** (°)**:**	**Procedure:**
☐Patella	___x___	_____	N/A_	☐Debridement ☐Microfx /drilling abrasion ☐None ☐Other____________
☐Trochlea	___x___	_____	_____	☐Debridement ☐Microfx /drilling abrasion ☐None ☐Other____________
☐MFC	___x___	_____	_____	☐Debridement ☐Microfx /drilling abrasion ☐None ☐Other____________
☐LFC	___x___	_____	_____	☐Debridement ☐Microfx /drilling abrasion ☐None ☐Other____________
☐MTP	___x___	_____	N/A_	☐Debridement ☐Microfx /drilling abrasion ☐None ☐Other____ _____
☐LTP	___x___	_____	N/A_	☐Debridement ☐Microfx /drilling abrasion ☐None ☐Other____________

☐**MEDIAL meniscus** *(check most important injury)*:

Type:	**Length**(mm)**:**	**Location**(*see tear code*)**:**
☐Complex	_______	_______
☐Radial	_______	_______
☐Horizontal	_______	_______
☐Vertical	_______	_______
☐Partial thickness tear	_______	_______
☐Other: ___________	_______	_______

Procedure *(check all that apply)*:
☐Repair-Implant type: _________ Number:_________
☐Partial menisectomy:_____%remaining
☐Trephinated ☐Rasped ☐Left in situ

☐**LATERAL meniscus** *(check most important injury)*:

Type:	**Length**(mm)**:**	**Location**(*see tear code*)**:**
☐Complex	_______	_______
☐Radial	_______	_______
☐Horizontal	_______	_______
☐Vertical	_______	_______
☐Partial thickness tear	_______	_______
☐Other: ___________	_______	_______

Procedure *(check all that apply)*:
☐Repair- Implant type: _________ Number:_________
☐Partial menisectomy _____ % remaining
☐Trephinated ☐Rasped ☐Left in situ

Physis: ☐ Open ☐ Closed **Intra-operative occurrences:** ☐Yes ☐No
Additional comments:______________________________
Femoral tunnel drilled via: ☐Tibial tunnel ☐Medial portal ☐Lateral approach ☐Unknown

Fig. 1.2 Kaiser Permanente Anterior Cruciate Ligament Reconstruction Registry form

with a third-generation all-inside suture-based repair system. Cartilage injuries were identified in 25 % of patients undergoing primary ACLRs.

The registry also provides information on utilization patterns such as ACLR graft choice. Within our system, 41 % of grafts used are allografts, 30.6 % are hamstring autograft, and 28.4 % are bone-patellar tendon-bone autograft [16]. These patterns vary from those reported by other national ACLR registries which report 61–86 % hamstring autograft [9] and other US studies which report allograft use ranging from 13 to 74 % [12, 18, 22]. Differences in graft choice may be related to surgeon and patient preferences, financial incentives, regional practices and training, or a combination of these factors.

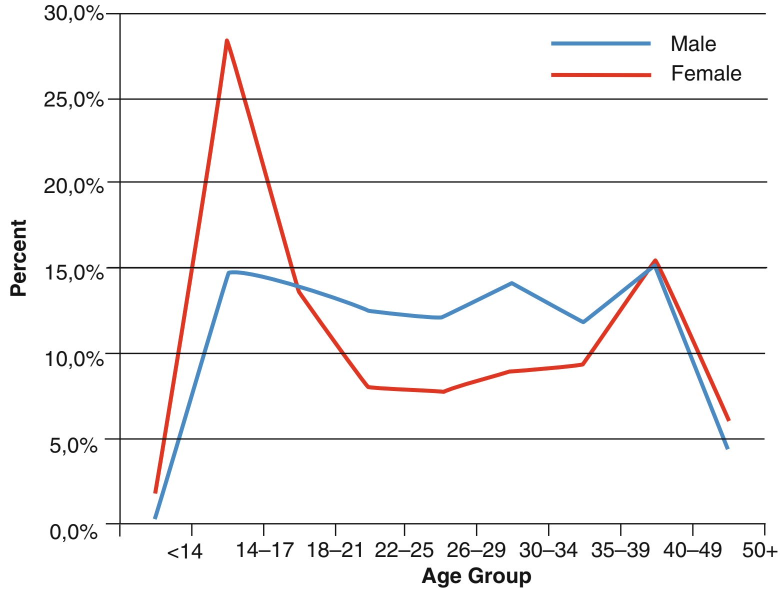

Fig. 1.3 Primary anterior cruciate ligament reconstruction percentage of cases by age group and gender

1.3.3 Evaluation and Monitoring of Patient Outcomes

In addition to identifying patient subgroups and assessing utilization patterns, registries provide a mechanism for tracking revisions, reoperations, and complications associated with ACL reconstruction. Within our system, we track and monitor all revisions and reoperations. As a result, we have found reoperations have occurred in 5.9 % of the index primary cases and revisions in 1.6 % of cases. The main reasons for ACLR revisions include graft failure, infection, instability, and fixation failure.

Registries are also important for tracking complications associated with ACLR. The KP ACLRR provides ongoing surveillance of infections and thromboembolic events. The KP ACLRR incidence of surgical site infection is 0.5 %, with only 0.2 % being deep infections. Deep vein thrombosis (DVT) occurs in 0.1 % of the cases and pulmonary embolism has been diagnosed in <0.1 % of the total population.

1.3.4 Surgeon Feedback

Another critical feature of the KP ACLRR is the ability to provide feedback regarding clinical practices and ACLR outcomes to participating surgeons. Surgeons who contribute to the registry receive confidential reports on their ACLR patient populations, procedures, and outcomes including revisions, reoperations, and complications. These profiles allow surgeons to benchmark their individual practices and outcomes to those at their medical center, within their region, and within our national system. The ultimate goal of providing this feedback is to identify variations in practice and enhance patient care quality. Our physicians have strong ownership of the KP ACLRR and are responsive to registry findings because they are the ones providing the data to the registry. This physician ownership is necessary to influence clinical care and improve outcomes.

1.3.5 Benchmarking and Collaboration Efforts

Collaboration among existing registries provides a unique opportunity to compare techniques, implants, and outcomes. The KP ACLRR and the Norwegian Knee Ligament Registry have collaborated on a baseline population comparison, profiling the patients in each registry [19]. Identifying similarities and differences among the two registries is necessary for future collaborations and understanding how information should best be handled. A study by Maletis et al. [19] demonstrated similar age distributions, preoperative patient-reported outcomes (measured by the KOOS), and soccer as the most common mechanism of injury between the KP ACLRR and the Norwegian Knee Ligament Registry cohorts. A slight difference in the proportion of females to males in the two registries was observed, as well as a difference in the types of sports played more frequently. A higher prevalence of meniscal tears was also found in the KP ACLRR. These findings provide the basis for future research project collaborations.

1.3.6 Research Studies

ACLR registries also play an important role in research. Registry data are treated as observational cohort studies' data [8]. The cohort of patients is well defined and registration of all cases is attempted to minimize selection bias. The cohort is then followed to ascertain outcomes prospectively in order to minimize informational bias. Because of the prospective design and the ability to control for many confounders when assessing exposure-outcome relationships, registry data are considered level-two evidence by most orthopedic journals. Registry data can also be used to conduct other types of studies, such as cross-sectional studies, case-cohort studies, and even failure analysis. Due to the limited follow-up of our cohort at this time, the majority of the studies the registry has published or has in press, highlighted here, address cross-sectional questions. However, investigations into short-term to medium-term outcomes are underway and mentioned as well.

1.3.6.1 Time to Surgery and Concurrent Injuries

A cross-sectional study was conducted to evaluate the effect of time to surgery, gender, and age on the type of concomitant injuries found at surgery [2]. The cohort included 1252 patients, 66 % of which were male. We found that the risk of medial meniscal injury increases with time from injury to surgery. An increased odds of medial meniscal injury (odds ratio (OR) = 1.8) was found in patients who had surgery between 6 and 12 months, and greater than 12 months after ACL injury (OR = 2.2), compared to those whose time to surgery was 0–3 months. The likelihood of medial meniscal repair also decreased in both the 3- to 6-month and the greater than 12-month time to surgery groups. Lateral meniscal tears were more common in males but did not show a similar increased incidence with increasing time to surgery.

Cartilage injuries were associated with all time to surgery, gender and age. Time to surgery greater than 12 months (OR = 1.6) and increasing age (OR = 1.05) were associated with increased risk of cartilage injuries. Compared to males, female gender was associated with a decreased risk of cartilage injury (OR = 0.71).

This study suggests that with increasing time to surgery, associated meniscal and cartilage injury increases and surgical repair becomes less likely.

1.3.6.2 Patient and Surgeon Characteristics Associated with Graft Selection

Within the KP ACLRR, there has been a change in graft use incidence for primary ACLRs. In 2009, allograft was used 38 % of the time. Our most recent analysis in 2011 reveals an increase in allograft usage to 41 %. In a recent study, we evaluated the patterns of graft usage in our registry and variables that were associated with graft choice [16]. We found that a significant variation existed between patient and surgeon characteristics and choice of graft. This study showed that patient factors such as gender, body mass index (BMI), race, and age were all associated with graft choice. In addition, surgeon and hospital factors such as sports medicine fellowship training, surgeon annual average volume, and hospital volume were also associated with the graft choice. More specifically, we found that patients who were older, female, and had lower BMIs were more likely to have received allografts and hamstring autografts than bone-patellar tendon-bone autografts. We also found that non-sports medicine fellowship trained surgeons, lower volume medical centers, and lower volume surgeons were more likely to use allografts or hamstring autografts than bone-patellar tendon-bone autografts.

These findings are informative as graft choice is a debated topic in the orthopedic community, especially among certain subpopulations. This registry study indicates that certain characteristics influence graft choice independent of the certainty of outcomes associated with graft performance.

1.3.6.3 Graft Survival Analysis

In a cohort of 9817 primary ACLR patients, a survival analysis based on the type graft used for initial ACLR (bone-patellar tendon-bone autograft, hamstring tendon autograft, or allograft) was performed in order to evaluate the factors associated with early ACLR revisions [20]. The mean age of the cohort was 29.5 years old and 64 % were males. The median follow-up was 1.1 years (range 0–5 years). BPTB grafts were used in 28 % of cases, hamstring tendons in 31 %, and allografts in 41 %. Revision surgery was performed in 150 patients (1.5 %). Revision surgery was chosen as the outcome of interest because it is the most definitive marker of graft failure. After adjusting for age, gender, race, and BMI, allografts were noted to have a three times higher risk of revision surgery compared with BPTB autografts. Hamstring tendon autografts were found to be at a 1.82 times higher risk of revision than BPTB autografts. Age was also found to have a significant effect on the need for revision surgery. There was a 7 % per year protective effect on the need for revision surgery with each year of increasing age. The probability of graft failure can be predicted based on graft type and age while holding gender, race, and BMI constant.

1.4 Strengths and Limitations of Registries

Certain limitations are inherent to observational studies. Mainly, registries are not randomized, and therefore research using registry cohorts cannot establish causality. While known confounders can be adjusted for using multivariate analyses, unknown confounders may not be accounted for resulting in lower internal validity. Certain selection bias may exist in the entry of patients into the registry, namely, not all ACL-injured patients have reconstructions, and therefore the registry is limited to studying the outcomes and utilization of patients with reconstructions and not injury. Loss to follow-up provides an additional challenge as members leave our health-care system. Sensitivity analyses and follow-up questionnaires for members who have left our health plan have been implemented to address this issue.

While registry studies have limitations, they also have several strengths. One strength is the generalizability of findings that are based on a wide range of patients, surgeons, and implants. Unlike clinical trials with strict inclusion and exclusion criteria, registries include all patients, surgeons, and hospitals, and therefore results may be more applicable [11]. As a result, registries provide an opportunity to conduct community-based comparative effectiveness studies. Registries also provide a unique method for ongoing monitoring of treatment and outcomes and provide large samples to detect rare adverse events. Most importantly, registries can be used to influence clinical care through feedback to key stakeholders including surgeons and hospitals who have ownership of the data [5, 11].

Conclusion

Patient registries provide a unique opportunity for assessing ACLR treatment and outcomes. Specifically, registries allow assessment of a wide variety of patients in various practice settings thus having high external validity. Unlike clinical trials, registries can compare the effects of multiple variables on outcomes in a real-world setting. Registries also provide large sample sizes to detect rare adverse events and allow longitudinal monitoring of patients, implants, and outcomes. Large registry samples allow identification of factors associated with rare patient outcomes. Registries also play a critical role in identification of early implant failures and patients with recalled implants. Through ongoing surveillance and feedback, registries can also track changes in clinical practice and outcomes and influence clinical care [5, 11].

The KP ACLRR has provided important information on patient characteristics, graft selection, risk factors for revision and reoperations, graft performance, and ACLR epidemiology, and has been instrumental in identifying and monitoring patients with recalled implants. The KP ACLRR plays an important role in patient safety, quality, and research within our health-care system. Future collaborations with other national registries may provide an opportunity for addressing key clinical questions and ultimately influence clinical practice.

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2 The Danish Anterior Cruciate Ligament Reconstruction Registry: What We Are Doing, How We Do It, and Which Would Be the Best Way to Do It

Martin Lind and Alma B. Pedersen

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2.1 Background for Initiation of a National Anterior Cruciate Ligament Reconstruction Registry

Reconstruction of the anterior cruciate ligament (ACL) is increasingly performed for restoration of knee stability in typically young athletic active patients. In the age group that mainly is prone to ACL injuries (15–40 years), the incidence of surgery is 85 per 100,000 [6].

ACL reconstructions have evolved rapidly over the last two decades, from an open technique to a minimally invasive arthroscopic technique. Other factors are under constant modification such as surgical technique, multiple graft choices, and graft fixation implant possibilities [13, 16]. Furthermore, standardization of surgical technique and improved instrumentation can be partly the reasons for the more widespread performance of ACL reconstructions from previously specialized arthroscopic surgeons to general orthopedic surgeons. It is still unknown which graft types and fixation technique provide the best clinical outcome. Thus, the literature lacks reliable data concerning epidemiology, revision rates, clinical outcome with different implants and surgical techniques, and true functional outcome in mixed patient groups after knee ligament reconstructions.

Randomized clinical trials (RCT) have typically been considered as the gold standard for the design of clinical research in order to improve the outcome of patients. Some consider RCT to be

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the only valid design to evaluate the efficacy of treatment or intervention. Unfortunately, well-designed RCT are often costly in both money and time. In addition, RCT are often characterized by limited follow-up and small sample size. All these issues reduce the ability of RCT to provide clinical decision-making data in the practice setting. Given the high number of graft types and implants available, in addition to rare outcomes such as ACL revision, RCT may not be the most appropriate, practical, and ethically the best design to use to determined optimal techniques for ACL reconstructions.

The knowledge of the epidemiology and outcome of ACL reconstruction has typically been generated from academic single centers [1, 3, 5, 19]. Studies from such centers can generate biased data due to selected patient materials and highly dedicated surgeons.

Studies performed from registries offer an alternative to RCT and single-center studies. National clinical registries for joint replacement have existed for more than two decades in Scandinavia [4, 12]. These registries have been highly successful in the sense that outcome data with long-term performance of multiple implants and techniques have been generated. Most importantly, poor-performing implants and techniques have been identified early, avoiding unnecessary poor clinical results for numerous patients. A clinical registry allows for studying a number of exposures and outcomes for low cost rapidly, and if registry comprises complete population data including variety of surgeons and techniques, the study results may be more likely to reflect daily clinical practice.

In Scandinavia, three national registries for knee ligament reconstruction were established in 2004–2005. The first ACL registry was initiated in Norway [6], and later on, Sweden and Denmark adapted the Norwegian registration form and started each their national ACL registries with similar data registration [7, 9]. The registries were coordinated in regard to anamnestic, perioperative, and outcome data. The common database setup was established to enable future comparison of data between the Scandinavian registries.

At the same time, in the Unites States, a multicenter cohort of prospectively followed patients with ACL reconstruction and ACL revision procedures has been established in the Multicenter Orthopaedic Outcome Network (MOON) and Multicenter ACL Revision Study (MARS) in the USA [15, 18].

Presently, clinical results after ACL reconstructions still have significant shortcomings: inconsistent ability of patients to return to previous activity levels, limited reproducibility of knee stability restoration, and lack of prevention of knee osteoarthritis development [8, 10]. In addition, an important challenge when evaluating clinical outcome after ACL reconstruction is to have established definitions of good outcome and clinical failures. An ultimate failure of ACL reconstruction is the need for revision ACL reconstruction (defined as removal or exchange of primary ACL). However, the indication for revision ACL reconstruction is not universally defined, and certainly, not all patients that have poor outcome after ACL reconstruction end up having a revision ACL reconstruction or will benefit from it. Thus, other outcomes, including lack of ability to return to previous activity levels, lack of restoration of sagittal knee stability, lack of restoration of 3-D knee biomechanics, pain level in operated knee, low score levels in validated knee-specific subjective score, and low score levels in general quality of life scores, may be more relevant to consider as ACL reconstruction failure indicators. Up to date, there is no common consensus among orthopedic surgeons concerning the definition of these failure parameters.

The existence of both European and American large-scale cohorts is important for prediction of prognosis, monitoring, quality improvement, research, and comparison between ACL reconstruction strategies in different parts of the world [11]. As an example, the successful collaboration between Scandinavian hip and knee registries was established for 5 years ago and has, so far, resulted in definition of minimal dataset with common definition of variables, definition of revision and patient-related outcomes, and data quality. Likewise, national ACL registries have the possibility to monitor selected parameters and provide data for better understanding of failure mechanisms and true levels of failure following ACL reconstruction.

This chapter presents the organization of the Danish ACL registry and presents data on epidemiology and outcome after primary and revision ACL reconstruction.

2.2 The Registry

2.2.1 Registry Organization

The Danish ACL reconstruction registry was set up by the Danish Orthopaedic Society and the Danish Society for Arthroscopic Surgery and Sport Traumatology on January 1, 2005 [9]. The aim of the register is to examine the epidemiology of ACL reconstruction procedures in Denmark and to monitor and facilitate continuously improvement of ACL reconstruction surgery outcomes on both local and national levels. In order to achieve this aim, a nationwide clinical database, Danish ACL reconstruction registry, on all primary ACL reconstruction procedures and revision ACL performed in Denmark was established. In addition, posterior cruciate ligament (PCL) reconstruction and multi-ligament reconstruction procedures were included in the registry.

The Danish ACL reconstruction registry has a steering committee of orthopedic surgeons representing Danish Society for Arthroscopic Surgery and Sport Traumatology and Danish regions, representative from the Department of Clinical Epidemiology, Competence Centre North, and the public authority, Region Middle Jutland. The steering committee is responsible for the work of the Danish ACL reconstruction registry. The Danish ACL reconstruction registry cooperates closely with Danish Hip Arthroplasty Registry, Danish Shoulder Arthroplasty Registry, and Danish Knee Arthroplasty Registry as a part of the Danish Orthopaedic Common Database. The Danish Orthopaedic Common Database (including the Danish ACL reconstruction registry) obtains its funding from the Danish Regions after yearly application. The total annual costs for the Danish Orthopaedic Common Database are about 180,000 EUR. Department of Clinical Epidemiology, Competence Centre North, performs the statistical analyses for the Danish ACL reconstruction registry.

The Danish National Board of Health has approved the ACL registry as a nationwide and population-based clinical database. The registration in the Danish ACL reconstruction registry is compulsory for all public and private hospitals, according to the notification from 2006 on improvement of nationwide and regional clinical quality database passed by the National Board of Health.

The data collection is taking place prospectively online at department level directly into the Danish ACL reconstruction registry using data entry system called "Klinisk Male System (KMS)." All 69 departments, which perform this type of surgery, including private clinics, participate in the Danish ACL reconstruction registry. At each participating department, a contact person is responsible for data registration to the Danish ACL reconstruction registry and continuous communication and spread of information between the registry and department.

Steering committee is responsible for optimizing the database management and interpretation of data. The Danish ACL reconstruction registry publishes an annual report on the Internet, including descriptive data and department-specific quality indicators. Each department is able to compare their own results with the results from the other departments and the national average.

2.2.2 Registry Data

Data are collected by the operating surgeon before (i.e., anamnestic data), during (i.e., surgery-related data), and 1 year after the surgery, using a standardized form and online access (Table 2.1).

The following anamnestic data are registered in the database: personal identification number, previous surgeries to the affected knee, objective ligament instability, including instrumented anterior–posterior laxity, and cause of injury including types of sports. Instrumented knee sagittal laxity can be measured by KT1000, Rolimeter, or other instrumented device.

Table 2.1 ACL registry content

Preoperative	Operation	1-year follow-up	5- and 10-year follow-up
Index side	Graft choice	Instrumented ACL stability	*KOOS*
Previous surgeries	Implants	Pivot shift (IKDC grading)	*Tegner score*
Date of injury	Meniscus lesion treatment	MCL laxity (IKDC grading)	
Cause of injury	Cartilage lesion types	Rotatory laxity (dial test, IKDC grading)	
Instrumented ACL stability	Cartilage lesion treatment	Complications	
Pivot shift (IKDC grading)	Other procedures	Reoperations	
MCL laxity (IKDC grading)	Surgical complications	Cause of reoperation	
Rotatory laxity (dial test, IKDC grading)	Day procedure		
	Duration of surgery	*KOOS*	
KOOS	*Antibiotics*	*Tegner score*	
Tegner score	*DVT prophylactics*		

The surgery-related data include the following: ligament, meniscus and cartilage procedures, types of reconstruction technique, graft choice, implant choice, operative complications, duration of surgery, type of antibiotics and deep venous thrombosis prophylactic treatment, and date of surgery.

The patient's subjective functioning of the knee is evaluated by use of the self-assessment score systems the Knee injury and Osteoarthritis Outcome Score (KOOS) and Tegner functional score [17]. The patients submit these data via the Internet before surgery and 1, 5, and 10 years after surgery. The KOOS is a knee-specific subjective measurement system with five subscales determining pain, symptoms, activities of daily living, sports and recreation, and quality of life. The score is validated for ACL-reconstructed patients [14].

The number of departments that perform ACL reconstruction surgery has changed over time due to closing of some departments, merging of others, or initiating of a number of new private clinics/departments. In 2010, there were 69 orthopedic departments, including 33 public and 36 private, performing this surgery, and of these, 57 (83 %) departments reported data to the ACL reconstruction registry. The goal of the registry is to achieve registration coverage of more than 90 %. Another goal is to achieve surgical registration completeness of ACL reconstructions of more than 90 % on both national and department level, i.e., more than 90 % of ACL reconstruction procedures performed in Denmark should be reported in the ALC registry.

The ACL reconstruction registry analyzed the entered data every 3 months identifying missing procedures using the Danish National Registry of Patients as a gold standard. List with personal identification number for all missing procedure registration has been afterward sent to every orthopedic department with request for data entering. Registration completeness in 2010 was 83 % (2,813 procedures was registered out of 3,381 procedures performed in Denmark in the same year), which is considered acceptable for a national prospective cohort.

The entered data are regularly subject to missing value control for all variables included in the dataset. In addition, continuous coding error checks for several of the most important variables, such as date of surgery, laterality and type of procedures, and implant design, are ongoing. Several logical checks are incorporated online-entering system.

2.2.3 Registry Output

The Danish national health system provides free access to tax-supported medical care for all Danish residents. Since 1968, all Danish citizens have been assigned a unique 10-digit personal identification number at birth, encoding age, gender, and date of birth. This identifier is part of all Danish electronic medical databases, permitting unambiguous record linkage among the databases [2].

The ACL registry is no exception. The ACL registry has been linked to Danish Civil Registration System, a national registry of all Danish residents established in 1968, which maintains data on vital status and residence for the entire Danish population. This enables us to have complete follow-up for all ACL patients, since we, at every time, know exactly if patient is alive, dead, emigrated, or revised. Thus, studies based on ACL registry data are not limited with loss to follow up issue, although a long term follow-up design is used. In addition, we are able to send questionnaires and other contact letters to each patient, since residence and change of residence have been recorded and kept.

ACL registry has also regularly been linked to the Danish National Registry of Patients in order to measure registration completeness of patients. For this purpose, standardized surgery codes have been used. Further, The Danish National Registry of Patients contains data on all hospital admissions since 1977 (and since 1995 on all hospital outpatient visits), including the dates of admission and discharge and up to 20 discharge diagnoses recorded according to the International Classification of Diseases (8th edition until the end of 1993, 10th edition thereafter). This linkage gives us possibility to study alternative ACL outcomes, such as medical and surgery complications not recorded in the ACL registry. Furthermore, we are able to construct medical comorbidity level for each patient before surgery and study the association between different risk factors such as diabetes or chronic pulmonary disease and ACL outcome.

2.3 Results from the Danish ACL Registry

2.3.1 Epidemiology of Patients Undergoing ACL Reconstruction (Table 2.2)

The incidence of primary ACL reconstruction was 38 per 100,000 citizens in Denmark and 91 per 100,000 in the 15–39 years age group. Age distribution at the time of primary ACL reconstructions is clearly different for males and females, with females having a higher incidence at a lower age than males, and the incidence drops quickly after 25 years (Fig. 2.1). For males, the incidence remains high until 35 years of age. Male gender was present in 60 % of primary ACL.

The time from injury to surgery was less than 6 months for 38 % of patients, less than 12 months for 60 % of patients, and more than 2 years for 20 % of patients. So in Denmark, a large proportion of patients are operated as chronic cases.

The cause of ACL injury is sports activity in 81 % of patients. The three most common sports activities for women causing injury are team handball 37 %, alpine skiing 25 %, and soccer 21 %. For male, the three most common sports activities are soccer 68 %, team handball 10 %, and alpine skiing 9 %. Previous surgery on the same knee before the ACL surgery was performed in 28 % of patients. Of those, a medial meniscus resection was the most common procedure, counting for 44 % of cases.

Among revision ACL patients, 54 % were males. Revision ACL reconstruction was performed at younger age than primary ACL reconstruction (Fig. 2.2). The primary cause for graft failure leading to revision ACL was new trauma (38 %), followed by unknown cause for graft failure (24 %) and poor femoral tunnel placement (20 %). Sport was the most frequent type of trauma, registered in 83 % of revision ACL patients.

Table 2.2 Characteristics of the study population according to type of cruciate ligament reconstruction in the period between July 1, 2005 and December 31, 2010

Characteristics		Primary ACL	ACL revision	Multi-ligament reconstruction
Number of procedures, *n*		12,322	1,099	914
Gender (%)	Male	60.1	55.9	67.3
Time from injury to surgery (%)	<½ year	38		
	>5 years	10		
The common reason for injury (%)	Sport	80.5	58.4	50.8
	ADL[a]	9.6	14.9	10.5
	Traffic	3.6	5.0	25.2
	Work/job	1.7	3.4	7.2
	Unknown	4.5	18.3	6.3
The common sports injury (%)	Football	48.8	42.2	38.8
	Handball	20.6	27.1	10.8
	Alpine	15.4	10.1	22.8
	Other sport	15.2	15.5	23.3
Perioperative complication (%)		3.9	4.6	6.3
Deep venous thrombosis (%) prophylactic treatment		24.6	17.7	36.3
Outpatient surgery (%)		84.2	72.4	29.1
Duration of surgery (min[b])		71.9 ± 21.1	90.0 ± 32.3	120 ± 44.3

Data are percentage (%), unless otherwise specified
[a]Activity of daily living
[b]Presented as mean values with standard deviation

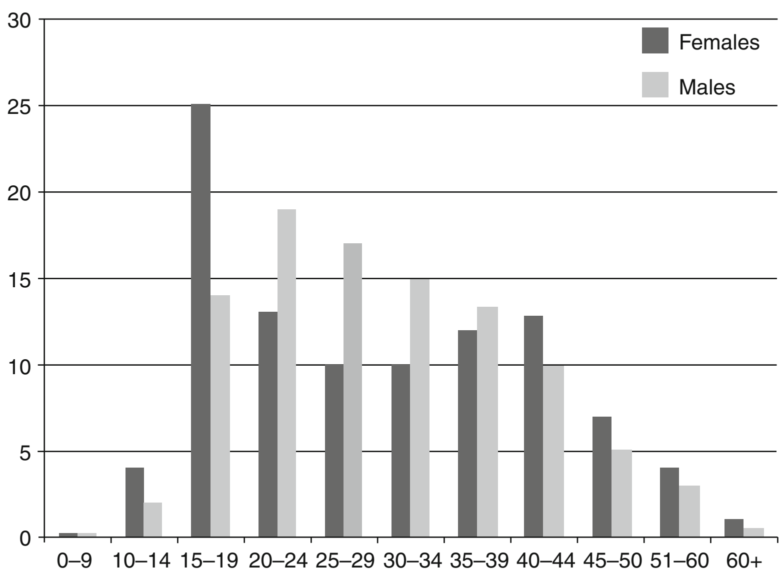

Fig. 2.1 Age distribution primary ACL for females and males

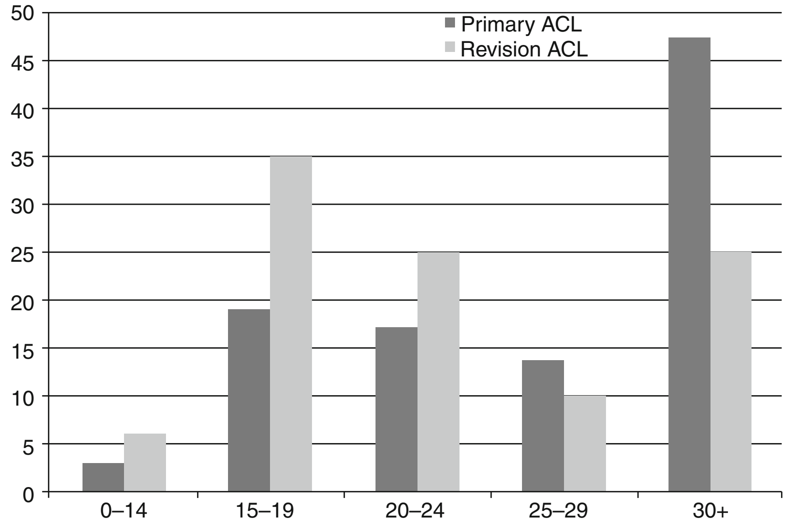

Fig. 2.2 Age distribution primary ACL and revision ACL

2.3.1.1 Other Knee Injuries Before ACL Reconstruction

At the time of primary ACL reconstruction, medial meniscus lesions requiring surgical treatment were seen in 18 % of patients, lateral meniscus lesions requiring surgical treatment were seen in 14 % of patients, and both lateral and medical meniscus lesions were seen in 6 % of patients. Repair was used in 25 and 20 % of patients with medial and lateral meniscus lesions, respectively. For revision ACL operations, any new meniscus lesions were seen in 26 % of patients.

Cartilage lesions are only registered in the registry if they are greater than 2 cm^2 and grade 2 or deeper, and location is not indicated. Such cartilage lesions were reported in 10 % of primary ACL reconstruction patients and 20 % of revision ACL patients.

2.3.1.2 Posterior Cruciate Ligament (PCL) Reconstruction and Multi-ligament Reconstructions

A total of 914 PCL and multi-ligament reconstructions were registered in the ACL registry. The most common combined ligament reconstructions reported were the following: ACL combined with lateral collateral ligament (LCL) and/or postero-lateral corner reconstruction (PLC) was reported in 27 % of patients, ACL combined with medical collateral ligament (MCL) reconstruction was reported in 16 % of patients, isolated PCL reconstructions were reported in 16 % of patients, and PCL combined with collateral reconstruction in 12 % of patients.

Meniscus lesions were seen and treated surgically in 31 % of cases. Cartilage lesions were reported in 16 % of cases, of which 41 % received surgical treatment.

2.3.2 Surgical Technique

Shortly after registry initiation, focus has been on rediscovery of anatomical ACL reconstruction. Thus, the registry has collected data on anatomical ACL reconstruction principles since 2007. The use of anterior medial portal for femoral tunnel placement increased from 12 % in 2007 to 63 % in 2011. Double-bundle reconstruction technique has not been very popular in Denmark used in only 0.8 % of ACL reconstructions in 2007 and 1.8 % in 2010.

Regarding graft choice for primary ACL reconstruction, registry has seen an increase in the hamstring tendon graft usage from 68 % in 2005 to 83 % in 2010. Patella tendon bone grafts were used in 22 % of primary ACL in 2005 and 7 % in 2010. Allografts for primary ACL reconstruction are practically unused in Denmark in only 0.1 % of procedures. For revision ACL hamstring tendon, bone-patella tendon and allograft tendons were used as graft in 41, 27, and 17 % of procedures, respectively.

Regarding fixation implant choice for hamstring reconstructions, the following implant types are used. In the femur transfixation, implants are the most popular and used in 63 % of procedures. The Mitek RIGIDFIX® implant was the most popular. Button-type fixation was used in 29 % of cases. Interference screw fixation was used remaining cases. For tibial fixation interference, screw implants were used for all cases except for 1 % post-screw and washer mainly used in pediatric cases. Resorbable implants were used in 43 % of cases, and 63 % of these implants were composite implants consisting of polymer and calcium phosphates. For patella tendon grafts, all implants were metal interference screws.

The median operating time for primary ACL is 66 min, which has been unchanged over 5 years. Day surgery (outpatient's treatment) was applied for 84 % of primary ACL patients. Pharmacological thromboprophylaxis was used in 16 % of all ACL patients.

2.3.3 Objective Outcome After ACL Reconstruction

Knee laxity measured as side-to-side difference preoperatively was 5.2 mm and 5.7 for primary ACL reconstructions and revision ACL, respectively. At 1-year follow-up, knee laxity was 1.5 mm for primary ACL reconstructions and 1.9 mm for revision ACL reconstructions. Among primary ACL patients, 2.4 % had unsatisfactory knee stability with side-to-side difference of >5 mm at 1-year follow-up, corresponding to IKDC grades C and D. For revision ACL, this failure incidence was seen in 6.2 % of patients.

2.3.4 Subjective Outcome After ACL Reconstruction

The subjective impact of ACL reconstruction can be evaluated by a patient-related outcome measure (PROM). The registry has chosen the KOOS as the primary PROM for the evaluation and the Tegner function score as the secondary PROM. These PROMs are used in the other Scandinavian ACL registries as well. The KOOS instrument consists of five subscales evaluating pain, symptoms, activity of daily living, sports activities, and quality of life. Each subscale ranges from 0 to 100 points, with 100 being the best score. The results for primary and revision ACL patients can be seen in Table 2.3. Characteristically, the subscales pain, symptoms, and activities of daily living were only moderately impacted by the ACL reconstruction treatment, with improvement of around 10 points. Sports activities and quality of life improved more with 23 and 20 points. For ACL revisions, the improvements are slightly different, with less improvement in sports activities and quality of life scores of 17 and 16.

When comparing subjective outcome between primary ACL reconstruction and revision ACL reconstruction, the following findings were made. Of 12,322 primary ACL and 1,099 revision ACL, 1-year KOOS data was available for 4,799 primary ACL (39 %) and 303 (28 %) revision ACL reconstructions. Subjective outcome scores based on the KOOS demonstrated significantly lower scores 1 year after revision than after primary ACL surgery ($p<0.001$) (Table 2.3). Functional activity based on the Tegner score was also lower 1 year after revision than after primary ACL surgery. A modified parameter of the KOOS being the average of the four most responsive subscales is designated the $KOOS_4$ and represents the impact of surgery. For primary ACL reconstruction, this score was 70 at 1-year follow-up, whereas the score was 63 for revision ACL reconstruction. However, the change in score from preoperative to 1-year follow-up is almost the same with 15 points for primary ACL reconstruction and 13 points for revision ACL reconstruction.

2.3.5 Failure After ACL Reconstruction

The ultimate failure of primary ACL reconstruction is revision ACL. At 5 years, 95.9 % of primary ACL reconstruction was still intact, corresponding to revision rate of 4.1 % (Fig. 2.3). Nevertheless, mean revision rate during the entire follow-up period was 4.7 %.

Table 2.3 Preoperative and 1 year after surgery KOOS and Tegner score for primary and revision ACL reconstruction in the period between July 1, 2005 and December 31, 2009

Preoperative KOOS		ACL primary	ACL revision
Number of preoperative KOOS, *n*		4,799	303
KOOS subscores[a]	Symptoms	71 ± 16	67 ± 17
	Pain	71 ± 17	67 ± 20
	ADL[b]	79 ± 18	75 ± 20
	Sports/ recreation	39 ± 25	35 ± 25
	Quality of life	40 ± 17	32 ± 17
$KOOS_4$[c]		55 ± 19	50 ± 21
Tegner score		3 (2–4)	3 (1–4)
1-year follow-up KOOS		ACL primary	ACL revision
Number of preoperative KOOS, *n*		2,862	203
KOOS subscores[a]	Symptoms	77 ± 17	73 ± 18[d]
	Pain	84 ± 15	78 ± 17[d]
	ADL[e]	89 ± 13	84 ± 16[d]
	Sports/ recreation	62 ± 25	52 ± 28[d]
	Quality of life	59 ± 21	48 ± 21[d]
$KOOS_4$[c]		71 ± 20	63 ± 22[d]
Tegner score		5 (4–6)	4 (3–5)[d]

[a]KOOS subscores are presented as mean values with standard deviation
[b]Tegner scores are presented as median values and lower and upper quartiles in brackets
[c]$KOOS_4$ is the modified KOOS defined as the mean score of the four most responsive subscores: symptoms, pain, sports, and quality of life subscores
[d]Significant difference between ACL primary and ACL revision parameter at 1-year follow-up
[e]Activity of daily living

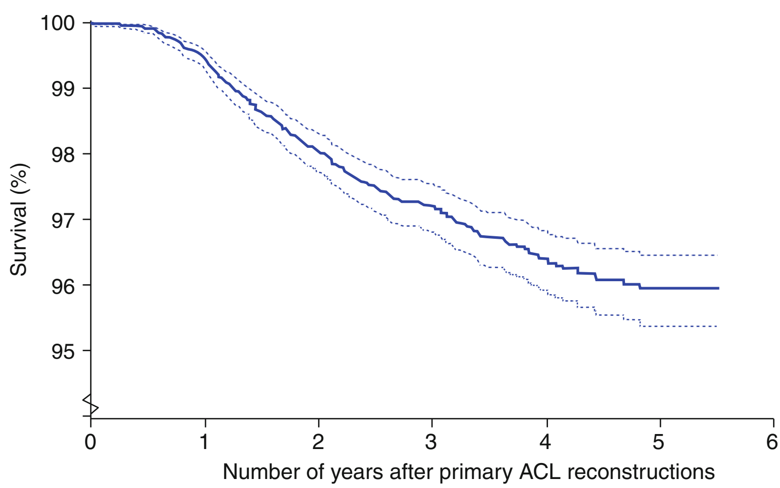

Fig. 2.3 Kaplan–Meier survival curve with 95 % confidence interval for primary ACL reconstructions performed from 2005 to 2010

The time of revision ACL after primary ACL reconstruction can be seen in Fig. 2.3. In the time period 0–1, 1–2, 2–3, 3–4, and 4–5 years after primary ACL, 0.6, 1.2, 0.5, 0.3, and 0.1 % of primary ACLs were revised, respectively. Thus, the incidence of revision ACL reconstruction peaks between 1 and 2 years and seems to be at a very low level up to 5 years.

We studied in the registry the influence of age, sex, and cause of initial ACL injury (sports/

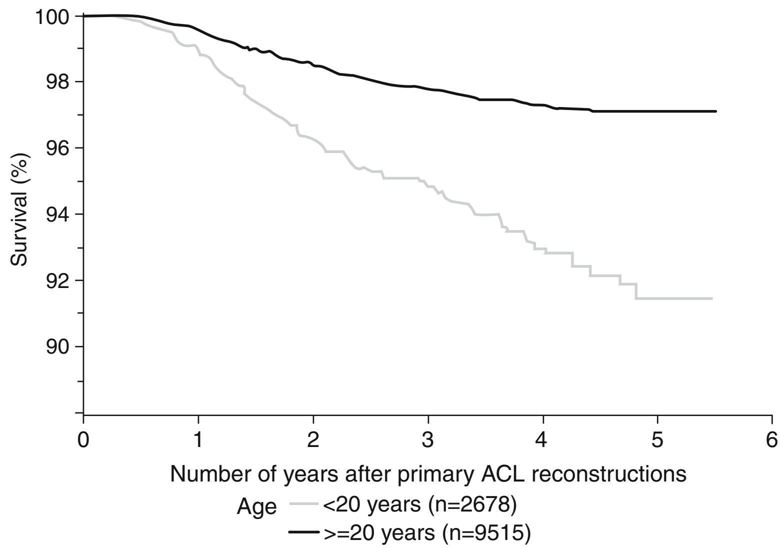

Fig. 2.4 Kaplan–Meier survival curve with 95 % confidence interval for primary ACL reconstructions performed in patients below and above 20 years

nonsports) on risk of revision ACL. Patients below 20 years at the time of primary ACL surgery had a significantly higher risk of revision ACL reconstruction than patient above 20 years (adjusted RR = 2.58; 95 % CI: 2.02–3.30) (Fig. 2.4). Sex and cause of primary injury (sports/nonsports) did not influence the risk for ACL revision.

Conclusion

An important vision for national clinical database is the ability to identify good and bad treatment strategies for the clinical entity being investigated. After collecting data from more than 14,000 patients, we have large amount of clinical data on knee ligament reconstruction as well as both subjective and objective outcome data, with the genuine spectrum of patients. These data can serve as reference material for comparative studies with respect to incidence and outcome measures such as revision rates and subjective score level for the KOOS and Tegner instruments.

The most important finding after 5 years of Danish ACL reconstruction registration is that we have established the 5-year revision cohort after primary ACL reconstruction with revision rate of approximately 4 %, that ACL-reconstructed patients are limited with sports and recreative abilities, as well as age younger than 20 years is an independent risk factor for ACL revision, and that the outcome after primary ACL reconstruction is better than after revision reconstruction. At the present time, our data provides no evidence that use of a certain graft choice or fixation method choice is associated with better clinical outcome than other choices.

Analysis of outcome after knee ligament reconstruction is a great challenge for numerous reasons in any research design, not only in the registry studies. Primarily, definitions of a successful outcome and clinical failure are not uniformly defined. One can use hard end points such as revision surgery to define failure, and most would agree that only a very poor outcome after primary ligament reconstruction will result in a revision procedure. However, the primary cause for revision is reinjury during sports activity, and such reinjury can be caused by factors unrelated to the outcome of the primary procedure, including sports activities beyond what the patient have be rehabilitated to and bad luck. Other potential outcome measures are knee stability measurement either instrumented or assessed clinically. These parameters are important, as preoperative knee laxity determination is a key element of the indication for knee ligament reconstruction. But no established thresholds for good and bad outcome exist for these parameters. Finally, patient-related outcome measures (PROMs) are very important element in determining outcome after knee ligament reconstruction. Numerous instruments with PROM data have been applied on patients with ACL reconstructions: subjective International Knee Documentation Committee (IKDC) score, KOOS, Lysholm score, and others. Generally, these scores tend to have moderate responsiveness, which may lessen our ability to detect differences between study groups.

Although registry studies have many advantages and provide data that can only be obtained in registry studies, we should also be aware of important limitations of registry study data. One of the problems is data completeness. In the ACL registry, registration completeness is more than 80 %. Given the prospective registration of primary ACL data and all outcomes in ACL registry, it is highly unlikely that any missing registration of ACL procedures is systematically linked to later ACL outcome. Thus, any comparison between risk groups of interest would provide valid and unbiased relative risk estimate.

Another problem of registry data is compliance of subjective patient registrations. The task of having patients report subjective scores over the Internet has been very challenging. Average of 40 and 30 % of patients report data preoperatively and at 1-year follow-up, respectively. This is not optimal in order to use these subjective data as a valid measure of ACL outcome. For that reason, a validation study has been performed to test whether there was a difference in subjective outcome between responders and nonresponders at a follow-up time of 2–3 years. A validation study did not demonstrate any such difference (unpublished data), and we therefore consider our subjective data valid and representative for the entire ACL registry cohort.

Clinical registries are population-based with large sample size providing high precision of estimates and ensure generalization. They enable multiple subgroup comparisons that normally would not be feasible in randomized controlled trials. Collection of data is done prospectively and independently of the future research aim, reducing both selection and information biases.

Registry-based observational studies lack the benefit of random assignment, which is useful for controlling both measured and unmeasured confounding. However, registry-based studies have the possibility to use epidemiological and statistical methods to control for confounding, including matching, restriction, stratification, standardization, and regressions analyses. A number of potential confounding and prognostic factors have also been reported in the ACL registry for that purpose. It is clear that registry-based observational studies cannot replace randomized clinical trials, nor do randomized clinical trials make registry-based observational studies less valuable. Both designs can contribute usefully to answering adequate clinical and research questions.

2.4 Future Perspectives

With future increase in data volume, we expect to be able to present outcome data on different surgical technique principles, selective patient groups, and specific implants. Based on the present experience, revisions rates are probably the most sensitive outcome parameter to detect differences between groups. To be able to detect differences in subjective outcome measures, more responsive and more knee ligament insufficient symptom-based instruments need to be developed and adapted into clinical databases such as the Danish Knee Ligament Reconstruction Registry. For that purpose, Scandinavian ACL registry network is additional valid tool.

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3 ACL Ruptures in the Female Athlete: Can We Predict Who Is at Increased Risk and Can We Reduce Noncontact Injury Rates?

Frank R. Noyes and Sue D. Barber-Westin

Contents

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3.1 Introduction: The ACL Injury Gender Dilemma

Many studies have shown that female athletes have a greater risk of sustaining a noncontact anterior cruciate ligament (ACL) tear compared with male athletes participating in the same sport. The initial reports of this problem occurring in activities such as soccer and basketball appeared in the medical literature in 1994 [32] and 1995 [3]. Since then, researchers worldwide have spent considerable time and effort in attempting to understand why this gender disparity exists, how to detect athletes who have an increased risk of injury, and if interventions such as neuromuscular retraining can lessen the incidence of ACL tears in women.

In 1994, Lindenfeld et al. [32] reported that female soccer players had nearly six times the rate of serious knee ligament injuries than male players (0.87 and 0.29 per 100 player-hours, respectively; $P < 0.01$). A few years later, Gwinn et al. [22] found that women at the United States Naval Academy had a fourfold increase in ACL tears compared with men in intercollegiate soccer, basketball, and rugby, collectively (0.511 and 0.129 per 1,000 athlete exposures, respectively; $P = 0.006$). The greatest disparity in injury rates was found during military training, where women had nearly 11 times the incidence of ACL ruptures as men during obstacle course running (6.154 and 0.567 per 1,000 athlete exposures; $P = 0.004$). Agel et al. [2] analyzed data over a 13-year period and reported a noteworthy gender

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Table 3.1 Meta-analysis of anterior cruciate ligament injury rates for men and women

		Female			Male		
Sport	Level	Incidence[a]	ACL tears	Exposures	Incidence[a]	ACL tears	Exposures
Basketball	Professional	0.20	9	45,036	0.21	15	70,185
	Collegiate	0.29	2,049	7,119,962	0.08	645	8,300,072
	High school	0.10	27	233,538	0.02	4	169,885
Soccer	Collegiate	0.32	1,570	4,873,287	0.12	842	6,881,281
	High school	0.45	70	155,822	NA	NA	NA
Handball	Elite	0.56	23	40,799	0.11	5	43,891
	Adult recreational	0.86	5	5,815	0.24	5	20,462
Lacrosse	Collegiate	0.18	146	799,611	0.17	169	984,292
Rugby	Collegiate	0.36	24	66,771	0.18	4	22,788
Wrestling	Collegiate	0.77	1	1,306	0.19	2	10,582

Data from Prodromos et al. [43]
Females had significantly higher mean incidence rates than males in basketball, soccer, and handball ($P<.0001$)
[a]ACL tears per 1,000 exposures

disparity in ACL injury rates in collegiate basketball and soccer players. Prodromos and associates [43] conducted a meta-analysis of 33 studies to test the hypothesis that the incidence of ACL tears would show variation by sport and gender (Table 3.1). The mean ACL injury rate for females was significantly greater than males in basketball (0.28 and 0.08, respectively, $P<.0001$), soccer (0.32 and 0.12, respectively, $P<.0001$), and handball (0.56 and 0.11, respectively, $P<.0001$).

3.2 Risk Factors for ACL Ruptures in Female Athletes

Regardless of gender, at least two-thirds of ACL tears occur during noncontact situations such as cutting, pivoting, accelerating, decelerating, or landing from a jump [10, 49]. Perturbation of the athlete from an opponent has been reported in at least 90 % of injuries in several studies [12, 28]. Fatigue appears to increase the risk of ACL injury in both genders [9, 26]. Reduced knee flexion angles, increased hip flexion angles, valgus collapse at the knee, increased hip internal rotation, increased internal or external tibial rotation, and a flatfoot position are frequently reported at the time of or just prior to ACL injury. A debate exists regarding exactly which of these neuromuscular mechanics are present at exactly the time of the injury and which may occur milliseconds following the injury. From videotaped analyses of ACL injuries, it appears that the amount of time in which an ACL rupture occurs ranges from 17 to 50 ms after initial ground contact [28, 29]. The authors believe that a noncontact ACL rupture occurs immediately following initial foot strike (commonly with a flatfoot position), internal rotation and adduction of the hip, high quadriceps forces, and a low knee flexion angle of less than 30°. The subsequent knee abduction (valgus) position then occurs as a result of the pivot-shift subluxation event after the ACL has ruptured.

The question of what places female athletes in certain sports at a higher risk for sustaining a serious knee ligament injury than male athletes represents an ongoing dilemma not yet answered. The major risk categories that have been the focus of research to date include genetics, environmental, anatomical, hormonal, and neuromuscular/biomechanical [6, 7, 21]. Unanswered questions are due in part to problems with prior studies such as small sample sizes of each gender, data collected on only one risk category, or examination of neuromuscular characteristics in a controlled laboratory environment using preplanned tasks.

Studies have attempted to investigate whether anatomic differences between genders are responsible or partially responsible for the disparity in noncontact ACL injury rates. It is well appreciated that differences are present between men and women in many anatomic indices including the quadriceps femoris angle (Q angle), femoral anteversion, tibial torsion, foot pronation, size of the intercondylar notch, and the size of the ACL. Even so, no study has proven that inherent anatomic differences alone are responsible for the higher risk of noncontact ACL injuries in female athletes.

Researchers have speculated that fluctuations in sex hormones could be deleterious to the material and mechanical properties of the female ACL, thereby increasing its vulnerability to rupture during certain phases of the menstrual cycle [11]. Studies involving a total of 145 women who sustained ACL ruptures found a greater proportion of injuries occurred in the preovulatory (follicular) phase compared with the other phases of the cycle [11, 50, 56]. However, a study from our laboratory found no significant effect of the variations of the menstrual cycle or the use of oral contraceptives on moments, or knee flexion angles during jumping and landing tasks [16]. Twenty-five women, 13 of whom used oral contraceptives, and 12 men performed repeated trials of jumping tasks in which lower limb kinematics and peak moments were calculated. The women were tested twice for each phase of the menstrual cycle (follicular, luteal, ovulatory). The conclusion was reached that the observed difference in ACL injury rates between genders is more likely to be due to differences in strength, neuromuscular coordination, or ligament properties. It is apparent that further study on larger numbers of athletes is required before definitive conclusions may be reached regarding this risk factor.

Many investigations have found differences between genders in neuromuscular and biomechanical factors that are hypothesized to be responsible for the disparity in noncontact ACL injury rates. These differences involve movement patterns; muscle strength, activation, and recruitment patterns; and knee joint stiffness. One of the first studies to demonstrate gender differences in movement patterns was performed at the authors' laboratory using a 2-camera, video-based optoelectronic digitizer and a multicomponent force plate [23]. Adolescent males demonstrated greater external knee extension moments on landing and take-off compared to age-matched females, which was believed to be due to their high use of the hamstrings musculature. Males also had a greater mean hamstring/quadriceps ratio on isokinetic testing.

Men consistently demonstrate greater knee flexion angles than women on landing from a drop jump [17, 45] and during single-leg hopping [31, 48]. Women tend to land with a more erect posture on initial impact and use the ankle musculature to absorb impact forces, resulting in higher knee extension and ankle plantar-flexion angles. Female athletes were found in one study to have smaller knee flexion angles, greater valgus angles, increased quadriceps muscle activation, and decreased hamstring muscle activation during the stance cycle of straight running and in two preplanned cutting maneuvers [33]. Another study found that women had significantly greater proximal anterior shear forces, extension moments, and valgus moments on landing compared to men during various stop-jump tasks [15]. The hypothesis was advanced that the increased proximal shear force was due to a high quadriceps muscle force, a low hamstring muscle force, a straight knee on landing, or a combination of all of these factors. In the laboratory, a high quadriceps load (4,500 N) simulated in cadaveric knees at 20° of flexion produced significant anterior tibial translation (mean, 19.5 mm) [18]. This investigation concluded that the quadriceps could serve as a major intrinsic force in noncontact ACL injuries.

Significant differences between genders in quadriceps and hamstring peak torques have been reported by numerous investigations [4, 45]. One study conducted on 853 females and 177 males aged 9–17 years found that significant gender differences in lower extremity strength occurred at age 14 [4]. A concerning finding was that female athletes appeared to obtain peak hamstring strength at age 11, with no significant difference found between girls 11 years of age and those up to 17 years of age (Fig. 3.1).

In order to determine which risk factors for noncontact ACL ruptures are significant and which may play a more negligible role, future investigations should use greater sample sizes,

Fig. 3.1 No significant difference was found in the mean flexor peak torque ratio values between females and males in the 9- to 13-year-old age groups. However, from the ages of 14–17 years, males had significantly greater mean flexor peak torque ratio values than females (Reprinted from Barber-Westin et al. [4])

analyze factors from all of the major risk categories (anatomical, environmental, hormonal, and neuromuscular), and follow athletes for at least one entire athletic season for injury. Athletes from multiple sports should be included to determine if certain factors are sports-specific in terms of injury risk. Future studies should incorporate reactive tasks, as there appear to be significant differences in movement and muscle activation patterns under these conditions versus those of controlled preplanned maneuvers. The effect of fatigue on multiple neuromuscular indices needs to be continued to be analyzed [46].

3.3 Identification of Athletes at Increased Risk for ACL Injury

The identification of athletes who may have an increased risk of sustaining a noncontact ACL rupture is of paramount importance in the continued development of knee injury prevention programs. The ability to detect certain individuals who may be predisposed to this injury entails understanding all of the risk factors previously discussed. While some potential factors may not be alterable, research has shown that high-risk neuromuscular characteristics can be successfully changed, which the authors believe will reduce the risk of noncontact ACL injuries [41, 58]. In this chapter, various factors to consider and testing options that are feasible and practical to perform in the clinic setting are discussed. It is important to note that no one single test has been found to be an indicator or predictor of a high-risk athlete; multivariate analyses are required, and our understanding of the hierarchy of all of the possible risk factors remains inconclusive at present.

3.3.1 Anatomic Factors: Body Mass Index

Uhorchak et al. [53] reported that a higher than average body mass index (BMI) was a risk factor for noncontact ACL injuries in female cadets. Higher than average was defined as one standard deviation above the mean value of 22 ± 2 in 118 women aged 17–23 years (Table 3.2). The authors postulated that this could be due to a poorer level of fitness or lower level of activity; however, they acknowledged that those explanations were very speculative and further research is required to understand the relationship between BMI and noncontact ACL injuries. BMI is calculated as weight (in kilograms)/height (in meters) squared.

3.3.2 Anatomic Factors: Femoral Notch Width

Some investigators have reported that a narrow femoral notch width is a risk factor for noncontact ACL injuries in female athletes [25, 53], although

Table 3.2 ACL noncontact injury risk screening for female athletes

Factor	Method	Possible risk factor results
Body mass index	Wt (kg)/Ht (m)^2	>24
Femoral notch index	Radiograph, see text	<12.7 mm
Generalized joint laxity[a]	1 point each side: Passive hyperextension finger, lies parallel to forearm Passive apposition of thumb to flexor aspect of forearm Hyperextension elbow >10° Hyperextension knee >10° Dorsiflexion ankle >30°	Total score ≥ 5 points
Drop-jump video test	See text, use normalized knee separation distance	>60 %
Single-leg squat test	The athlete stands on one extremity, places their hands on their hips, squats down as far as possible, and then returns to a single-legged stance without loosing their balance	Lateral tilt of the pelvis and/or the knee moves clearly into a valgus position and/or there is definite medial/lateral movement of the knee
Single-leg triple hop test	The athlete stands on one leg and hops three consecutive times on that leg as far as possible, crossing diagonally over the tape on each hop.	<85 % limb symmetry
Surface electromyography	See text, Zebis et al. [59]	Muscle preactivity: low semitendinosus, high vastus lateralis

[a]Carter and Wilkinson [14]

others have refuted this finding [47]. In a multivariate model, Uhorchak et al. [53] found that the combination of a narrow femoral notch width, higher than average BMI, and generalized joint laxity explained 62.5 % of the variability in noncontact ACL tears (R^2=0.625). This model was statistically related to 75 % of noncontact ACL injuries in women. A narrow notch width was defined as one standard deviation below the mean value of 15.6 ± 2.9 mm obtained from 113 women. In that investigation, notch width was measured on standard tunnel radiographs in which a line was drawn parallel to the tibial plateau through the femoral condyles and intercondylar notch at the level of the lateral sulcus. The authors stated that their results did "not add any insight into whether narrow femoral notch width is a risk factor for noncontact ACL injuries or merely a noticeable radiographic finding that is associated with ACL size." They did suggest, however, that women and men with narrow femoral notches may be at higher risk for injury than those with larger notches, regardless of whether the notch size itself contributes to ACL injuries. One criticism of using radiographs to measure notch width is that this provides only a single plane measurement and not a three-dimensional area of the actual size of the ACL.

3.3.3 Anatomic Factors: Generalized Joint Laxity

Generalized joint laxity may be a risk factor for noncontact ACL injuries [53]. Pacey et al. [40] in a meta-analysis of 18 studies, reported a statistically significant relationship between generalized joint hypermobility and risk of a knee joint injury during sports and military training with combined odds ratios ranging from 3.98 to 4.69 (P<.05). There was a statistically significant increase in the proportion of knee joint injuries in hypermobile participants compared to nonhypermobile athletes (P<.001).

The assessment of generalized joint laxity may involve the 8-point scale proposed by Wynne-Davies [57]; this includes small finger metacarpophalangeal hyperextension (≥ 90° of extension), elbow hyperextension, knee hyperextension, and the ability to touch the thumb to the

Fig. 3.2 The drop-jump take-off sequences from a 14-year-old female athlete before and after neuromuscular training. This basketball player demonstrated marked improvement in both the absolute cm of knee separation distance (from 17 to 37 cm) and normalized knee separation distance (from 47 to 92 %) after neuromuscular training (Reprinted with permission from Barber-Westin and Noyes [60], Fig. 16.11)

volar aspect of the forearm. Generalized joint laxity is considered present when five or more of these signs were observed bilaterally and in at least three joints. Carter and Wilkinson [14] also published a rating scale for assessing generalized joint laxity in which five factors are rated on each side to produce a total score of 10 possible points. A score of 5 points or greater indicates generalized joint laxity.

3.3.4 Neuromuscular Factors: Video Drop-Jump Screening Test

Video footage obtained during noncontact ACL injuries shows athletes had reduced knee flexion angles, increased hip flexion angles, valgus collapse at the knee, increased hip internal rotation, increased internal or external tibial rotation, and a flatfoot position [12, 29]. Therefore, testing that depicts these abnormal mechanics during activities such as landing from a jump, cutting, or sidestepping is recommended. The majority of research conducted over the past two decades on neuromuscular indices has utilized expensive force plate, multi-camera motion analysis systems. More recent studies employed "clinic-based" measures, but these still included isokinetic muscle strength testing and a 2-camera analysis of lower limb alignment during a drop jump that required three different software packages and intensive labor efforts [35].

A cost-effective and simpler method of determining lower limb alignment in the coronal plane on a drop jump has been described [37]. Performed with a single camera in any setting, this procedure clearly depicts a valgus lower extremity alignment on landing and demonstrates changes after neuromuscular training (Fig. 3.2).

A camcorder equipped with a memory stick is placed on a stand 102.24 cm (40.25 in.) in height. The stand is positioned approximately 365.76 cm (12 ft) in front of a box 30.48 cm (12 in.) in height and 38.1 cm (15 in.) in width. One-inch velcro circles are placed on each of the four corners of the box that faces the camera. Athletes should wear fitted, dark shorts and low-cut gym shoes. Reflective markers are placed at the greater trochanter and the lateral malleolus of both the right and left legs, and velcro circles are placed on the center of each patella. The jump-land sequence is demonstrated and one practice trial is done to ensure the athlete understands the test. No verbal instruction regarding how to land or jump is provided. Athletes are only told to land straight in front of the box to be in the correct angle for the camera to record properly. The athletes perform a jump-land sequence by first jumping off the box, landing, and immediately performing a maximum vertical jump. This sequence is repeated three times.

After completion of the test, all three trials are viewed, and the one that best represents the athletes' jumping ability is selected for measurement. Advancing the video frame-by-frame, the following images are captured as still photographs: (1) pre-land, the frame in which the athletes' toes just touch the ground after the jump off of the box; (2) land, the frame in which the athlete is at the deepest point; and (3) take-off, the frame that demonstrates the initial forward and upward movement of the arms and the body as the athlete prepares to go into the maximum vertical jump.

The captured images are imported into a hard drive of a desktop computer and digitized on the computer screen. A calibration procedure is done by placing the cursor and clicking in the center of each Velcro marker on each of the four corners of the drop jump box. The anatomic reference points represented by the reflective markers are selected by clicking in a designated sequence the cursor for each image.

The absolute cm of separation distance between the right and left hip and normalized separation distances for the knees and ankles, standardized according to the hip separation distance, are analyzed. Normalized knee separation distance is calculated as knee separation distance/hip separation distance, and normalized ankle separation distance is calculated as ankle separation distance/hip separation distance (Fig. 3.3). The authors believe that <60 % knee separation distance represents a distinctly abnormal lower limb valgus alignment position.

The reliability of the drop-jump video test was determined previously [37]. Test-retest trials produced high intraclass correlation coefficients (ICC) for the hip separation distance (pre-land, .96; land, .94; take-off, .94). For the within-test trial, the ICCs for the hip, knee, and ankle separation distance were all ≥.90, demonstrating excellent reliability of the videographic test and software capturing procedures.

If desired, a second camera may be implemented to assess knee and hip flexion angles in the sagittal plane. Many studies have reported that female athletes land with significantly less knee flexion than male athletes, and this is considered a risk factor for noncontact ACL injuries. A third option is to use a camera in the coronal plane to measure or classify lower limb alignment during motions such as cutting. Athletes may be categorized as valgus, varus, or neutral by observing the angle between the shank and thigh in the frame that represents the initiation of the cutting maneuver.

It is important to note that this test performed during one maneuver only depicts hip, knee, and ankle positions in a single plane, whereas noncontact ACL injuries frequently occur in side-to-side, cutting, or multiple complex motions. However, this test provides a general assessment of lower limb position and depicts those athletes who have poor control on landing and acceleration into a vertical jump. It is reliable, practical, and feasible for individuals who do not have funds or access to multiple cameras, force plates, and research personnel required to perform extensive data collection and reduction with more complex systems.

3.3.5 Neuromuscular Factors: Single-Leg Squat Test

The single-leg squat (SLS) test has been described in several studies as a useful clinical measure to detect dynamic knee control and hip muscle function [1, 51, 55]. The athlete stands on one extremity, places their hands on their hips, squats down as far as possible, and then returns to a single-legged stance without loosing their balance. Standing in front of the athlete, the observer may document the lower limb and knee position during the task (Fig. 3.4). One proposed rating involved a scale from 0 to 2, where 0 indicated good performance; 1, reduced performance; and 2, poor performance [51]. A score of 0 is given when there is no significant lateral tilt of the

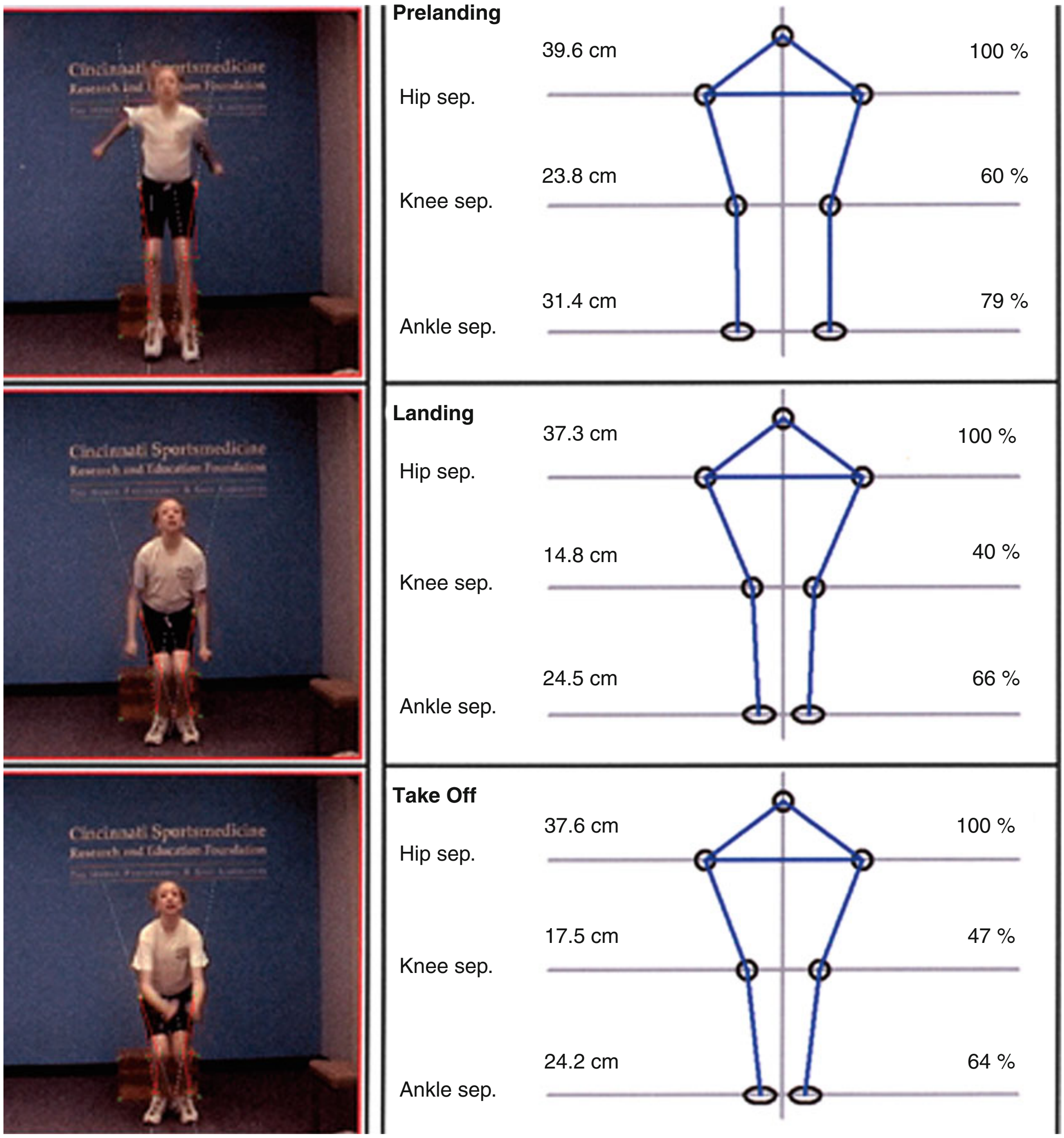

Fig. 3.3 The videographic test produced photographs of three phases of the drop-jump test. The cm of distance between the hips, knees, and ankles was calculated along with normalized knee and ankle separation distance (according to the hip separation distance). Shown is the test result of a 14-year-old female (From Noyes et al. [37])

pelvis, no obvious valgus motion of the knee, and no medial/lateral movements of the knee. A score of 1 is indicated when there exists some lateral tilt of the pelvis and/or the knee moves slightly into a valgus position and/or there is some medial/lateral movements of the knee. A score of 2 is given if there is lateral tilt of the pelvis and/or the knee moves clearly into a valgus position and/or there is definite medial/lateral movement of the knee.

3.3.6 Neuromuscular Factors: Single-Leg Functional Hop Testing

Single-leg functional hop tests are worthwhile to conduct to determine if abnormal limb symmetry exists and to subjectively assess the athlete's ability to hop and hold the landing on each limb [36]. These tests may involve a single hop, a timed hop over 6 m, a crossover hop, or a triple hop.

Fig. 3.4 Single-leg squat test. (**a**) Patient demonstrates good control of the lower extremity with no significant lateral tilt of the pelvis and no obvious valgus motion of the knee. (**b**) Patient demonstrates poor control with an obvious valgus position as the knee goes into flexion

One test the authors prefer is the single-leg triple crossover hop for distance. A marking strip made of masking tape is placed on the floor that extends approximately 6 m (Fig. 3.5) [36]. The athletes stand on one leg and hop three consecutive times on that leg as far as possible, crossing diagonally over the tape on each hop. They are encouraged to go as far as possible while maintaining balance and control. The final landing must be held for 2–3 s for the test to be considered valid. The furthest hop recorded on each limb is used for subsequent analyses. The limb symmetry index is calculated by taking the furthest hop obtained of the two legs (designated as leg #1), dividing it by the furthest hop distance of the contralateral leg (designated as leg #2), and multiplying by 100. A subjective assessment may also be made of the athlete's body position on landing (Fig. 3.6) and the determination made if they are able to hold a single-leg hop for at least 3 s.

The authors assessed data from on the single-leg triple crossover hop test in 1,023 athletes 9–18 years of age. An increase was found with age in the absolute distance hopped in all athletes ($P<.001$). There was no effect of age or gender on limb symmetry; the majority of athletes had a limb symmetry index ≥85 %. Female athletes who completed Sportsmetrics training had a significant increase in the absolute distance hopped and in their limb symmetry scores ($P<.05$). The conclusion was reached that the

Fig. 3.5 Single-leg triple crossover hop test

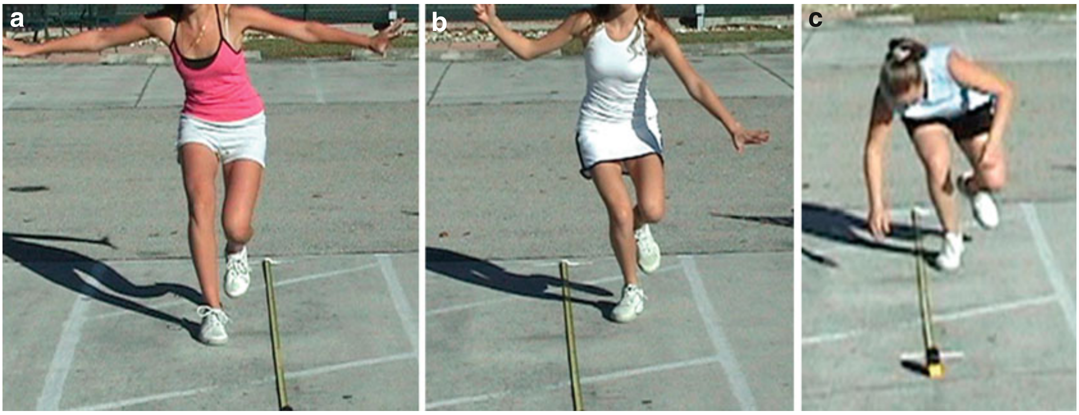

Fig. 3.6 Single-leg hop for distance video screening allows a qualitative assessment of an athlete's ability to control the upper and lower extremity upon landing, which may be rated as either good (**a**), fair to poor (**b**), or complete failure, fall to ground (**c**) (Reprinted with permission from Barber-Westin and Noyes [5], Fig. 19.4)

single-leg triple hop test is useful for measuring lower limb function in young athletes.

3.3.7 Other Tests to Consider: Electromyographical (EMG) Analysis of Muscle Function

Zebis and associates [59] used surface EMG to measure hamstring and quadriceps muscle activation that occurred just prior to landing during a side-cut maneuver. Before the start of the season, 55 elite female handball and soccer players aged 24 ± 5 years underwent testing during which only the preferred leg used to push-off was analyzed. During the season, five ACL noncontact ruptures occurred, all on the preferred push-off leg. There was a significantly lower preactivity of the semitendinosus muscle in the injured subjects compared to the noninjured players (21 ± 6 and 40 ± 17 %, respectively, $P < .001$), as well as a significantly higher preactivity of the vastus lateralis muscle (69 ± 12 and 35 ± 15 %, respectively, $P < .01$). The authors postulated that the EMG analysis may be an effective screening tool and proposed a high-risk category of one standard deviation above the mean vastus lateralis-semitendinosus difference. Future studies involving larger populations are required to determine if these conclusions are valid.

3.3.8 Other Tests to Consider: Maximal Aerobic Power

Many ACL injuries occur late in games or practices that are postulated to be due, in part, to fatigue. Neuromuscular fatigue has been shown to alter lower extremity kinematics and has the potential to increase the risk of noncontact ACL injuries due to deleterious changes in neuromuscular control [9, 13]. Aerobic fitness is a critical component for athletic performance and injury prevention [27]. Maximal oxygen uptake (VO_2max) may be measured most accurately using laboratory tests; however, they are expensive, time-consuming, and require trained personnel. These procedures typically measure VO_2max using indirect pulmonary gas exchange during a maximal treadmill run or stationary bicycle test. In order to provide coaches, athletes, and trainers with a simpler and more feasible alternative, field tests have been developed that provide an estimate of VO_2max. One of the most common is the 20-m multistage fitness test (MSFT) [30].

The equipment required are the MSFT commercially available audio compact disc (CD) and a CD player. Two cones may be used to mark the course. The athlete begins with their toes behind the designated starting cone. The second cone is located 20 m away. The athlete is instructed that, on the "go" command, they are to begin running back and forth between the two cones in time to recorded beeps on the CD. The athlete performs shuttle runs back and forth along the 20-m course, keeping in time with the series of signals (beeps) on the CD by touching the appropriate end cone in time with each audio signal. The frequency of the audible signals (and hence, running speed) is progressively increased until the athlete reaches volitional exhaustion and can no longer maintain pace with the audio signals, indicated when three beeps are missed in a row. The athletes' level and number of shuttles reached before they were unable to keep up with the audio recording are recorded.

The athletes' VO_2max is estimated using the equation described by Ramsbottom et al. [44]: $VO_2max = (5.857 \times \text{speed on the last stage}) - 19.458$

The results may be compared to those published according to sport, or may be analyzed according to gender and age-matched percentile groups published by the American College of Sports Medicine [19]. Whether a correlation exists between a poor MSFT score and an increased risk for a noncontact ACL injury is unknown and requires future investigation.

3.3.9 Other Tests to Consider: Neurocognitive Function Testing

To date, only one study has investigated a potential association between neurocognitive performance and noncontact ACL injuries. Swanik et al. [52] conducted neurocognitive testing using the Immediate Post-Concussion Assessment and Cognitive Test (ImPACT) on athletes from 18 universities before the start of their athletic season. Eighty athletes (45 women, 35 men) sustained noncontact ACL injuries and were matched with 80 controls for height, weight, age, gender, sport, position, and years of experience at the collegiate level. The test assessed verbal memory, visual memory, processing speed, and reaction time. There were statistically significant differences between the injured and control groups for all variables, with the injured athletes demonstrating slower reaction times ($P = .002$), slower processing speeds ($P = .001$), lower visual memory scores ($P < .001$), and lower verbal memory scores ($P < .05$). Compared to previously published normative values for this age group, the scores in the injured athletes ranged from low-average to average, indicating diminished function. The authors observed that mild deficits in reaction time and processing speed could make athletes more susceptible to errors or loss of coordination during the complex environment in athletic competition. In addition, the poorer visual and verbal memory scores indicated that these athletes might have difficulty interpreting and handling conflicting information during unanticipated events. Uncertainty or hesitation diminishes muscle activity, which could affect dynamic restraint and increase the risk of a noncontact ACL injury. The authors cautioned that further work was required to determine if deficits in higher brain center neurocognitive function could be clearly linked to dynamic restraint mechanisms. No gender comparison was performed in this study.

3.4 Effective Neuromuscular Retraining Programs That Reduce the Risk of a Noncontact ACL Injury

Several knee ligament injury prevention training programs have been published and comprehensive analyses of these have been presented elsewhere [7]. Unfortunately, methodological flaws and study limitations exist and few programs have demonstrated that training improved neuromuscular deficiencies and reduced the incidence of noncontact ACL injuries in female athletes. Problems include small sample sizes, inadequate number of noncontact ACL injuries to avoid the potential for a type II statistical error, lack of randomization, and no control group studied concurrently with a trained group. Some authors cited a reduction in noncontact ACL injury rates, while others failed to find a beneficial effect.

Programs have been published even though no evidence was presented regarding a reduction in ACL injuries.

As of the time of writing, only two studies [24, 34] have reported a statistically significant and relevant impact on reducing the incidence of noncontact ACL ruptures in female athletes. The first program, Sportsmetrics [23], involves three training sessions per week of 60–90 min duration for 6 weeks [5]. The program includes five major components: a dynamic warm-up (seven exercises); jump training (Table 3.3); strength training for the core, hip, and lower extremity (Table 3.4); sports-specific speed, agility, and conditioning drills [8, 38, 39]; and flexibility (ten stretches). A major emphasis is placed on the jump retraining exercises regarding correct body posture, form, and techniques (Fig. 3.7). Strength training is accomplished with weights in a school's facility or fitness center or with resistance bands and hand weights. Before and immediately upon completion of the program, athletes complete a series of tests including single-leg hops, drop jumps, vertical jumps, flexibility, and agility and speed tasks to determine the effectiveness of training in improving these tasks.

Sportsmetrics is effective in inducing changes in neuromuscular indices in female athletes, as studies have shown improved overall lower limb alignment on a drop-jump test [37], increased hamstrings strength [23, 37, 54], increased knee flexion angles on landing [42], and reduced deleterious abduction/adduction moments and ground reaction forces [23]. The program significantly reduced the incidence of noncontact knee ligament ruptures in high school athletes [24]. Three groups of soccer, volleyball, and basketball players were followed over the course of one season: 366 females who underwent training before their sport season began, 463 untrained females, and 434 untrained males. The total numbers of athlete exposures were 23,138 for the untrained group, 17,222 for the trained group, and 21,390 for the male control group. The knee injury incidence per 1,000 athlete exposures was 0.43 in untrained female athletes, 0.12 in trained female athletes, and 0.09 in male athletes ($P=0.02$). Untrained female athletes had a 3.6 times higher incidence of knee injury than trained female athletes ($P=0.05$) and 4.8 times higher than male athletes ($P=0.03$). The incidence of knee injury in trained female athletes was not significantly different from that in untrained male athletes ($P=0.86$).

The second training program, prevent injury and enhance performance program (PEP), significantly reduced the incidence of noncontact ACL injuries in female soccer players [34]. PEP is a 20-min warm-up program available on videotape. The traditional warm-up is replaced with this program on the soccer field before practices and games. PEP consists of three basic warm-up activities, five stretching exercises for the trunk and lower extremity, three strengthening exercises, five plyometric drills, and three soccer-specific agility activities. Instruction for the drills and jump exercises, including proper biomechanical technique, is described on the videotape.

Mandelbaum et al. [34] reported the initial results of the PEP program in 1,885 trained female soccer players and 3,808 untrained female soccer players 14–18 years of age over the course of one season. The total number of athlete exposures was 205,308. The knee ligament injury incidence per 1,000 athlete exposures was 0.49 in untrained female athletes and 0.09 in trained female athletes ($P<.001$). Then, a second investigation was conducted in female collegiate soccer athletes whose mean age was 19.8 years; 583 of whom underwent training and 852 served as controls [20]. The athletes were followed during the course of one season. The total number of athlete exposures was 88,139. The incidence of noncontact ACL ruptures per 1,000 athlete exposures was 0.189 in untrained female athletes and 0.057 in trained female athletes ($P=0.066$). The study lacked the statistical power to compare subgroups because of the smaller than expected number of noncontact ACL injuries reported.

Table 3.3 Sportsmetrics neuromuscular training program: Jump training component

Phase	Jumps	Duration		Emphasis, goals
1. Technique development		*Week 1*	*Week 2*	Proper form and technique for each jump
Weeks 1–2	Wall jump	20 s	25 s	Correct posture, body alignment throughout each jump
	Tuck jump	20 s	25 s	Jump straight up with no excessive side-to-side or forward-backward movement
	Squat jump	10 s	15 s	Soft landings that include toe-to-midfoot rocking and bent knees
	Barrier jump (side-to-side)	20 s	25 s	Deep knee flexion
	Barrier jump (forward-back)	20 s	25 s	Instant recoil preparation for the next jump, no double bouncing
	180° jump	20 s	25 s	
	Broad jump (stick 5 s)	5 reps	10 reps	
	Bounding in place	20 s	25 s	
2. Fundamentals		*Week 3*	*Week 4*	Proper technique to build a base of strength, power, agility
Weeks 3–4	Wall jump	25 s	30 s	Focus on well-performed, quality jumps
	Tuck jump	25 s	30 s	Same jumps from phase 1 done for longer duration
	Jump, jump, jump, vertical jump	5 total	8 total	New, more difficult jumps introduced to build on skills mastered from phase 1
	Squat jump	15 s	20 s	
	Barrier hop side-to-side[a]	25 s	30 s	
	Barrier hop forward-back[a]	25 s	30 s	
	Scissors jump	25 s	30 s	
	Single-leg hop[a] (stick)	5 reps	5 reps	
	Bounding for distance	1 run	2 runs	
3. Performance		*Week 5*	*Week 6*	Enhance basic skill and muscle control learned in first two phases
Weeks 5–6	Wall jump	20 s	20 s	Increase quantity, speed of jumps with well-performed, quality jumping technique
	Jump up, down, 180°, vertical	5 total	10 total	
	Squat jump	25 s	25 s	
	Mattress jump side-to-side	30 s	30 s	
	Mattress jump forward-back	30 s	30 s	
	Hop, hop, hop, stick[a]	5 reps	5 reps	
	Jump into bounding	3 runs	4 runs	

Reprinted with permission from Barber-Westin and Noyes [5]
s seconds, *reps* repetitions
[a]Repeat on both sides for duration or repetitions listed

Table 3.4 Sportsmetrics strength exercise options

Exercise	Comments
Hamstring curls	Using weight machine
Leg extension	Using weight machine
Leg press	Using weight machine
Abdominal crunch	Using weight machine
Back hyperextensions	Using weight machine
Bench press	Using weight machine
Latissimus pulldown	Using weight machine
Dynamic standing squats	May add medicine ball or free weights
Walking lunges (forward, backward)	May add free weights
Lateral lunge – moving	May hold medicine ball at waist
Diagonal lunge – stationary	May hold medicine ball at waist
Diagonal lunge – moving	May hold medicine ball at waist
Long stride lunge with knee lift	May hold medicine ball at waist
Wall sits	May add medicine ball or free weights
Toe/calf raises (neutral, internal, external)	May perform both legs together or single leg
Standing hamstring curls	May add resistance band or cuff weight
Prone hamstring curls	May add resistance band or cuff weight
Latissimus pulldown	With resistance band
Seated row	With resistance band
Triceps extension	With resistance band
Triceps dips	With hand weight
Lateral step	With resistance band
Lateral step with squat	With resistance band
Hip kicking	With resistance band
Backward walking	With resistance band
Seated hip rotation	With resistance band
Push-ups	
Superman	
Supine hamstring (bridge)	
Abdominal crunch with ball (side-to-side)	With medicine ball
Abdominal crunch with ball (in and out)	With medicine ball
Abdominal crunch with backward cycling	
Abdominal leg lowering	
Modified plank position; alternating leg raise	
Standing abductor ball roll	With medicine ball
Supine throw-ins with partner	With medicine ball
Bridging with foot on ball	With medicine ball
Bridging with ball roll	With medicine ball
Abdominal rotation with partner	With medicine ball
Abdominal overhead pass with partner	With medicine ball

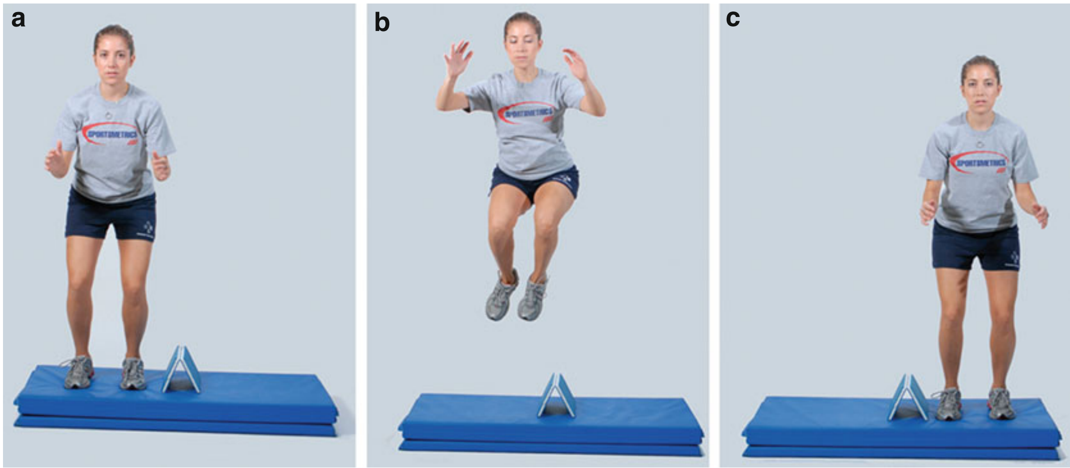

Fig. 3.7 The mattress jump, side-to-side is demonstrated. A cone or barrier is placed on a cushioned surface approximately 2–3 inches deep. The athlete performs a double foot jump from one side (**a**) over the barrier (**b**) to the other side (**c**). The feet are kept together and the athlete is instructed to begin and end the jump in the same amount of knee flexion (Reproduced with permission from Barber-Westin and Noyes [5], Fig. 19.19)

3.5 Take Home Messages: Future Research

Female athletes have a higher risk of knee ligament injuries than male athletes in sports such as soccer, basketball, and handball. The factors responsible for this problem remain under investigation. Future investigations should use greater sample sizes, analyze factors from all of the major categories (anatomical, environmental, hormonal, and neuromuscular), and follow athletes for at least one entire athletic season for injury. Athletes from multiple sports should be included to determine if certain factors are sports-specific in terms of injury risk. Future studies should investigate neuromuscular indices using unplanned, reactive movement patterns in an athletic environment versus controlled, preplanned maneuvers in a laboratory setting.

The identification of athletes who have an increased risk of sustaining a noncontact ACL injury requires continued research efforts. These include developing tests that have a reasonable predictive value which are feasible from a cost and personnel standpoint.

Few neuromuscular retraining programs have significantly (and with adequate statistical power) reduced the incidence of noncontact ACL ruptures in female athletes. The two published successful programs implement specific teaching techniques designed to alter movement patterns and strength in the core and lower extremity. Future studies should include larger number of athlete exposures either over the course of a single season or over multiple seasons in order to have sufficient power to avoid the potential for a type II statistical error.

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4 Anterior Cruciate Ligament Surgery: Risk Factors for Development of Osteoarthritis: What Can We Do to Prevent It?

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4.1 The Incidence and Prevalence of Osteoarthritis in the ACL-Deficient Knee and in the ACL-Reconstructed Knee

The anterior cruciate ligament (ACL) injury is well known as a risk factor for knee osteoarthritis (OA) with or without reconstruction. Oiestad et al. [36] reported the prevalence of knee OA of ACL-injured subjects treated surgically or non-surgically in their systematic review. They concluded that the highest rated studies on methodology reported low prevalence of knee OA for individuals with isolated ACL injury (0–13 %) and a higher prevalence for ACL-injured subjects combined with meniscus and/or medial collateral ligament injury (21–48 %). Their group also reported prevalence of OA at 10–15 years' follow-up after ACL reconstruction with bone-patella tendon-bone (BTB) autograft [37]. The total prevalence of radiographic knee OA after ACL surgery was 74 % (the Kellgren and Lawrence -K&L- grade over 2), and subjects with combined injury had significantly higher prevalence of OA compared with isolated injury (80 and 62 %, K&L grade over 2), but no significant (n.s.) group differences were shown for *symptomatic* radiographic knee OA (46 and 32 % defined as K&L grade over 2 with knee pain during past 4 weeks). In addition, this study showed that radiographic knee OA (including both isolated and combined ACL injury, BTB, and hamstring tendon autograft) was detected in 71 % (K&L grade over 2), and 24 % showed

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Table 4.1 The prevalence of knee osteoarthritis after ACL reconstruction

Author	Year	Follow-up period (years)	Autograft	Prevalence of radiographic OA
Ferretti et al. [8]	2011	6	Hamstring	11 % (K&L grade 2)
				14 % (IKDC grade B)
				9 % (Fairbank grade 3)
Hui et al. [15]	2011	15	BTB	51 % (IKDC grade ≥B) isolated injury
Oiestad et al. [39]	2011	10–15	BTB or Hamstring	71 % (K&L grade ≥2); 24 % (K&L grade 3,4) isolated or combined injury
Struewer et al. [51]	2011	13.5	BTB	54 % (K&L grade ≥2) isolated injury
Oiestad et al. [37]	2010	10–15	BTB	74 % (K&L grade ≥2); 80 % (combined injury); 62 % (isolated injury)

Table 4.2 The middle-long follow outcome after ACL nonoperative treatment

Author	Year	Follow-up period (years)	Outcome (prevalence of radiographic knee OA)
Neuman et al. [34]	2008	15	16 % (K&L grade ≥2)
			23 % ACLR was performed
Neberung et al. [33]	2005	10	79 % menisectomy was performed
		20	95 % menisectomy was performed
		35	62 % TKA was performed
Lofmandar et al. [23]	2004	12	51 % (K&L grade ≥2)
			56 % ACLR was performed
			42 % nonoperative treatment
Fink et al. [9]	2001	5–7	13 % (modified Fairbank grade 3)
		10–13 years	35 % (modified Fairbank grade 3)

moderate or severe radiographic knee OA (K&L grades 3 and 4) [39].

In other recent studies, high prevalence of OA after ACL reconstruction using BTB autograft for isolated ACL injury was reported. Hui et al. [15] reported that 51 % of patients had radiographic evidence of OA (International Knee Documentation Committee evaluation – IKDC – grade B 41 %, grade C 10 % at 15 years after surgery). According to Struewer et al. [51], radiographic degenerative change over K&L grade 2 was recognized in 54 % of patients, and prevalence of grade 3 or 4 was found in 20 % of all patients at an average of 13.5 years after surgery. Ferretti et al. [8] reported the result of a medium to long-term follow-up of ACL using hamstring tendon. Radiographic evaluation demonstrated early signs of OA in 9 % (Fairbank classification grade 3) of patients at 6 years after surgery (Table 4.1).

The development of OA after ACL reconstruction has been reported for all types of surgical procedures. It is suggested that the ACL-reconstructed knee cannot restore joint kinematics fully to a normal level [10, 11, 29, 57].

Less data exists on the long-term OA in nonoperated ACL-injured patients (Table 4.2). As reported by Lohmander et al. [23], there are n.s. in the prevalence of radiographic knee OA 12 years after ACL injury between the subjects who had undergone ACL reconstruction and those who had not. Fink et al. [9] also reported that the risks for degenerative joint changes were similar for both the operative and the nonoperative group 10–13 years after injury. In the study of Neuman et al. [34], the prevalence of OA at 15 years after nonoperative treatment of ACL injury was 16 %, and 23 % of patients had undergone ACL reconstruction with a mean time of 4 years after injury. They concluded that in patients with ACL injury willing to moderate activity level to avoid reinjury, initial treatment without ACL reconstruction should be considered.

In contrast, Nebelung et al. [33] showed that in a cohort of 19 elite athletes with untreated ACL ruptures, almost all had medial meniscectomies by 20 years, and 10 had TKA by 35 years. Therefore, they concluded that strong consideration should be given to ACL reconstruction for elite athletes who continue to be active despite ACL insufficiency. It was also reported that ACL reconstruction could help the patients to regain the preoperative level of activity [28] and could diminish percentage of OA in comparison to conservatively treatment [56].

4.2 The Risk Factors for the Development of Osteoarthritis After Injury and Surgery

Magnussen et al. [26] reported the radiographic outcome based on graft choice of ACL reconstruction in their systematic review. It was reported that a minority of studies showed a significantly increased rate of tibiofemoral OA in the BTB group, and others showed no differences in tibiofemoral OA between groups. Therefore, they concluded that radiographic evidence of OA was inconsistent with autograft choice between BTB and hamstring tendon.

There are many reports comparing grafts as risk factors for OA (Table 4.3). Comparing autograft between BTB and single-bundle (SB) reconstruction using hamstring tendon, almost all studies have concluded that there are n.s. in clinical outcome and prevalence of OA between the graft types [2, 5, 13, 21, 54]. However, some studies have reported that patients with BTB graft had a greater prevalence of OA at long term [41, 43, 55] and recommended using hamstring tendon because of decreased harvest-site symptoms and radiographic OA [41].

Comparing autograft between double-bundle (DB) and SB reconstruction, the majority of studies have reported good short-term outcomes of DB reconstruction which was associated with improved rotational laxity, manual test of joint stability, and better subjective scores, which again it is suggested to avoid or reduce meniscus degeneration or OA [12, 42, 48]. In particular, anatomic DB reconstruction has been reported to restore closely normal kinematics [30, 52] and exhibited better clinical results than nonanatomic SB reconstruction [42].

It was reported in the systematic review by Oistead et al. [36] that the meniscal injuries and meniscectomy are well-documented risk factors for the development of knee OA after ACL injury. They reported that meniscal injury and/or chondral lesion exhibited significantly higher odds for radiographic knee OA 10–15 years' follow-up after ACL reconstruction [38]. Magnussen et al. [25] also reported the relationship between meniscus status at the time of ACL reconstruction and radiographic signs of OA at 5–10 years' follow-up in their systematic review. It was shown that patients undergoing partial meniscectomy at the time of ACL reconstruction were significantly more likely to develop radiographic evidence of OA than those with normal meniscus. Meanwhile, meniscal repair resulted in inconsistent findings.

Additional risk factors which may influence development of OA after ACL reconstruction have been discussed (gender differences, kinematic

Table 4.3 The prevalence of knee osteoarthritis BTB vs. hamstrings tendon autograft

Author	Year	Follow-up period (years)	Prevalence of radiographic OA BTB	Hamstrings (%)	*p*-value
Sajovic et al. [43]	2011	11	84 % (IKDC grade ≥B)	63	0.08
Holm et al. [13]	2010	10	64 % (K&L grade ≥2)	55	n.s.
Ahlden et al. [2]	2009	7	19 % (Ahlbäck rating system)	13	n.s.
			67 % (Fairbank rating system)	70	n.s.
Liden et al. [21]	2008	7	25 % (Ahlbäck rating system)	20	n.s.
			76 % (Fairbank rating system)	71	n.s.
Pinczewski et al. [41]	2007	10	39 % (IKDC grade ≥B)	18	0.04

Table 4.4 The risk factors of knee osteoarthritis after ACL reconstruction

Author	Year	Reported risk factors of OA
Li et al. [22]	2011	Medial menisectomy, medial chondrosis, length of follow up, BMI
Shelbourne et al. [47]	2011	Knee range of motion after ACLR
Spindler et al. [50]	2011	Allograft, smoking, BMI
Webster et al. [58]	2011	Kinematic differences (higher knee adduction moment of females)
Deneworth et al. [7]	2010	Single legged landing 4 months after ACLR
Keays et al. [17]	2010	Menisectomy, chondral damage, BTB, weak quadriceps, low-quadriceps/hamstring strength ratios
Oiestad et al. [37]	2010	Combined ACL injury (meniscal injury and/or condral lesion)
Ichiba et al. [16]	2009	Cartilage damage, menisectomy
Kessler et al. [18]	2008	Age, BMI
Pinczewski et al. [41]	2007	<90 % single legged hop test 1 year after injury
Seon et al. [45]	2006	Meniscal injury, interval of more than 6 months from injury to ACLR, age more than 25 years at ACLR

differences, age at surgery, muscle weakness, rehabilitation methods, BMI, smoking, time from injury to surgery) [16–18, 24, 38, 45, 50] (Table 4.4). Shelbourne et al. [46, 47] reported that the prevalence of OA on radiographs in the long term after ACL reconstruction is lower in patients who achieve and maintain normal knee range of motion, regardless of the status of the meniscus. Therefore, they concluded that proper perioperative rehabilitation may reduce the effect of partial meniscectomy for developing knee OA after surgery. In gender differences, Webster et al. [58] showed that the higher knee adduction moment seen in females compared with males after ACL reconstruction may suggest an increased risk factor for the development of osteoarthritis, and female patients were reported to exhibit statistically significant worse patient-reported outcomes than male patients before and at 1 and 2 years after surgery [1]. Comparing accelerated (19 week) with non-accelerated (32-week) rehabilitation after ACL reconstruction, it was reported that patients in both programs had the same clinical assessment, functional performance, proprioception, and thigh muscle strength [6]. However, in kinematic study during a single-legged hop landing after ACL reconstruction, Deneweth et al. [7] reported that tibiofemoral joint kinematics of the ACL-reconstructed knee are significantly different from those of the uninjured contralateral limb at 4 months after surgery. They concluded that early returning to sports involving dynamic single-legged landings may contribute to accelerated knee joint degeneration. Quadriceps muscle weakness is also considered one risk factor of OA after ACL reconstruction [17]. Pinczewski et al. [41] reported that <90 % single-legged hop test at 1 year was predictor of radiographic OA in association with muscle weakness. On the contrary, there is a report that quadriceps muscle weakness after ACL reconstruction was not significantly associated with knee OA [38].

4.3 The Relationship Between Radiographic Knee Osteoarthritis, Subjective Status, Functional Status, Quality of Life, and the Return to Sports

Oiestad et al. showed that subjects with severe radiographic knee OA (K&L grade 4) had also significantly more pain, impaired function, and reduced quality of life compared with those without radiographic knee OA, but no significant associations were detected between the KOOS (Knee Injury and Osteoarthritis Outcome Score) subscales and mild or moderate knee OA (K&L grades 2 and 3) 10–15 years after ACL reconstruction [37].

According to the systematic review about returning to sports after ACL reconstruction [3], the percentage of patients who could return to some kind of sports participation was 82 %. However, patients who could return to competitive sports at final follow-up were only 44 %. This was despite approximately 90 % achieving a successful surgical outcome in terms of impairment-based measures of knee function and 85 % achieving a successful outcome in terms of activity-based measures. And in other reviews, 3 objective criteria were reported to return sports activities [4]. The most common was lower extremity muscle strength, followed by lower limb symmetry and knee examination parameters of range of knee motion and effusions.

A number of previous studies have reported that ACL reconstruction using both BTB and hamstring tendon autografts provided good objective, subjective, and functional outcomes at from middle to long follow-up regardless of their prevalence of OA [2, 5, 13, 21, 26, 54].

Therefore, we considered that to achieve normal knee range of motion, lower extremity muscle strength and lower limb symmetry were likely to be important factors for both returning sports activity and preventing knee from OA after ACL reconstruction [4, 46, 47].

4.4 Prevention and Treatment of Osteoarthritis in the ACL-Deficient Knee and in the ACL-Reconstructed Knee

Takeda et al. [53] have reported about prevention and treatment of OA for athletes in their review. OA has three strong risk factors: excessive musculoskeletal loading, high body mass index, and previous knee injury in which prevention may work. All these factors may be avoided. Especially in ACL injury, prevention programs for sports injury have recently shown encouraging results. Norwegian studies showed that the prevention of ACL injuries was possible with the use of neuromuscular training programs [32, 40, 49]. However, if the ACL was injured, it is suggested that ACL reconstruction is effective in preventing knee osteoarthritis. Mihelic et al. [28] concluded that 94 % of patients who underwent ACL reconstruction had stable knees after 15–20 years, and there was a significantly lower percentage of OA in comparison to conservatively treated patients. Meanwhile, patients with knee OA after ACL reconstruction who are not obtaining adequate pain relief and functional improvement from a combination of rehabilitation and pharmacological treatment are considered for surgical treatments. There is agreement that arthroscopic debridement is not an efficient procedure in OA patients [31]. Cartilage treatments (microfracture, autologous chondrocyte implantation (ACI), mosaicplasty, osteochondral autologous grafts) are effective to restore normal knee function by regeneration of hyaline cartilage in case of early OA with cartilage defect. A Norwegian study comparing ACI with microfracture did not see a deterioration in the clinical results even 5 years after surgery; however, 25 % of the patients had early OA [19]. Otherwise, a number of animal studies with mesenchymal stem cell (MSC) transplantation method have been reported [20]; however, more clinical studies are needed. For the young and active athletes with symptomatic medial unicompartmental knee osteoarthritis, a high tibial osteotomy (HTO) may be indicated to avoid progression of disease. Only two studies that reported clinical results involving return to sports and heavy works after HTO were found. They showed that 75–91 % of patients after HTO were engaged in sports and recreational activities and regained the frequency and duration of sports activities [35, 44].

For older athletes with knee osteoarthritis, unicompartmental or total knee arthroplasty (TKA) may be considered to improve function and outcome score [14, 27]. However, further studies focusing on the appropriate level of sports activity after TKA and prevention of implant problems among athletes are needed.

4.5 Future: Does Prior ACL Reconstruction Have a Deleterious Impact on the Outcome of Knee Arthroplasty?

The impact of prior ACL reconstruction on TKA has been very little studied. Thirty-six patients who underwent ACL reconstructions and then

TKA at a later date were retrospectively reviewed [14]. The authors suggested that previous ACL reconstruction does not have a negative impact on the outcome of future TKA with respect to range of motion, outcome scores, infection, or patella baja.

Meanwhile, 22 patients undergoing TKA, with a mean of 26 years after ACL reconstruction, were compared to a matched control group, and difficulties obtaining tibial exposure and postoperative stiffness requiring manipulation under anesthesia were reported [27].

4.6 Future Research

In the future, specific prevention methods of OA after ACL surgery or nonsurgical procedures will be developed and evaluated. Specifically, differences of surgical procedures, sports activity level, sports items, and patients individual circumstances (gender differences, kinematic differences, meniscus and cartilage injuries, muscle weakness, age at surgery, rehabilitation methods, BMI, smoking, time from injury to surgery) must be elucidated. In general, little literature exists about the relationship between OA, rehabilitation, and follow-up after ACL reconstruction when other variables are controlled for. We believe that to achieve normal knee range of motion, normal lower extremity muscle strength and lower limb alignment are important factors for preventing early OA. Therefore, developing a research-based specific and adequate training protocol for each patient will be needed for prevention of OA after ACL injury and/or reconstruction.

4.7 Take Home Messages

- The prevalence of knee OA was over 70 % (K&L grade ≥ 2) 10–15 years after ACL reconstruction [36] (evidence level 1).
- The prevalence of knee OA of combined ACL injury (with meniscus and/or chondral lesion) was higher than isolated ACL injury [37] (evidence level 2).
- To perform meniscectomy at the time of ACL injury was significantly more likely to develop radiographic evidence of OA than patients with normal meniscus [25] (evidence level 2).
- Subjects with radiographic knee OA showed significantly more symptoms than those without radiographic OA 10–15 years after ACL reconstruction [37] (evidence level 2).
- Almost all patients who underwent ACL reconstruction had stable knees after 15–20 years, and there was a significantly lower percentage of OA in comparison to conservatively treated patients [28] (evidence level 3).
- The proper perioperative rehabilitation to achieve normal knee range of motion may reduce the effect of partial meniscectomy for developing knee OA after surgery [47] (evidence level 3).
- As deleterious impact on the outcome of total knee arthroplasty after prior ACL reconstruction, difficulties obtaining tibial exposure and postoperative stiffness requiring manipulation under anesthesia were reported [27] (evidence level 3).

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The Need for an Objective Measurement In Vivo of Rotational Stability of the ACL-Deficient Knee: How Can We Measure It?

5

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5.1 Introduction

Rotational stability plays a key role in restoring normal function of the knee after anterior cruciate ligament (ACL) reconstruction [15]. Therefore, the accurate evaluation of rotational stability would be an important outcome indicator of ACL reconstruction. The only clinical test for examining rotational stability of the knee is the pivot-shift test [46]. Most surgeons now recognize the importance of the pivot-shift test. A positive pivot-shift test, regardless of the grade, is indicative of a functionally deficient ACL and remains the *sine qua non* indication for surgery [13]. Moreover, it is predictive of poor subjective and objective outcome, patient discomfort, disability, failure to return to previous level of sport, increased scintigraphic activity in the subchondral bone, and development

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of osteoarthritis of the knee at long term [20, 21, 24, 50]. Therefore, accurate assessment of the pivot-shift phenomenon is clinically mandatory. However, currently, the gold standard for evaluation of rotational knee stability after ACL tears in the office is based on patient history and subjective un-instrumented physical examination, the pivot-shift test, which is highly variable and dependent on examiner's skill and experience and has both a low sensitivity and low interobserver reliability [32]. Moreover, the rotational load applied to the knee during the pivot-shift test is much lower than the load applied to the knee during sports activities. Furthermore, patient guarding can lead to false negatives. Moreover, clinical pivot-shift test cannot evaluate small rotational differences between the pathological/reconstructed and the healthy contralateral knee. Finally, the pivot-shift test is often only testable during examination under anesthesia. In our series, the sensitivity of the physical examination with the patient awake was 37.5%, whereas the sensitivity of the physical examination with the patient under general anesthesia was 87.5% [42]. Therefore, a negative clinical pivot-shift test does not necessarily involve a normal rotational stability. Currently, however, there is no simple, commercially available device to measure knee rotational stability in vivo.

Much of the current knowledge about ACL biomechanics has been derived from cadaveric studies under controlled laboratory conditions. However, in vitro studies cannot duplicate the physiological scenarios encountered in everyday activities. Thus, it is difficult to predict clinical outcome based on the results of cadaver studies, which cannot replicate functional loading. Only in vivo studies can assess the combined effects of tissue healing and remodeling that occurs overtime, neuromuscular control on joint function, and weight-bearing conditions. Therefore, in vivo studies are crucial to understand the short- and long-term implications of reconstructive surgery. Therefore, it is necessary to find an objective method to evaluate in vivo rotational stability during complex motion which is produced by sports activities.

5.2 The Need for an Objective Measurement of Rotational Stability of the Knee

For many years, an ACL-operated patient who did not complain and who returned to a previous level of sports was considered functionally intact. Our methods of evaluation have improved, so we are now able to evaluate restoration of anatomic shape by means of CT and MRI. Currently, however, we demand much more, the integration into the static equation (anatomy) of a dynamic understanding (biomechanics – kinetics and kinematics). With new ACL reconstruction techniques emerging, the need for an objective outcome tool measure during dynamic functional activities increases. Meta-analysis comparing different ACL reconstruction techniques shows no outcome differences [29, 40]. Maybe, we need to find more precise or sensitive outcome measures to detect subtle differences in surgical techniques that in the long-term follow-up may be associated with the development of osteoarthritis. Thus, it would be interesting to find a sensitive tool to evaluate the rotational stability of the knee.

5.3 Background

There are several methods to evaluate in vivo rotational stability in the ACL-deficient knee. Some kinematic methods such as dynamic MRI, computer-assisted navigation, 3D radiostereometric analysis (RSA), kinematic measurement using electromagnetic sensors or goniometers attached to intracortical pins, and 3D–2D model registration techniques are limited to environments too restrictive to perform highly demanding activities such as those produced by sports activities [5, 6, 14, 16, 22, 51]. Moreover, they have a limited value for predicting clinical function because (1) some of them only evaluate laxity (i.e., maximum displacement of the joint in response to an external load in the absence of muscle force [46]), (2) they do not simulate force magnitudes developed during sports gestures because the rotational load applied to the knee joint during the pivot shift using these methods is

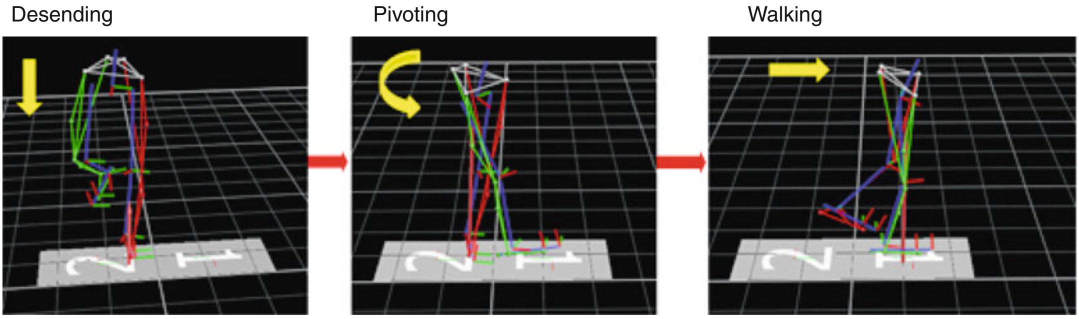


Fig. 5.1 A stick figure mimicking the descending and pivoting task which was performed by all subjects in the referenced study. During this task, the subject descended the stairway at his own pace. The descending period was concluded on initial foot contact of the ipsilateral (supporting) leg (that was tested) with the ground. After foot contact, the subject was instructed to pivot on the supporting leg at 90° and walk away from the stairway. While pivoting, the contralateral leg swung around the body (as it was coming down from the stairway), and the trunk was oriented perpendicularly to the stairway

considerably less than the load applied to the knee during sports, and (3) they do not evaluate the combined effect of dynamic neuromuscular control. The last is crucial because muscle forces play a significant role in knee stability, especially in the ACL-deficient and ACL-reconstructed knee [12, 19, 28]. On the other hand, computer-assisted navigation is invasive and requires that the patient undergoes surgery, and therefore, it cannot be used for clinical follow-up. Finally, RSA is also limited by the exposure to radiation.

Ideally, the best way to evaluate rotational stability should be during dynamic highly demanding functional activities. This can be done through kinematic analysis using skin-mounted marker-based video analysis or kinetic analysis using dynamometric platforms. Both methods could allow us to evaluate in vivo the knee under realistic loading conditions. This chapter focuses and discusses only the current techniques used to evaluate in vivo rotational stability in the ACL-deficient knee during high-stress activities.

5.4 Kinematic Analysis Using Optoelectronic Systems

5.4.1 What Is Kinematic Analysis?

Kinematics is the branch of mechanics that studies the motion of a body without consideration given to the forces that produce the motion. Data collection of kinematics during in vivo activities can be achieved through optoelectronic or video-based three-dimensional (3D) motion analysis systems that record the motion of skin-mounted reflective markers placed on selected osseous anatomic landmarks of the lower limbs and the pelvis according to the model described by Davis et al. [11].

5.4.2 Kinematic Analysis During Low- and High-Demanding Activities in ACL-Deficient and ACL-Operated Patients

In their benchmark study, Georgoulis et al. [16] examined ACL-deficient (ACLD) patients, bone-patellar tendon-bone (BPTB) ACL-reconstructed (ACLR) patients, and healthy matched controls during walking. It was demonstrated that during this low-demand activity, ACLD patients demonstrated greater tibial internal rotation which was decreased to closer to normal levels after ACLR. This study spotlighted the importance of tibial rotation for ACLR patients [16].

In a subsequent motion analysis study, Ristanis et al. [35] examined 20 ACLR patients with a BPTB autograft ACL reconstruction. The patients performed descending from a stairway and pivoting, a task that applies increased rotational load to the knee (Fig. 5.1). A matched control group of 15

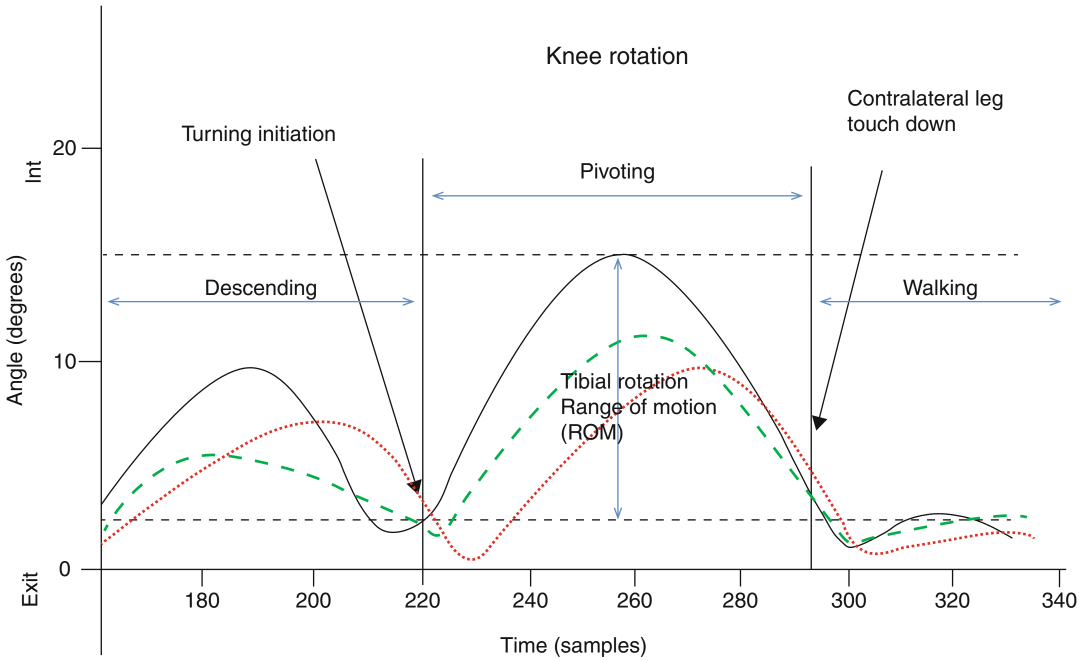


Fig. 5.2 The graph indicates the tibial rotation (*TR*) curve during the descending and pivoting task from a representative ACL-reconstructed subject. The evaluation period, that is, the pivoting period, and the tibial rotation range of motion (*ROM*) for this period are indicated. The *black solid line curve* represents the ACL-reconstructed knee, while *the green dashed line curve* and the *red dotted line curve* demonstrate the contralateral intact knee and the healthy control knee (healthy individual from the control group), respectively. The difference between the maximum and the minimum tibial rotation during the pivoting period is indicated (tibial rotation range of motion). The increased tibial rotation ROM for the ACL-reconstructed knee can be distinguished (From Zampeli et al. [52]. Reproduced with permission from ELSEVIER)

individuals as well as the contralateral intact knee of ACLR patients was also examined. The examined variable was the tibial rotation (TR). Specifically, the range of motion (ROM) during the pivoting period was determined (Fig. 5.2). The results showed that the ACL-reconstructed knee exhibits increased TR ROM as compared to the contralateral intact knee as well as compared to the knees of the healthy control group. Interestingly, the increased TR ROM of ACLR patients was found instead of the negative pivot-shift test and the normal anterior tibial translation as measured with KT-1000 arthrometer (SSD < 3 mm) [35].

In a subsequent study, another task that sets rotational load to the knee was examined. Eleven ACLR patients, 11 ACLD, and 11 matched controls performed landing from a platform and subsequent pivoting, while rotational kinematics were recorded using a 3D optoelectronic motion analysis system. The examined task imitates a sports activity task that is often performed by athletes during sports participation (Fig. 5.3). The ACL-deficient knee exhibits increased tibial rotation ROM as compared to both contralateral intact and healthy control knee. The ACLR knee showed increased TR ROM as compared to both contralateral intact knee and healthy control knee. In contrast, no significant differences were noted between the ACLD and ACLR knee [36].

Similarly, in a next study, the TR ROM was assessed in patients with a hamstring ACL reconstruction. The patients performed the descending and pivoting activity, and the ACLR knee was compared to the contralateral intact knee as well as the healthy control knee of a matched control group. The results showed that also with a hamstring autograft, the TR ROM is pathologically increased for ACLR knee when the patients perform a high-demanding activity that sets rotational load to the knee suggesting that transverse plane kinematic deficits after ACLR are independent of graft choice [17].

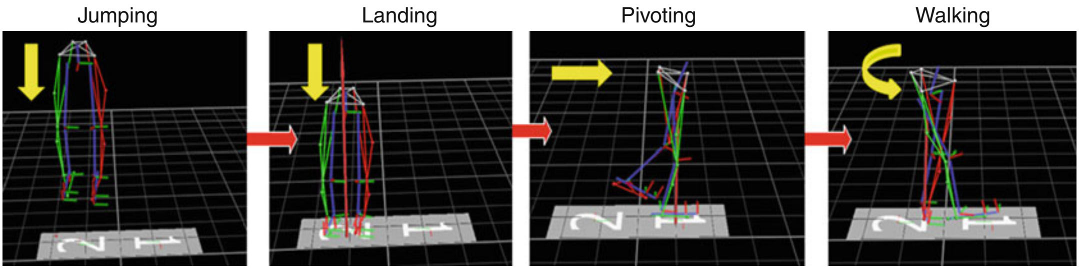


Fig. 5.3 The landing and pivoting task is indicated. During this task, the subject jumped off the platform and landed with both feet on the ground. After foot contact, the subject pivoted on the ipsilateral (supporting) leg at 90° and walked away from the platform. While pivoting, the contralateral leg swung around the body, and the trunk was oriented perpendicularly to the platform

Interestingly, similar findings were verified in a prospective follow-up study where the same methodology was used 2 years after the ACL reconstruction with a BPTB autograft. The rotational kinematics was collected with 3D motion analysis system while the patients performed the same high-demanding activities (i.e., descending and pivoting and landing and pivoting). The results showed that TR ROM still remains abnormally increased for ACLR knees as compared to contralateral intact and healthy control knees even 2 years after the ACL reconstruction. The authors suggested then for the first time that excessive tibial rotation over time may lead to further deterioration of the knee resulting from abnormal loading at areas of the cartilage that are not commonly loaded in a healthy knee [37].

In addition, when the two most commonly used autografts were evaluated in the same study, it was demonstrated that although both successfully restored anterior tibial translation, however, none was able to restore TR to normal values. Both ACL reconstruction groups had significantly increased tibial rotation when compared with the controls, whereas no differences were found between the two reconstructed groups. These results indicated that the two most frequently used autografts for ACL reconstruction cannot restore tibial rotation to normal levels, and the authors of the study suggested that new surgical techniques are needed that can better approximate the actual anatomy and function of the ACL [9].

In summary, when transverse plane biomechanics were assessed in a series of studies in the last 8 years, it was consistently found that ACLD patients demonstrate higher internal tibial rotation which is decreased but not restored to normal levels after ACLR. It was also found that the deficits are more apparent when high-demand activities placing rotational stress on the knee are investigated.

5.4.3 Clinical Relevance

The systematic and meticulous investigation of rotational knee kinematics provided all this information about ACL-deficient and reconstructed patients' movement pattern which has been proven to be particularly clinical relevant in the area of ACL reconstruction and to have great impact on the surgical technique.

The most important influence that in vivo rotational kinematics had on the surgical technique is the one relating to the single-bundle ACL graft placement. Ristanis et al. [38] examined for first time if a more horizontal placement of the femoral tunnel (in the 10 o'clock position rather than in the 11 o'clock position) can restore rotational kinematics, during highly demanding dynamic activities in patients with a BPTB single-bundle ACL reconstruction. The results demonstrated that none of the two ACL reconstruction techniques (i.e., with the femoral tunnel in the 10 or the 11 o'clock position) restored the TR in normal values, and both resulted in TR values that were significantly larger than those of the intact contralateral and healthy control knees. Besides, it was demonstrated that although tibial rotation did not differ significantly between

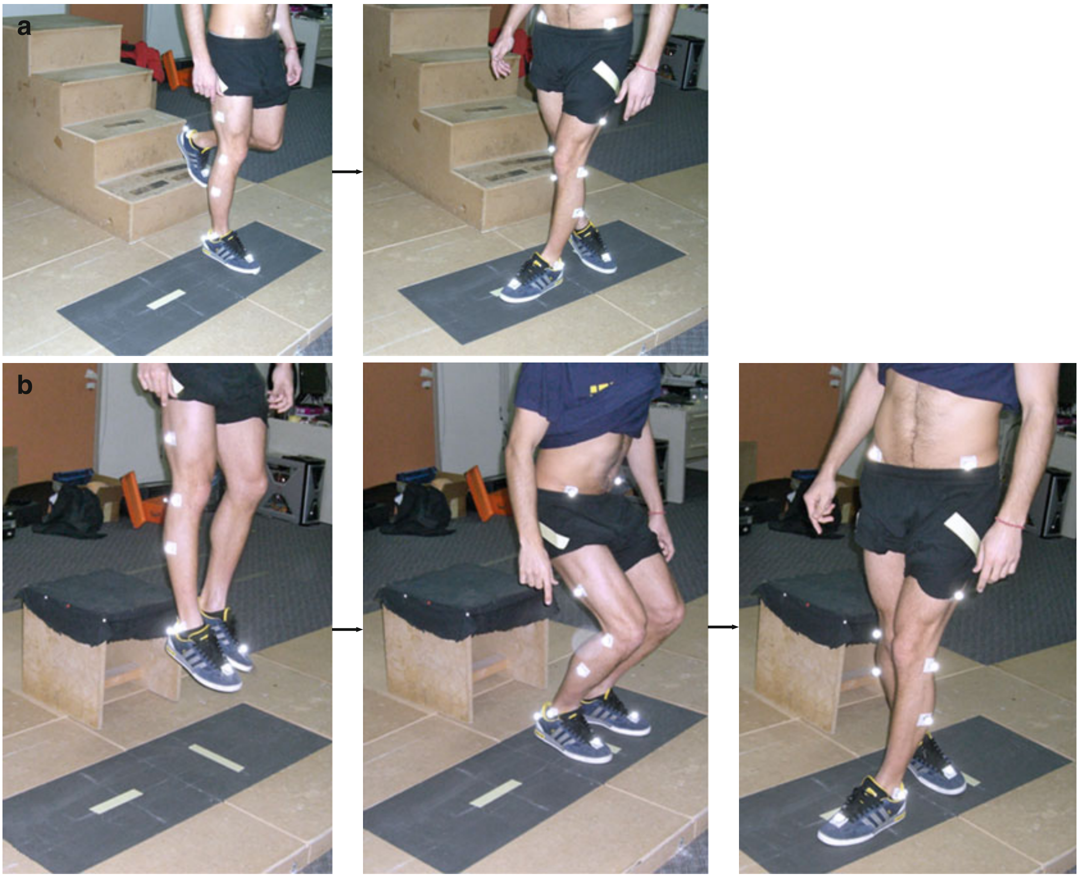


Fig. 5.4 A participant of the referenced study performing (**a**) the first activity that was examined, that is, descending and subsequent pivoting, and (**b**) the second activity, that is, landing from a jump and subsequent pivoting. During both tasks, each participant followed the floor markers to secure the reproducibility of the testing protocol regarding the pivoting period that was the evaluation period during which the tibial rotation range of motion was recorded for the examined knee (From Zampeli et al. [52]. Reproduced with permission from ELSEVIER)

the two reconstruction groups, however, it was noticed that positioning the tunnel at 10 o'clock resulted in slightly decreased rotation values that may have clinical relevance but not statistical significance. Indeed, the clinical relevance of those findings was verified in a subsequent motion analysis study in which Zampeli et al. [52] demonstrated that a significant positive correlation exists between TR ROM and the ACL graft angle in coronal plane MRI for the two in vivo dynamic tasks that were examined (i.e., descending and pivoting and landing and pivoting) (Fig. 5.4). A significant positive relationship was also observed between side-to-side TR ROM (i.e., the difference between the operated and contralateral intact knee) and coronal ACL graft angle. The findings of this study demonstrated that TR was better restored in ACLR patients with a more oblique graft in the coronal plane, and although these data do not imply a cause-and-effect relationship between the two variables, they can be indicative that a more oblique placement of single BPTB ACL graft in coronal plane is correlated with better control of TR [52].

Concerning the most optimal graft type for ACL reconstruction, several studies have set out to identify differences between the two most commonly used autografts, the BPTB and the hamstrings. Among them, of paramount importance are the studies that used motion analysis in order to identify the in vivo dynamic rotational kinematics of ACL-reconstructed patients. Ristanis et al. [35, 36] showed in their studies that the ACL-reconstructed patients with a BPTB autograft still have increased TR as compared to healthy knees, while Georgoulis et al. [17] showed that this was also a fact when the hamstring autograft was used. These studies showed that no one from the two grafts achieved normal rotational kinematic pattern for the ACLR patients. In addition, in their motion analysis study, Chouliaras et al. [9] compared two groups of patients, one with BPTB ACL reconstruction and one with hamstrings, and also showed that no differences exist between these two autografts concerning the restoration of abnormal rotational kinematics of the involved knee joint.

Double-bundle ACL reconstruction has been suggested as another surgical technique that can restore tibial rotation to normal values. Lam et al. [23] showed in their in vivo motion analysis study that the anatomic double-bundle ACL reconstruction successfully restores knee rotational stability from an impaired level during pivoting activities. Misonoo et al. [30] demonstrated that there were no significant differences in tibial rotation between their double-bundle group and the single-bundle group and suggested that anatomical double-bundle reconstruction restores normal tibial rotation no more than single-bundle reconstruction during a high-demand dynamic activity. Similarly, Tsarouhas et al. [47] examined the in vivo rotational kinematics of the knee after ACL reconstruction with single- or double-bundle techniques using an optoelectronic motion analysis system and showed that double-bundle ACL reconstruction does not reduce knee rotation further compared with the single-bundle reconstruction technique.

Recently, the issue of whether knee braces can effectively decrease tibial rotation in high-demanding activities that apply increased rotational load to the knee joint has been investigated with motion analysis studies. Giotis et al. [18] demonstrated that bracing decreased the range of motion of TR during the examined activities (descending and pivoting and landing and pivoting). Although these data came from healthy control individuals, the same authors recently examined ACL-deficient patients showing the effectiveness of bracing on decreasing the abnormal TR also for this population (unpublished data).

5.4.4 Theoretical Proposition for the Development of Osteoarthritis of the ACL-Reconstructed Knee

The pivot-shift test that is the most widely and commonly used clinical test for examining rotational stability of the knee is predictive of poor subjective and objective outcome, patient discomfort, failure to return to previous sports activity level, increased scintigraphic activity of the subchondral bone, and development of osteoarthritis of the knee at long term [20, 21]. Recently, it was shown that rotational knee kinematics during in vivo pivoting activities also predicts subjective functional outcome of the knee joint after ACLR, providing to the in vivo rotational knee kinematics special clinical value that has not been reported before (unpublished data). While the pivot-shift test examines the knee joint stability under a combined rotational and valgus load, the in vivo rotational knee kinematics may determine those subtle deviations from the normal knee joint kinematic pattern that cannot be detectable with the pivot-shift test. Interestingly, in most of the biomechanical studies that have examined rotational knee kinematics, the ACL-reconstructed patients that were tested exhibited negative pivot-shift test results. These abnormal rotational knee kinematics of ACL-deficient and reconstructed patients have been related to the initiation and progression of knee joint osteoarthritis (OA) in these patients [3, 4, 44]. Current ACL reconstruction techniques do not seem to fully restore normal kinetic/kinematic of the knee. Excessive tibial rotation is still present during highly demanding activities after ACL reconstruction. It has been suggested that pathologically increased tibial rotation causes the loading of specific regions of the articular cartilage that were not loaded prior to the ACL injury [4, 25, 44] and that

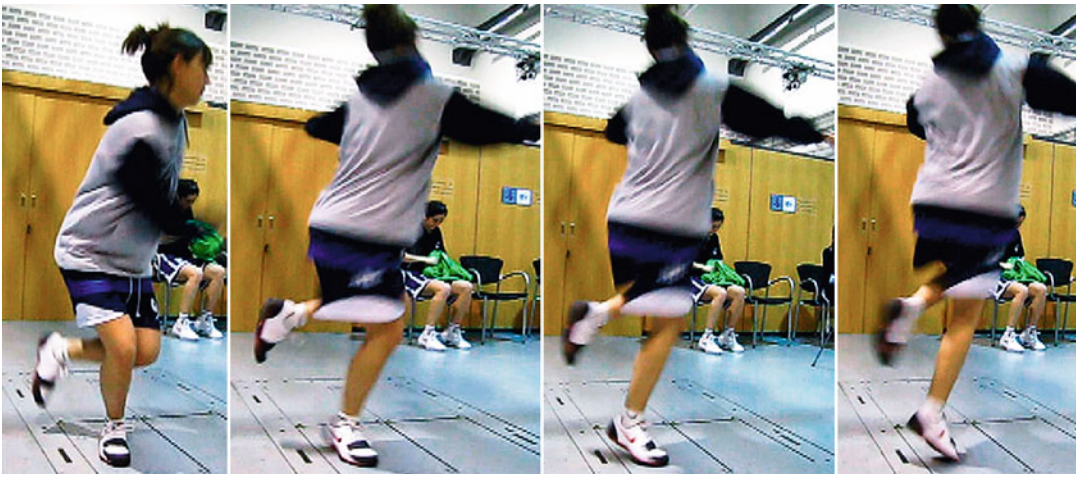


Fig. 5.5 The subject is placed in a standing position on the platform facing a reference point with both arms extended alongside the body. When the examiner says, "ready," the subject lifts up the uninvolved limb and keeps the one under study in full extension. Next, the subject will flex the involved knee and rotate the body in the direction opposite to the intended spin, in order to reach the joint's maximum contrary rotation. This is the loading phase. The second part of the movement is the pivoting phase, and it begins when the loading phase is completed. The subject begins rotating in the intended spin direction while extending the knee to push himself/herself upward. For the analysis to be effective, the pivoting phase has to be fast and explosive in order to achieve maximum rotation demand of the joint. After a preliminary study, we decided not to include patients with a body twist angle of less than 90º (unpublished data)

this altered contact mechanics in the newly loaded regions could produce local degenerative changes to the articular cartilage of the knee joint [2].

5.4.5 Limitations of Kinematics Data Collection and Proposals to Minimize Them

These are related to the use of skin markers in motion analysis [27]. There are certain circumstances under which motion analysis is currently widely accepted and is considered as a well-established and reliable method [8, 49]. The interoperator error can be minimized by having the same clinician place all the markers and acquire all the anthropometric measurements. Besides, before the dynamic data collection, a standing calibration procedure should be used to correct for subtle misalignment of the markers that define the local coordinate system and to provide a definition of 0° for all segmental movements in all planes. Finally, since it has been reported that outcomes after ACL reconstruction differ between men and women [1] and menstrual cycle-related hormonal factors affect knee joint laxity [53], it is strongly recommended that the sample in each motion analysis study consists of patients of the same gender (either males or females).

5.5 Kinetic Analysis

5.5.1 What Is Kinetic Analysis? Rationale

Kinetic analysis consists of the study of forces and moments that produce movement. Currently, dynamometric platforms are the most widely used technique for kinetic analysis. A dynamometric platform is an electronic instrument that measures and analyzes the reaction force that a person exerts on the ground during a certain movement or gesture, in this case would be the pivoting gesture with monopodal support (Fig. 5.5). Kinetic parameters are expressed in a curve with two humps: one positive and one

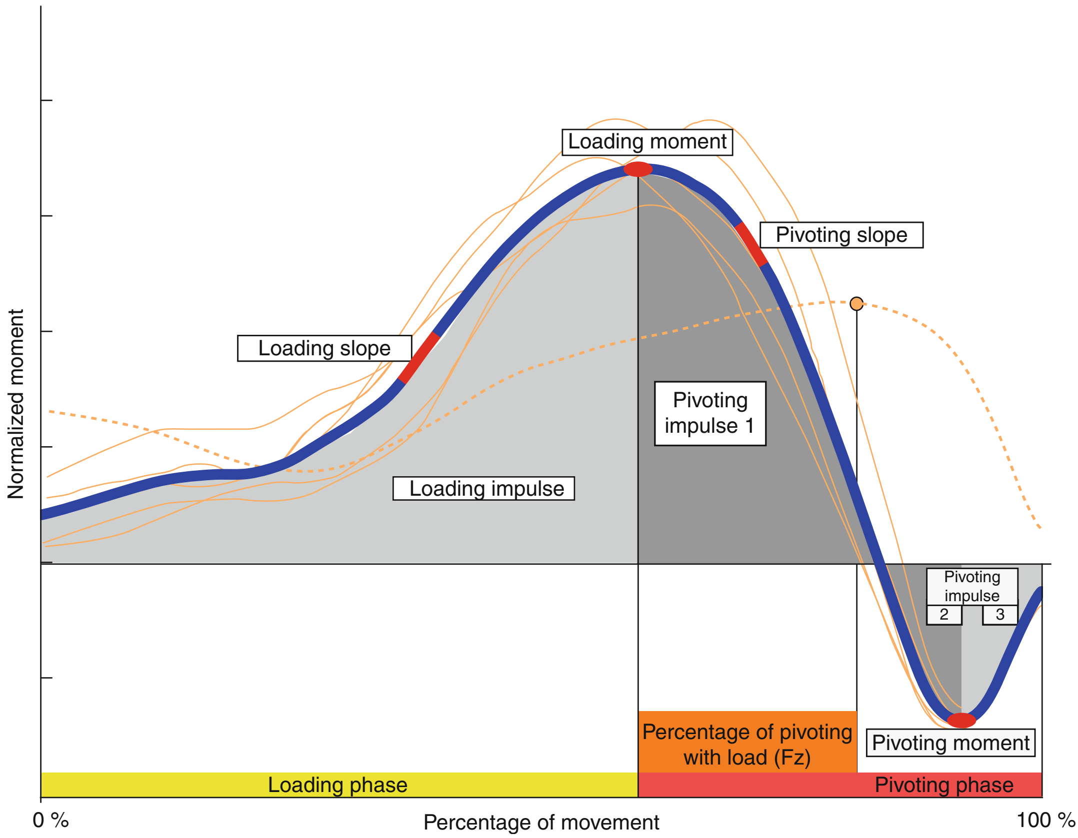


Fig. 5.6 Pivoting kinetic parameters. Curve for the normalized moment during the jumping with pivoting with external/internal tibial rotation test. We can compare the pivoting slope with a ski run slope. The greater the slope inclination, the higher the skier's speed will be; and the longer the ski run, the higher the speed reached by the skier. Fz = vertical ground reaction force exerted on the dynamometric platform during the performance of the test (From Sanchis-Alfonso et al. [42]. Reproduced with permission from the Journal of Bone and Joint Surgery, American Volume)

negative (Fig. 5.6). The torque measured on the platform given, the monopodal support, is directly proportional to the torque measured in the knee. The dynamometric platform registers the forces exerted by the subject and determines the exact point of application beneath the foot, which is called center of pressure (COP). It has been demonstrated using stereophotogrammetry that the COP nearly coincides with the vertical projection of the center of rotation of the knee joint during a pivoting gesture [42]. As we can see in Fig. 5.7, the rotational moment at the knee nearly coincides with the moment calculated at the dynamometric platform. Therefore, the moment registered with the platform would be a good estimation of the real torsional moment of the knee.

In a recent paper, Sanchis-Alfonso et al. [42] have introduced kinetic analysis as a new method for testing rotational instability. The objective of their study was to determine the usefulness of kinetic analysis to detect functional deficits in ACL-deficient knees and to determine parameters of knee function that are affected by ACL deficiency. They have shown that kinetic analysis using a dynamometric platform can objectively detect alterations of rotational stability in ACL-deficient knees which could make this a useful research tool for studying treatment strategies in patients with ACL injuries. The authors have designed two tasks (monopodal jumping with pivoting with external tibial rotation – similar to Clancy's test – and monopodal jumping with pivoting with internal tibial rotation – similar to

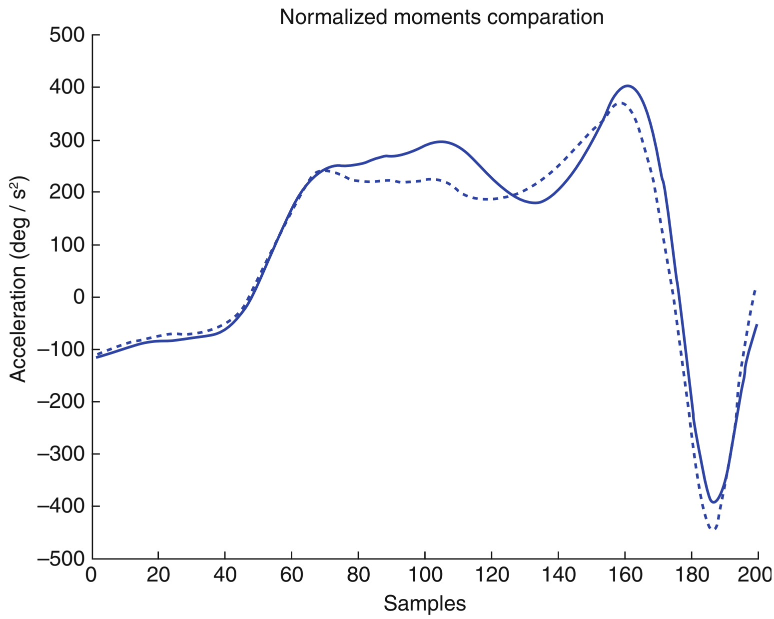


Fig. 5.7 The rotational moment at the knee nearly coincides with the moment calculated at the dynamometric platform

Losee's test) to reproduce the symptomatic pivot-shift phenomenon and therefore the pathomechanics of an ACL injury in order to analyze the "avoidance behavior" to guard against subluxation, which according to Strobel and Stedtfeld can also be interpreted as a positive sign [45].

It is well known that patients with chronic tears of the ACL modify their strategy of running. They try to run in a straight line to avoid pivoting, because they know that if they pivot, the knee will give way. This way of running is a defense mechanism. Based on this observation, Sanchis-Alfonso et al. [42] proposed the following hypothesis: if there is a rotational instability in the knee, the patient will avoid reaching high moments, generated by the foot stepping on a dynamometric platform, during pivoting activities as a self-defense mechanism, and therefore, the pivoting ground reaction moment would also be reduced.

Sanchis-Alfonso et al. [42] have evaluated a group of non-coper patients (i.e., patients that were not able to return to their previous level of sports due to knee instability when pivoting or even with activities of daily living) with a chronic ACL tear (defined as an ACL tear for more than 3 months). In this study, the authors excluded any patient who compensated his or her instability after a correct physical therapy program (copers). These authors have shown that the number and grade of altered kinetic parameters was significantly higher in the test performed with external tibial rotation than in the one performed with internal tibial rotation (Fig. 5.8) [42]. This fact is in accordance with previous clinical studies, which have shown that external tibial rotation increases significantly the pivot-shift phenomenon [10, 33]. Therefore, the authors recommend performing the test with external tibial rotation. They have observed a significant decrease of the pivoting moment (torque generated during the pivoting gesture), pivoting slope (speed at which the pivoting gesture is developed), and pivoting impulse (energy at which the pivoting gesture is developed) during the jumping with pivoting with external tibial rotation test in the ACL-deficient knee compared with the healthy contralateral knee [42]. This is reflected on a curve with a specific shape during the test performed with external tibial rotation (Figs. 5.9 and 5.10). Moreover, they have evaluated a group of healthy recreationally active athletes during the same task (Fig. 5.11). In the latter group, they have not found statistically significant differences between both knees in the pivoting moment, pivoting slope, and pivoting impulse [42]. Furthermore, these kinetic parameters were not influenced by limb dominance [42].

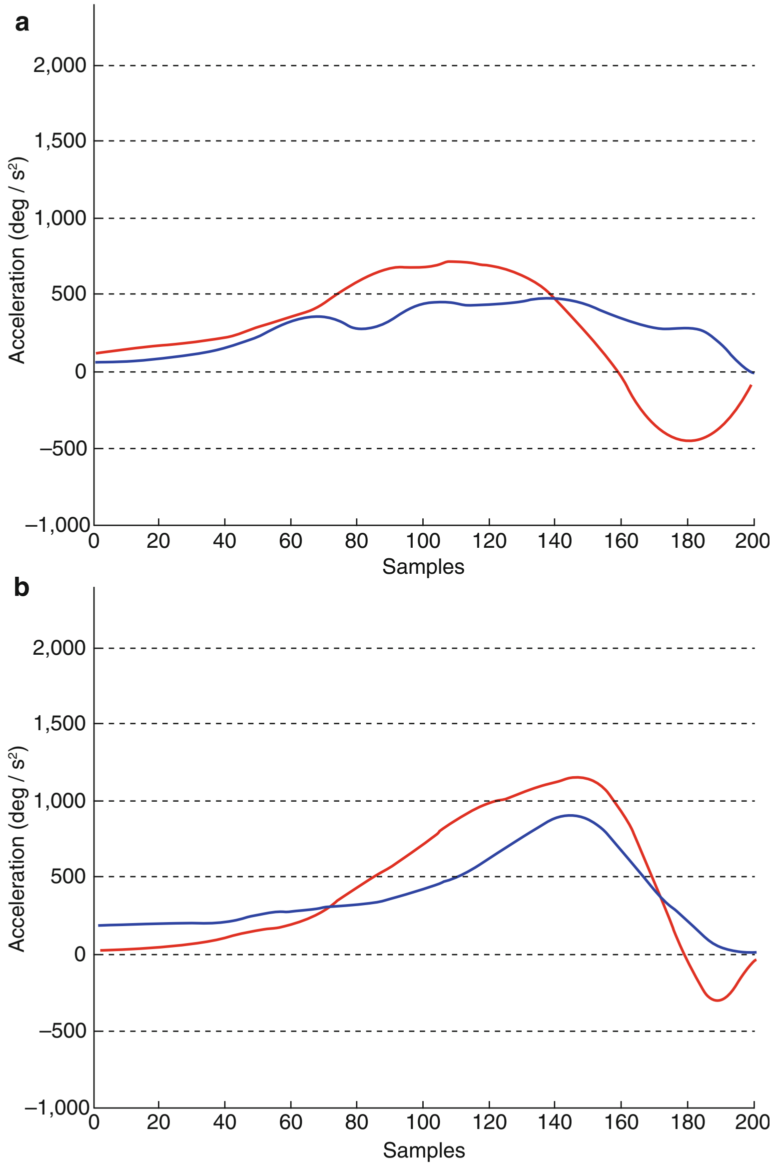


Fig. 5.8 16-year-old male with a left knee isolated chronic ACL tear. Right knee dominance. Pivot shift is grade 3+ with the patient awake. (**a**) The graph on the *top* represents the curves for the normalized moments registered during the jumping with pivoting with internal tibial rotation test. (**b**) The graph *below* represents the same curves during the jumping with pivoting with external tibial rotation. The red line indicates the right knee and the blue line indicates the left knee (From Sanchis-Alfonso et al. [42]. Reproduced with permission from the Journal of Bone and Joint Surgery, American Volume)

Weight bearing of the ACL-deficient knee during pivoting activities is very important to predict knee function or disability [51]. It is well known that an axial load of the knee is necessary for the pivot shift to be a symptomatic dysfunction [26]. Sanchis-Alfonso et al. [42] have found that a non-coper patient with a chronic ACL tear will try to keep the pivot shift from being a symptomatic dysfunction by decreasing the axial load exerted on the dynamometric platform and the percentage of pivoting with load (Fig. 5.12). These authors also interpret this finding as an avoidance behavior against pain.

5.5.2 Advantages: Kinematic Versus Kinetic Analyses

From a practical point of view, there are a number of advantages of kinetic analysis. Unlike the kinematic analysis, the kinetic analysis enables us to measure the associated forces and internal knee torques generated during the entire movement (in this case pivoting).

The accuracy of the measurement using kinematic analysis is affected by skin and soft tissue movement. The movement of skin, fat, or muscle around the bone affects the marker position and can cause considerable error in the kinematic analysis especially during the rotation movement, as occurs in pivoting, to predict bone movement [7, 34]. Cappozzo et al. [7] have shown that the motion of the skin marker over the underlying bone due to skin/soft tissue movement varies from a few millimeters up to 40 mm. The use of kinetic analysis avoids such errors.

Also, with this technique, there are no limits to performing highly demanding activities such as jumping with pivoting. Therefore, with this method, we duplicate muscle forces [26] (sling-shot effect and neutral anterior shift effect) and rotational loads caused by sports gestures (higher than the load applied to the knee during clinical pivot-shift test).

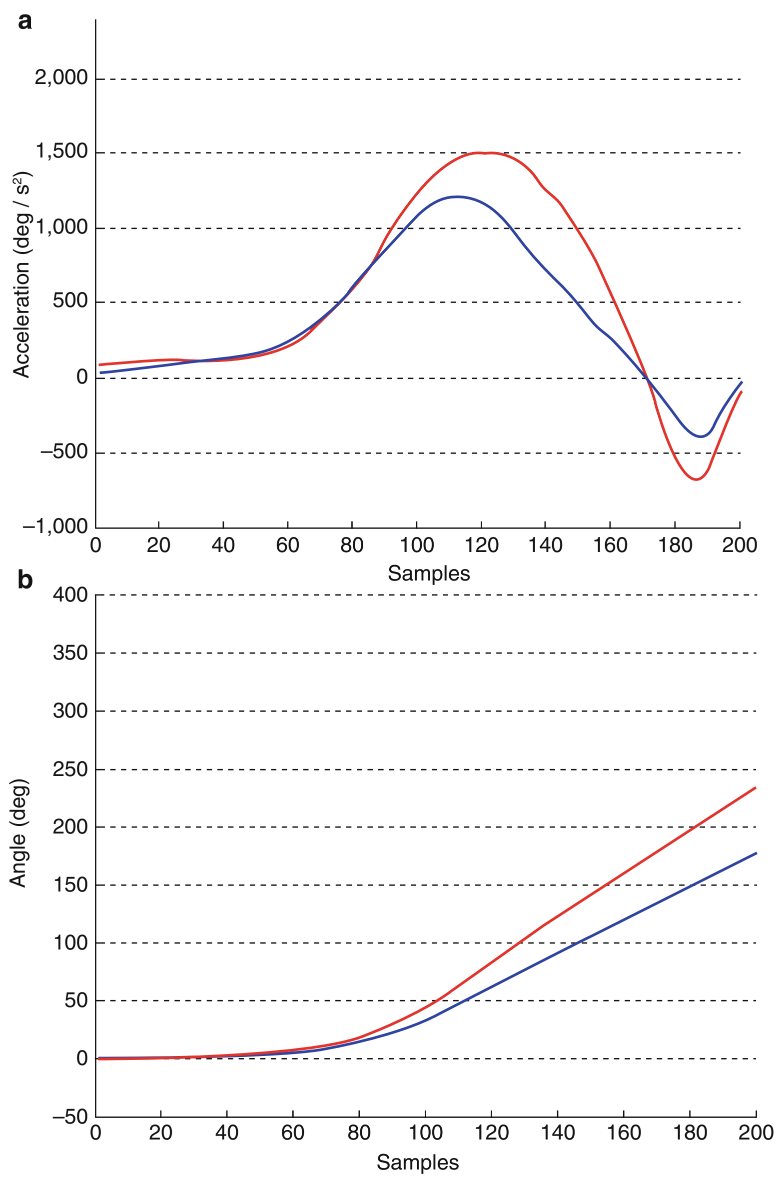
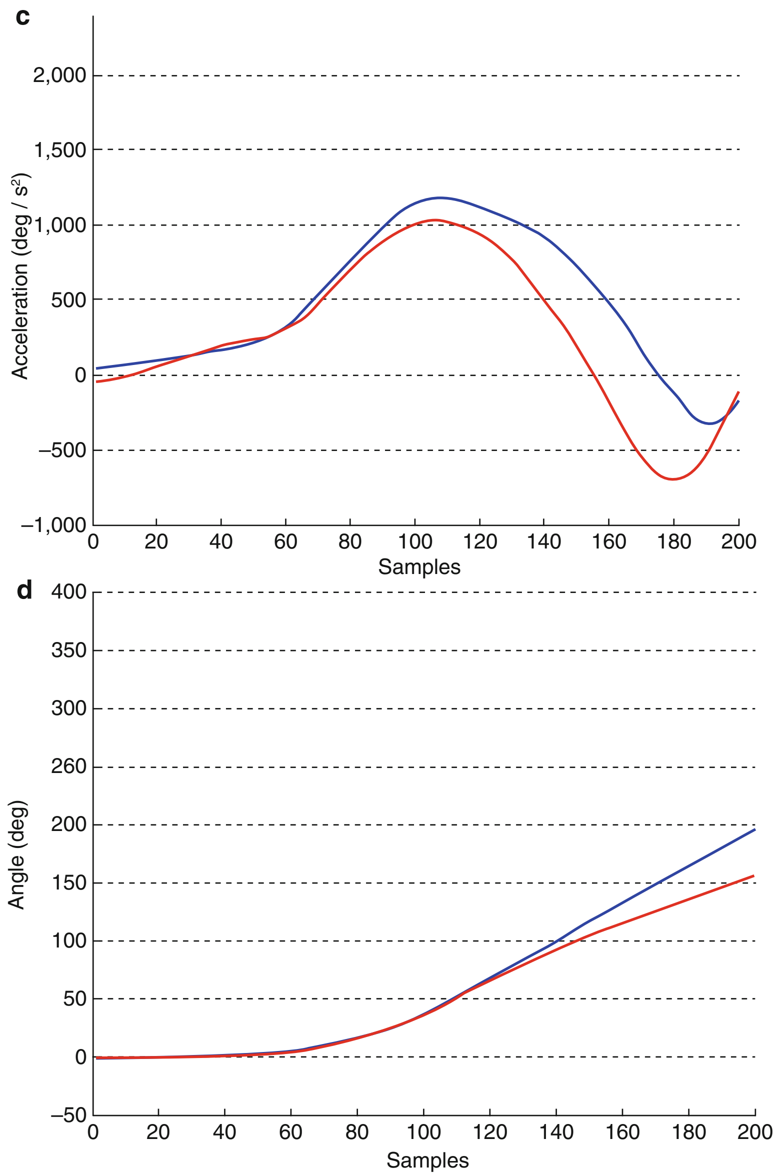


Fig. 5.9 Patient with a left knee isolated chronic ACL tear with left limb dominance. Positive pivot-shift with the patient awake that is increased with tibial external rotation. (**a**) Curves for the normalized moments registered during the jumping with pivoting with external tibial rotation test. (**b**) Body twist angle during the same task. (**c**) Curves for the normalized moments registered during the jumping with pivoting with internal tibial rotation test. (**d**) Body twist angle during the same task. The red line indicates the right knee and the blue line indicates the left knee. The diagnosis of ACL tear was confirmed arthroscopically (**e**) Posterior cruciate ligament -PCL-, ACL anteromedial bundle -AM-, ACL posterolateral bundle -PL-. The AM bundle is torn from its femoral insertion. (**f**) PL bundle elongated. (**g**) Femoral insertion of the PL bundle (From Sanchis-Alfonso et al. [42]. Reproduced with permission from the Journal of Bone and Joint Surgery, American Volume)

Fig. 5.9 (continued)



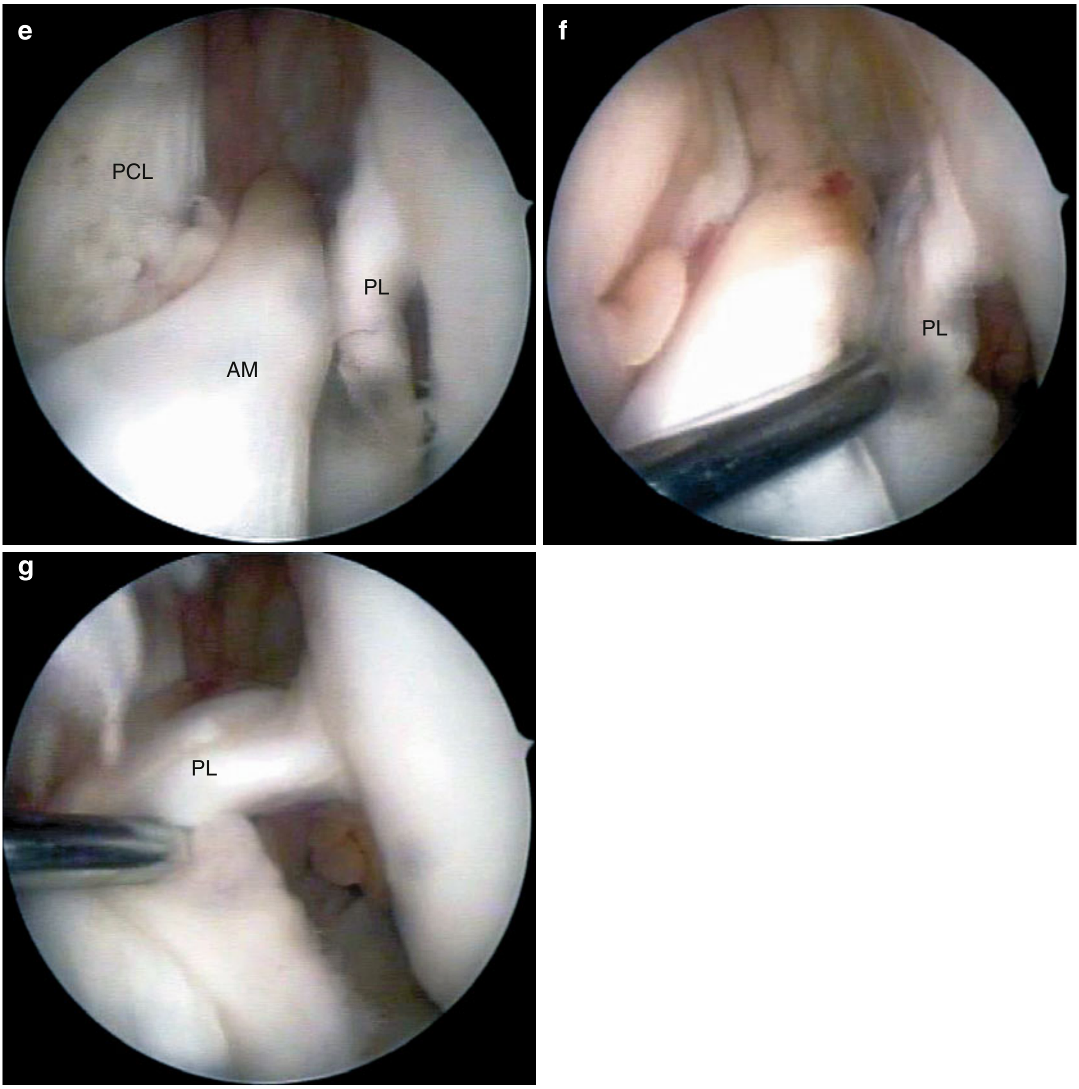
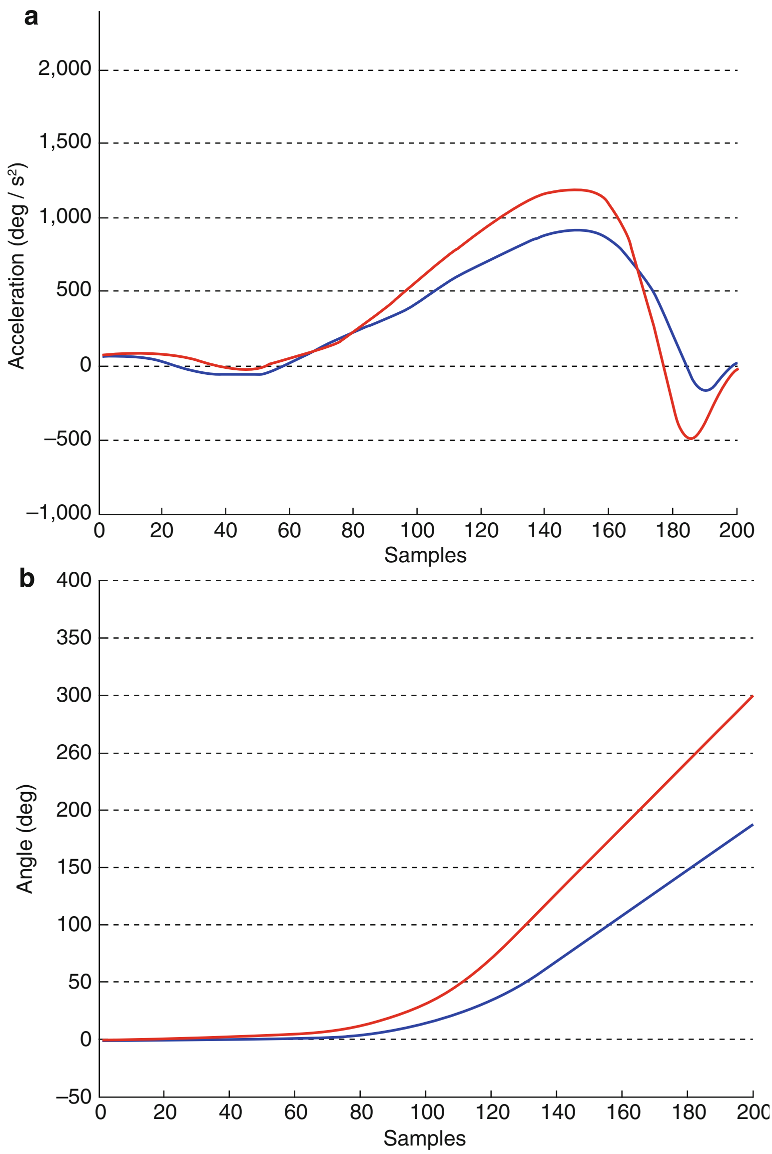


Fig. 5.9 (continued)

Fig. 5.10 Isolated ACL tear of the left knee, 6 months' follow-up. Rotational instability only when playing football. Right limb dominance. Positive pivot shift under anesthesia with an extra amount of compression applied to the lateral compartment of the knee by an assistant when the examiner performs the test. Negative pivot shift with the patient awake. (**a**) Curves for the normalized moments registered during the jumping with pivoting with external tibial rotation test. (**b**) Body twist angle during the same task. (**c**) MRI: ACL to PCL. The red line indicates the right knee and the blue line indicates the left knee. The diagnosis of ACL tear was confirmed arthroscopically (**d**) The ACL seems to be intact. (**e**) PL bundle femoral insertion is absent. (**f**) ACL to PCL (From Sanchis-Alfonso et al. [42]. Reproduced with permission from the Journal of Bone and Joint Surgery, American Volume)



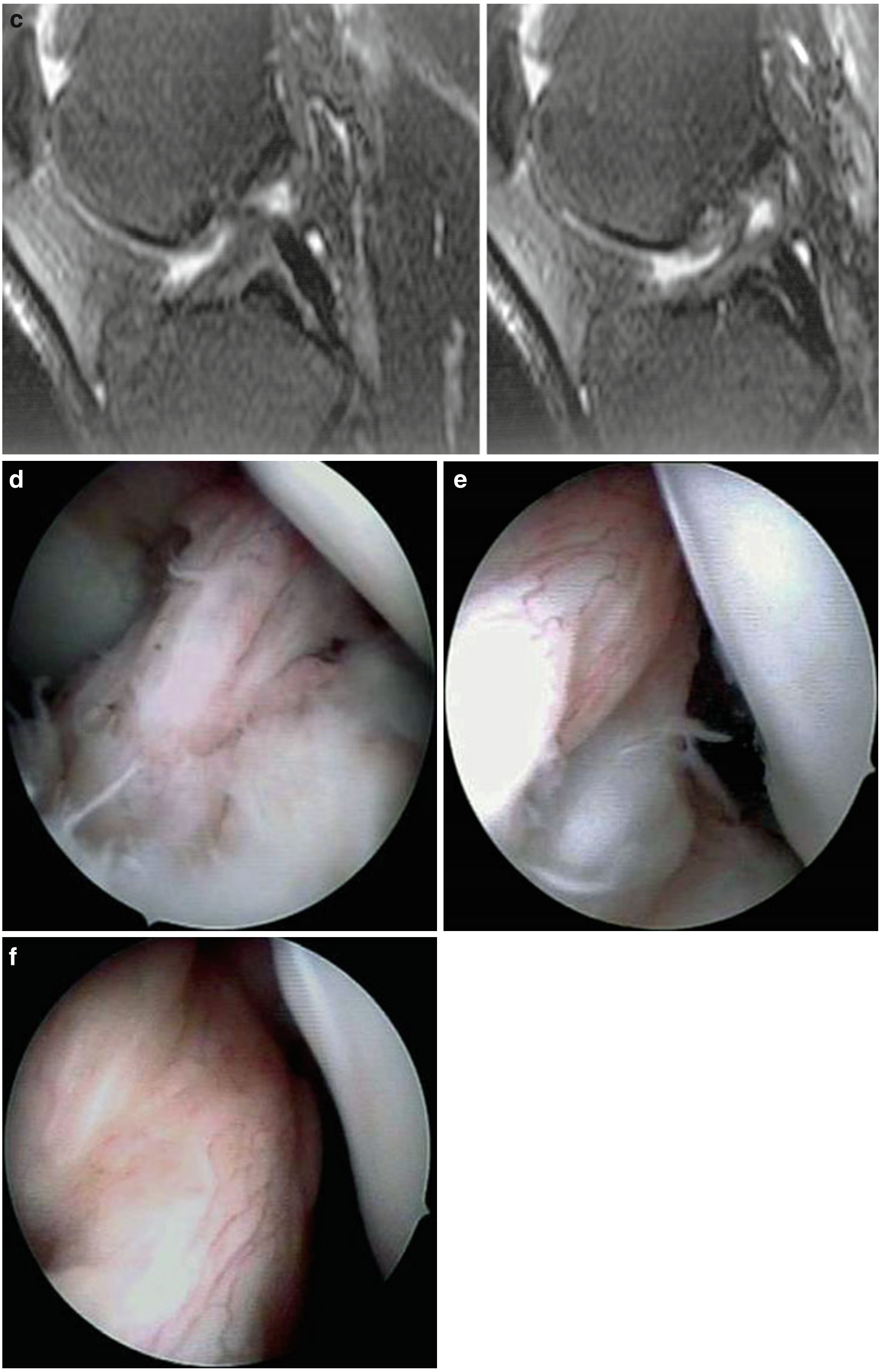


Fig. 5.10 (continued)

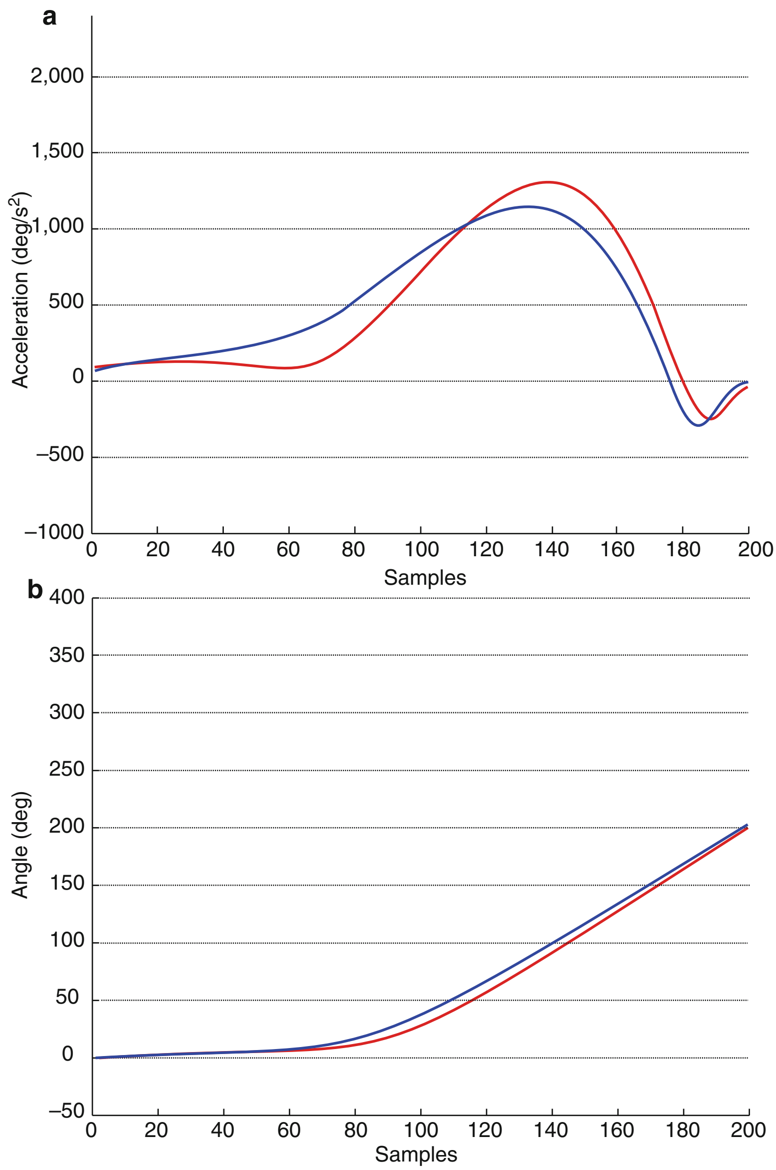


Fig. 5.11 Volunteer with normal knees. (**a**) The graph on the *top* represents the curves for the normalized moments during the jumping with pivoting with external tibial rotation test. (**b**) The graph *below* represents the body twist angle during the same task. On all of the graphs: Right knee – *red line*, left knee – *blue line* (From Sanchis-Alfonso et al. [42]. Reproduced with permission from the Journal of Bone and Joint Surgery, American Volume)

Finally, kinetic analysis is a noninvasive in vivo method.

5.5.3 Limitations of Kinetic Analysis

However, this method has some limitations. It is not useful in acute injuries or in the presence of marked muscle wasting because the patient cannot perform the task properly. The protocol requires a maximum effort on behalf of the patient when performing the test. We define maximum effort as the energetic use of the maximum intensity of physical strength to perform the impulse when performing the jumping with pivoting. The biomechanical effort to perform the twist with the jumping with

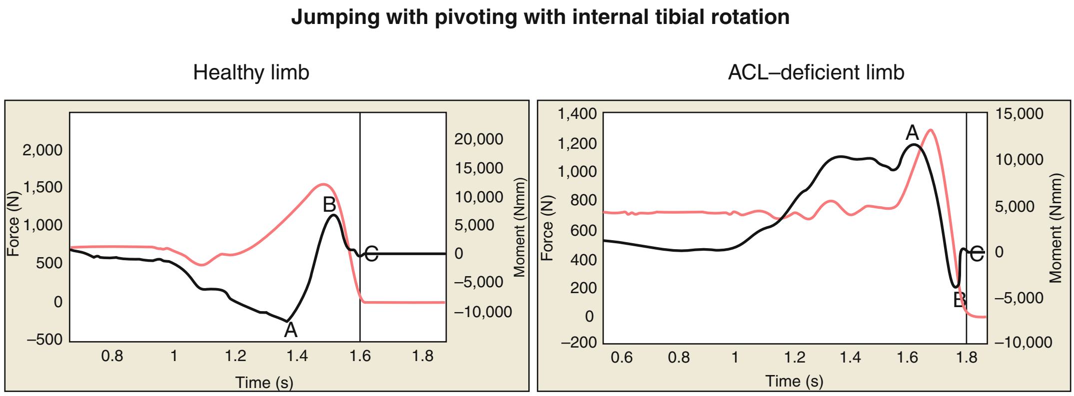


Fig. 5.12 We have synchronized the video performed during the pivoting with tibial internal rotation test with the vertical ground reaction force exerted on the dynamometric platform during the performance of the test (*red color* graph) and with the moments generated on the platform during the test (*black color* graph). We have synchronized both graphs because the axial load is necessary for the pivot shift to be a symptomatic dysfunction [31]. We have chosen the pivoting with internal tibial rotation test because the percentage of pivoting with load with internal tibial rotation is not influenced by limb dominance [9]. We can observe how in the healthy limb, as we progress in the pivoting phase (segment *A-B-C*), the vertical reaction force exerted on the dynamometric platform increases and then decreases smoothly, until it becomes 0 in the takeoff phase as can be expected. On the contrary, in a limb with a chronic ACL tear as we progress in the pivoting phase (segment *A-B-C*), the vertical ground reaction force exerted on the dynamometric platform decreases until it becomes 0, in the takeoff phase

pivoting test is directly related with the body twist that determines the impulse or energy with which the test is performed. Finally, it is not useful when both knees are involved because one of the knees must be healthy in order to be able to compare.

Another concern is that an objective measurement of a very subjective concept like a "defense mechanism" is difficult and can be influenced by many variables such as pain, a decrease in muscle strength, and a decrease in proprioception. For this reason, in order to be included in the study group, all the patients had to perform the jumping with pivoting test without pain in order to exclude this factor as responsible for the kinetic findings. Moreover, none of the patients had pain in their knee regularly, only temporary pain after a giving-way episode. Moreover, all the patients responded "yes" to the following question: do you believe that the limitation when performing the test is because you think that your knee is going to give way? None of the patients subjectively felt that a reduction in the muscle strength was a limitation for performing the test. Moreover, we have found in the follow-up of operated ACL-deficient patients with a good knee function (unpublished data) that a deficit for the quadriceps isometric strength using dynamometers greater than 20 % (compared to the intact knee) and a deficit for the hamstrings isometric strength greater than 50 % (compared to the intact knee) do not affect kinetic parameters. We have included in our study group only patients with normal proprioception because it has been reported that decreased proprioception in patients with an ACL deficiency reduced their functional ability [42]. The evaluation of the proprioception in the study group using the dynamometric platform and by means of the reproduction of passive positioning did not indicate any proprioception alteration. In patients evaluated with use of kinetic analysis both preoperatively and during follow-up of ACL reconstruction who had pain and/or significant reduction of the quadriceps strength, we found kinetic pivoting parameters similar to the preoperative ones and significantly lower than those at the 1 year follow-up, when the patient was asymptomatic and practicing sport (unpublished data). But an important point to validate our test is that when a patient felt pain while performing a certain gesture or with significant muscle weakness, the gesture was performed with a significantly higher vertical load than during preoperative studies. In this sense, it is important to remember that for a pivot to be symptomatic it is mandatory that a vertical load be applied.

Another worry with kinetic analysis in the pivot-shift evaluation is the possibility that associated lesions could influence the kinetic parameters studied. Therefore, we have evaluated only isolated ACL lesions arthroscopically confirmed a posteriori. We have excluded patients with meniscal or chondral lesions.

Another variable that can alter results is the footwear with which the test is performed. It is important that footwear have soles in good condition for the friction coefficient between the shoe and the dynamometric platform in order to avoid sliding during the performance of the pivoting gesture.

Moreover, kinetic tests must be performed by specialized personnel (physical therapists and engineers all specialized in biomechanics) in a specialized biomechanics laboratory. Another drawback to its daily clinical use is the high cost (the platform itself costs $40,000).

Finally, this method is completely unspecific. The kinetic findings are similar to those found in lateral patellar instability, and this test cannot differentiate between a rotational instability found in patients with lateral patellar instability and the one found in patients with a chronic ACL insufficiency [42].

5.5.4 Kinetic Analysis Does Not Intend at This Moment to Be a Diagnostic Clinical Tool

In our last series of patients, in only 65 % of the non-copers with a chronic ACL rupture evaluated with the jumping with pivoting with external rotation test was this test strenuous enough for the patient to feel the knee was going to give way during the test. But in the remaining 35 % of patients with a chronic ACL rupture, they performed the test without any problem, generating a curve with a symmetrical shape for both knees. This means that the pivot-shift phenomenon is also modulated by other factors besides the ACL. Also, in our study [42], there are too many exclusion criteria (bilateral ACL injury, association with other lesions in that knee, other injuries in the ipsi- and contralateral limbs) for this test to be considered as a diagnostic test for daily clinical practice at this moment. In conclusion, kinetic analysis is not a clinical diagnostic method but a laboratory research tool for the evaluation of rotational instability of the knee to improve our knowledge about the pivot-shift phenomenon. It would require similar studies performed by other independent authors to validate our results. Maybe, kinetic analysis will someday serve as a screening tool to determine who is a “coper” versus “non-coper.”

5.5.5 Clinical Relevance

Kinetic analysis could be a valuable tool for the follow-up of operated patients previously evaluated by means of kinetic analysis. Therefore, it could be a useful method to support the effectiveness of emerging surgical techniques such as double-bundle anatomical reconstruction technique that duplicates the anatomy of the ACL better than the single-bundle ACL reconstruction.

Our preliminary study of five patients preoperatively studied by means of kinetic analysis (unpublished data) showed that a single-bundle ACL reconstruction with an excellent clinical result at a mean follow-up of 14 months (12–16 months) is not sufficient in all the cases to restore normal knee kinetics during a simulated pivot-shift event, though anterior or sagittal laxity has been restored to normal values (see Table 5.1 and Fig. 5.13). We have seen a postoperative improvement in all the pivoting kinetic parameters during the monopodal jumping with pivoting performed with external tibial rotation compared with the preoperative ones. In two cases, only one out of four pivoting kinetic parameters analyzed postoperatively was similar to the contralateral healthy knee. In one case, it was 4 out of 4, in another case 3 out of 4, and in the remanent case 2 out of 4. Moreover, we have observed an increment in the percentage of pivoting with load in three cases (cases # 2, 3, and 5 – see Table 5.1), while in two cases, it was lower compared with the preoperative ones. So, some single-bundle ACL-reconstructed patients with an excellent clinical result would avoid reaching axial load forces during pivoting gesture maybe as a defense mechanism.

Table 5.1 Pivoting kinetic parameters during the jumping with pivoting with external tibial rotation test after single-bundle ACL reconstruction, comparing preoperative values with postoperative values

Preoperative					**Postoperative**											
	ACL-deficient knee				ACL-operated knee				Contralateral knee				Operated vs. healthy knee			
	M	I2	I3	S	M	I2	I3	S	M	I2	I3	S	M	I2	I3	S
Case 1	185	1,128	1,121	06,197	358	1,536	1,487	9,398	553	3,568	4,277	14,685	$P=0.056$	$P=0.006$	$P=0.005$	$P=0.041$
Case 2	410	3,983	2,556	05,891	536	5,827	3,607	4,884	773	7,812	7,538	07,139	$P=0.003$	$P=0.218$	$P=0.034$	$P=0.003$
Case 3	398	1,974	1,578	13,437	474	2,825	2,843	8,300	271	1,381	1,288	10,597	$P=0.173$	$P=0.194$	$P=0.153$	$P=0.094$
Case 4	358	2,992	2,301	04,123	483	4,883	7,439	5,230	358	5,391	3,998	03,440	$P=0.013$	$P=0.011$	$P=0.302$	$P=0.559$
Case 5	445	6,374	4,431	03,120	567	9,265	6,113	3,555	656	6,410	4,804	06,712	$P=0.225$	$P=0.062$	$P=0.178$	$P=0.003$

A $P<0.05$ was considered statistically significant

M pivoting moment, *I2* pivoting impulse 2, *I3* pivoting impulse 3, *S* pivoting slope

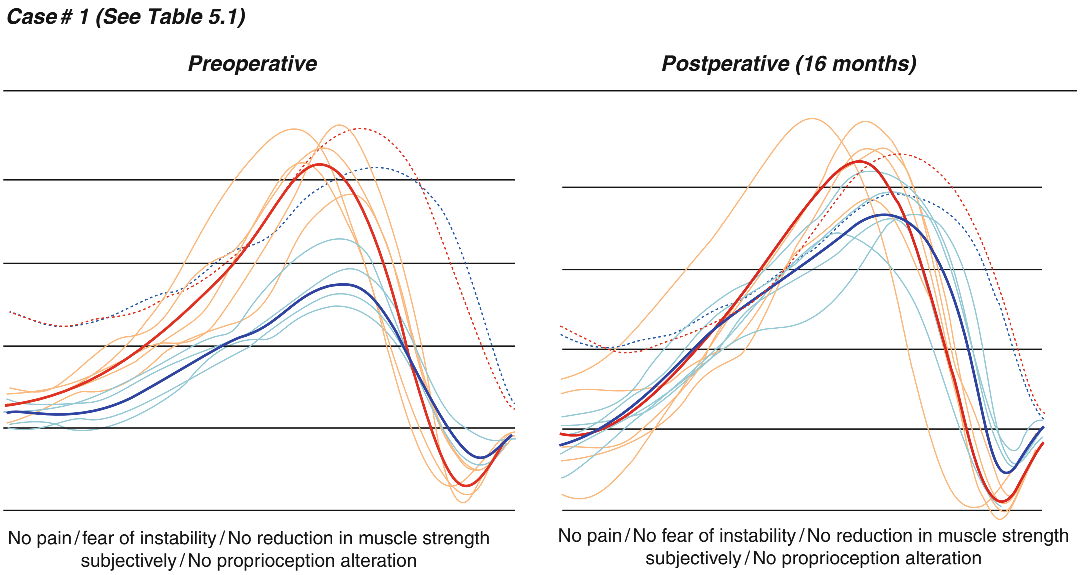


Fig. 5.13 (**a**) The graph on the *left* represents the preoperative curves for the normalized moments during the jumping with pivoting with external tibial rotation test. (**b**) The graph on the *right* represents the postoperative curves for the normalized moments during the jumping with pivoting with external tibial rotation test. Right knee (healthy knee) – *red line*, left knee (ACL-deficient/ACL-operated knee) – *blue line* (See Table 5.1)

Therefore, there must be other factors besides the surgical technique that influence rotational stability. Bony geometry of the knee joint could be one of these factors. Sherman et al. [43] have demonstrated that patients with high-grade pivot shift have greater degree of posterior-inferior tibial slope than the patients with low-grade pivot shift. Musahl et al. [31] correlate higher grades of pivot shift with smaller lateral tibial plateau diameter in the medial-lateral dimension. Finally, Walla et al. [48] described the presence of an active hamstring control that reduced the pivot shift in 95 % of a selected group of patients.

5.6 Take Home Messages

- Despite the abundance of methods to objectively measure the rotational stability of the knee, there is still no acceptable method. It remains the subject of ongoing research.
- Current ACL reconstruction techniques do not seem to fully restore normal kinetic/kinematics of the knee. Excessive tibial rotation and kinetics anomalies are still present during highly demanding activities after single-bundle ACL reconstruction. These abnormal biomechanical patterns may lead to the loading of cartilage and to osteoarthritis.
- In vivo evaluation methods to assess rotational stability in the ACL-deficient knee could assist in the development of new surgical procedures like double-bundle ACL reconstruction.
- The two-bundle technique has not been investigated dynamically, and future in vivo research using external loading should be performed to determine the advantages of the double-bundle ACL anatomic reconstruction.

5.7 Appendix: Relationship Between Obliquity of the Graft in the Coronal Plane and Rotational Stability After ACL Reconstruction

A correct femoral tunnel placement and graft obliquity in the sagittal plane are important for a successful ACL reconstruction; however, they are not enough. Graft orientation in the coronal

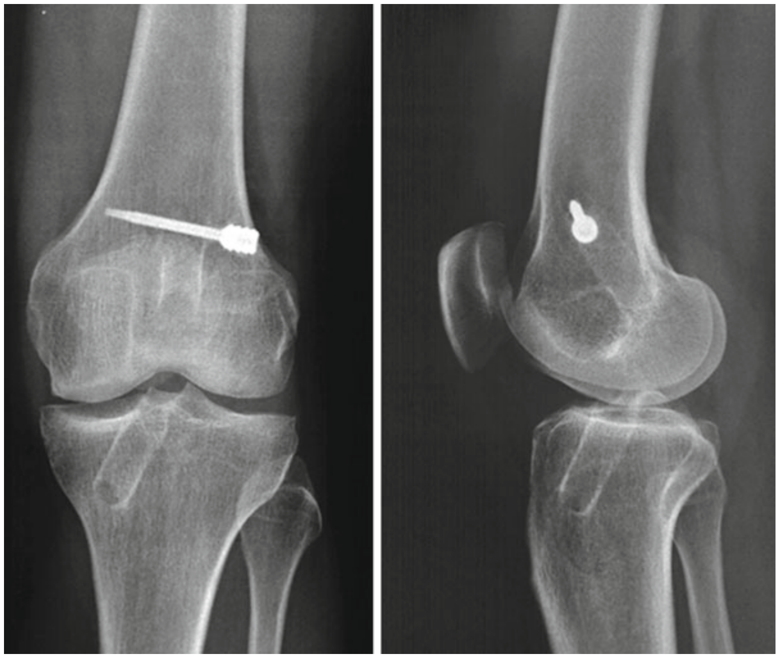


Fig. 5.14 Correct femoral tunnel placement and graft obliquity in the sagittal plane in a patient with intact ACL graft and a positive pivot-shift test. However, the graft has a vertical graft orientation in the coronal plane

plane has received less attention, and it is crucial in the clinical outcome after ACL reconstruction because there is a relationship between the obliquity of the graft in the coronal plane and rotational stability after ACL reconstruction without higher anterior tibial translation (Fig. 5.14).

A vertical graft orientation in the coronal plane does not control tibial rotation and is associated with a non-satisfactory clinical result (Fig. 5.15). In this sense, Sanchis-Alfonso in a preliminary study comparing ACL reconstructions in the 11 or 1 o'clock position versus 10 or 2 o'clock position have found no differences in the pivot-shift test and Lachman test between both groups [41]. However, the subjective IKDC score regarding rotational stability was higher in the 10 or 2 o'clock position group [41]. The questions of the subjective IKDC related to the rotational stability are the following: what is the highest level of activity you can perform without significant giving way in your knee, and how does your knee affect your ability to jump and land on your affected limb. Moreover, a vertical graft could predispose it to early failure particularly with rotational stress the way it occurs in sports (Fig. 5.16).

Rue et al. [39] have shown that if we place the femoral tunnel at 10:30 or 1:30 position, we reconstruct portions of the anteromedial and posterolateral bundles of the ACL. It is possible to perform a femoral tunnel at the 10:30 position through a tibial tunnel angled 60° from the proximal tibial joint surface [39]. So, a single-bundle ACL transtibial reconstruction with a femoral tunnel placed in this position should provide rotational and anterior translation stability similar to that of double-bundle ACL reconstruction. But even in the best cases, single-bundle ACL reconstruction at 10:30 or 1:30 fails to restore normal kinetics and kinematics provided by the intact ACL at the pre-injury level, during high-demand activities such as jumping with pivoting. However, these patients are performing sports activities at a high level, which means that rotational stability given by the graft is enough to perform high-demand activities. However, the abnormal rotational motion after single-bundle ACL reconstruction may contribute to long-term osteoarthritis associated with ACL reconstruction.

The key question would be: How can we control the pivot shift? There are several options: additive lateral extra-articular tenodesis (see Chap. 13), reconsider primary repair of ACL tears in selected patients (see Chaps. 7, 8, and 18), and finally anatomic single-bundle or double-bundle

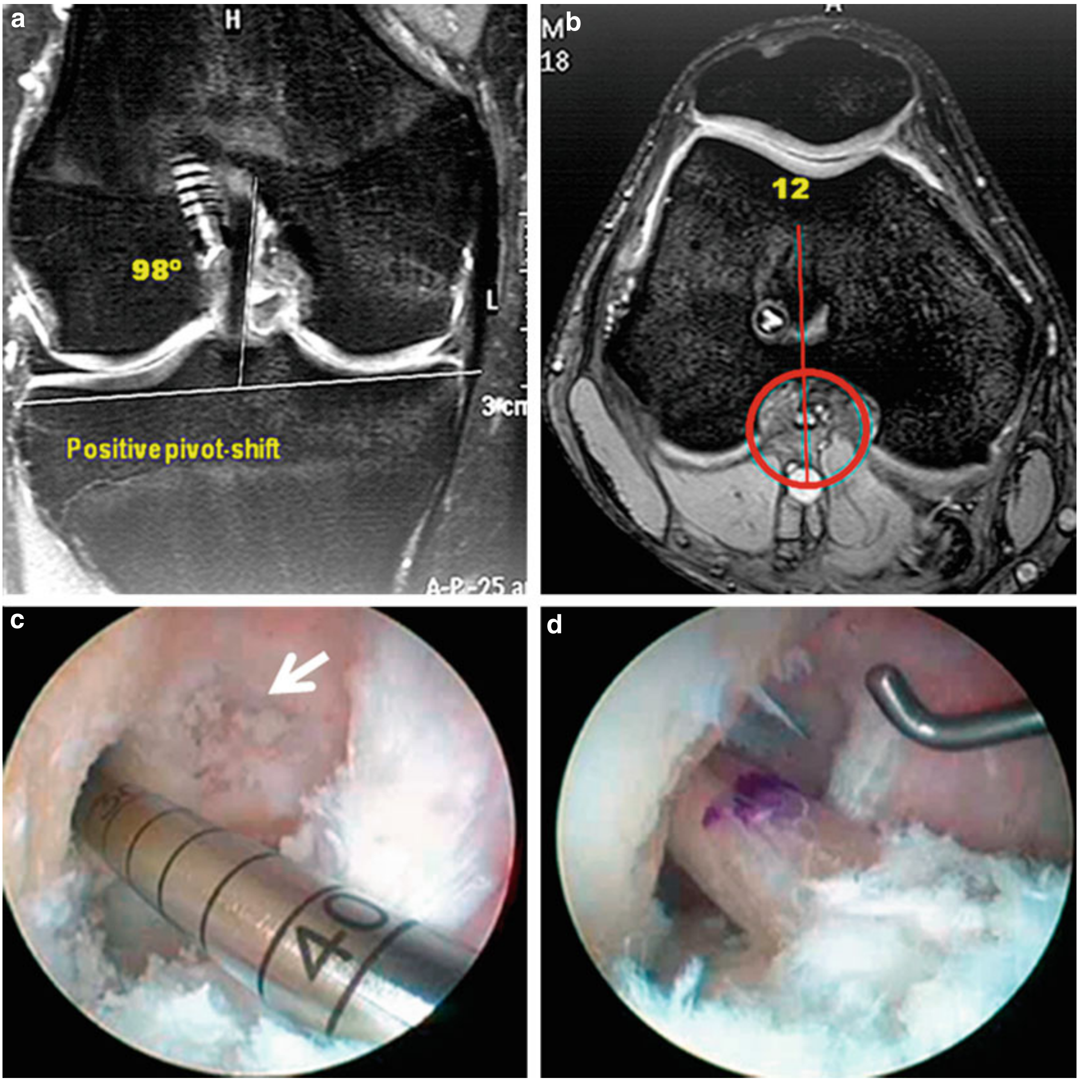


Fig. 5.15 This is the case of a patient with a vertical graft orientation and non-satisfactory clinical result (positive pivot-shift). (**a**) Coronal MR image. Vertical graft orientation. (**b**) Axial MR image. High noon femoral tunnel placement. (**c**) Arthroscopic view. Previous femoral tunnel placement -arrow- (**d**) Arthroscopy view. We can see the obliquity of the new graft in the coronal plane

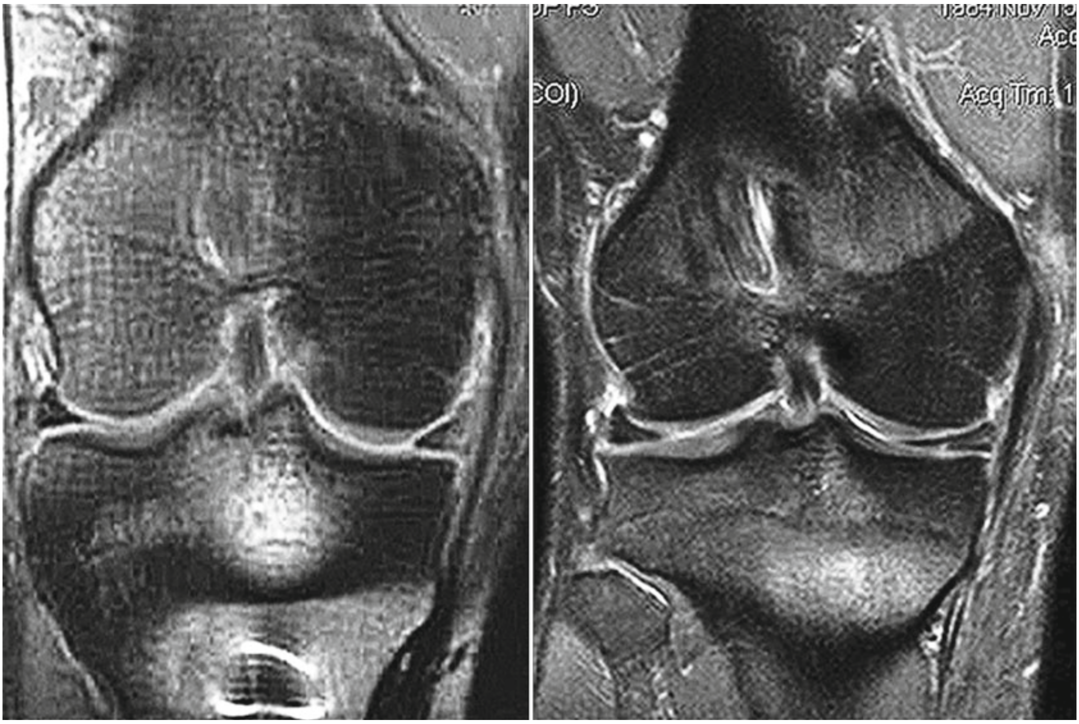


Fig. 5.16 This is the case of an elite international football player who was operated on twice. The graft failed at 6 months after the first operation after a banal noncontact mechanism after return to competitive sport. The question is, "what failed?" We believe that the key of the failure was a high-noon femoral tunnel placement. However, 8 years have passed since the second operation, and the patient is competing at a high level. What differences have we found regarding the first operation? A femoral tunnel at 10:30

ACL reconstruction (see Chaps. 19, 20, and 21). The final objective would be to improve knee kinematics in order to reduce the incidence of osteoarthritis.

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Guidelines for Operative Versus Nonoperative Management of Anterior Cruciate Ligament Injuries

6

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6.1 Introduction

In this chapter, we summarize the existing evidence comparing operative and nonoperative treatment of anterior cruciate ligament (ACL) injury in skeletally mature athletes. We present a validated program of screening and rehabilitation for use in nonoperative treatment or when delaying ACL reconstruction for any reason. We concentrate on patients presenting after acute injury, because patients presenting with a symptomatic, chronically ACL-deficient knee are very likely to have a meniscus tear or chondral damage [4, 18, 48, 54] which will affect the function and evolution of the knee. Even today, among patients who are not evaluated promptly by a clinician knowledgeable about knee ligament injuries, an ACL tear may go undetected and present later due to ongoing or recurrent symptoms. These patients, who present with a symptomatic ACL-deficient knee, are much more likely to have symptomatic meniscal or chondral damage that requires treatment. In contrast, aside from the initial pain and swelling associated with acute ACL rupture, functional deficits and symptoms often are more subtle and activity specific when only the ACL has been injured.

6.2 Understanding and Interpreting the Literature

In order to make sense of the literature on this topic and to apply it to patient care, a few simple

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principles should be understood. The first is the sampling matters. Counseling an ACL-injured patient about his or her future can only be based on evidence from prospective studies in which the sample population is identified at the time of the initial injury and the protocol specifically excludes chronically ACL-deficient knees and anyone else with prior symptoms. In other words, the study sample must represent subjects similar to the patient being counseled. As mentioned above, retrospective studies often include many patients presenting with symptomatic knees, rather than immediately after the initial knee injury. Patients returning for care of symptomatic knees have a higher likelihood of having already sustained meniscus or cartilage damage [4, 18, 48, 54], which obviously invalidates their usefulness in predicting the future of an acutely injured patient.

It is not always easy to distinguish prospective from retrospective sampling. For example, registries of ACL reconstruction generally represent level 2 prospective cohort studies of the surgical procedure. However, they are not prospective studies of the injury itself: in that context, registries represent level 3 (retrospective) evidence. Patients come to surgery under a variety of circumstances; yet surgical registries enroll patients who present at 6 or 12 months with a symptomatic knee without distinguishing their preoperative history from that of patients who had careful supervision and activity modification while waiting 6 or 12 months to have their surgery at a convenient time. It is not appropriate to interpret the interval from injury to surgery as a delay in care, without validating this important assumption. Yet it is quite common for this to occur. Several studies have documented that a greater interval is associated with a higher prevalence of cartilage and meniscus damage at the time of surgery [7, 29, 41, 59]. But this does not mean that the delay caused the additional damage. In our view, this has led to unwarranted conclusion that reconstruction must be done without delay in order to prevent meniscal injury [56, 57]. This leads us to the second principle, which is that interval from injury to surgery does not necessarily mean delay in care; a corollary is that delay in surgery does not equal neglect.

6.3 The Dilemma

Anterior cruciate ligament (ACL) injuries are prevalent and entail serious consequences, including loss of dynamic stability and an increased risk of subsequent knee injuries and early onset of knee osteoarthritis [43, 44]. While reconstructive surgery is widely accepted as the preferred treatment for highly active individuals, the role of nonoperative treatment of ACL injuries is still debated [46]. Structured rehabilitation supervised by a physical therapist is a key component in optimizing outcome after injury, regardless of reconstructive (ACLR) or nonoperative treatment [15, 58]. In the first randomized controlled trial comparing structured rehabilitation and early surgery with structured rehabilitation and optional delayed surgery, Frobell et al. [27] recently reported no significant differences between the two groups in patients' self-reported knee function after 2 years after inclusion. Still, almost 30 % of patients that were randomized to optional delayed surgery later underwent reconstruction due to symptomatic instability and low self-reported quality of life, and there was a trend toward more serious events in the group assigned to rehabilitation plus optional delayed surgery ($p = 0.07$).

Previous studies have also shown that there is considerable potential for success using nonoperative treatment in selected patient groups [6, 39, 51]. A paramount clinical challenge is therefore to identify patients who can regain adequate knee function following nonoperative treatment with structured rehabilitation. However, validated clinical decision rules for counseling patients to nonoperative management are nonexistent [5], and there is little evidence of which factors predict outcome following nonoperative treatment with current rehabilitation protocols.

Yet controversy remains because clearly not every patient benefits from early surgical reconstruction, and evidence is limited as to the basis on which the decision should be made between operative and nonoperative care [27, 42]. Prospective studies and well-documented database series [2, 10, 11, 13, 27, 30, 49] have documented that early ligament reconstruction after ACL injury is efficacious in reducing the risk of subsequent meniscal injury and late surgery, compared to nonoperative treatment. However, it is known that ACL reconstruction does not always yield improved outcomes compared to the natural history [11, 21, 22, 27]. Outcome studies of ACL reconstruction have illustrated that surgically restoring knee stability does not always permit a return to sports activities or prevent future symptoms or degenerative knee arthritis [19, 43, 44, 52, 66]. Furthermore, there is evidence that some individuals are able to participate regularly in high-level activities without symptoms or episodes of instability [11, 14, 28, 33, 34, 47, 64]. Thus, it appears that a nondiscriminating surgical approach may not be an appropriate strategy for providing the best possible outcomes for this patient population.

The idea that some ACL-injured athletes can "cope" or "compensate" for their injury is not new. Noyes et al. introduced the "rule of thirds" for ACL injuries in 1983 [54]. To paraphrase, one-third will compensate adequately and be able to pursue recreational activities, one-third will be able to compensate but will have to give up significant activities, and one-third will do poorly and will probably require future reconstructive surgery. Noyes et al. stressed the importance of activity modification.

Daniel et al. first used the term "coper" to describe ACL-injured patients who elected nonoperative treatment [11, 21, 22]. This group had a 20 % risk of meniscal injury at 5 years, had decreased hours and level of sports participation, and tended to be older [11]. More laxity, preinjury hours of sports participation, and younger age correlated with the need for surgery. Daniel et al. reported that patients who were able to "cope" with ACL deficiency had better outcomes in some respects than did patients who had undergone reconstruction [11, 22]. In caring for an individual patient, the risks and expense of surgery must be weighed against the risks of sports disability, impaired knee dysfunction, and re-injury that are associated with conservative management. These studies supported the concept of the "high-risk" patient (e.g., the young, competitive athlete) who is thought to benefit from early ligament reconstruction to reduce the risk of subsequent injury and sports disability [3, 11, 12, 16, 26, 36, 67]. Athletes participating in extensive hours of IKDC level I and II sports spend a great deal of time at risk of joint subluxation and secondary injury; it is these patients that have the most to lose in terms of subsequent injury and return to preinjury sports participation levels, whether or not they elect to undergo reconstruction.

Snyder-Mackler et al. have further refined the concept of the "coper." They have defined copers as ACL-injured athletes who continued for at least 6 months after their injury at full participation in sports activities without surgical treatment [64]. This group embarked on defining the characteristics of coper and noncoper groups [14, 23, 25]. Patients were screened and assigned a status as a candidate or noncandidate for nonoperative treatment based on unilateral hop tests, self-assessed knee functional scores, and give-way episodes [31, 33, 34]. The formal classification of coper was given if there was no more than one giving-way episode since injury, greater than or equal to 80 % on the timed hop test (compared to the contralateral leg) and greater than or equal to 60 % on the global rating scale. At 10 years, less than 1 % of those screened were truly copers in that they continued to participate in preinjury levels of sports and had excellent KOOS and global ratings of knee function.

Thus, a subset of ACL-injured patients can be considered potential copers, and a subset of these patients may be able to participate in sports without instability. The risk of meniscal and chondral injury remains, but clearly this can be minimized with rigorous adherence to the treatment and supervision algorithm [32].

6.4 Selecting Potential Candidates for Nonoperative Treatment

Identifying the best candidates for nonoperative care early after ACL injury is one of the keys to successful patient outcomes. Although there are descriptions in the literature of differential responses after ACL rupture, there is little evidence to assist in prospectively identifying individuals who may forego ACL reconstruction and remain active in high-demand activities (i.e., cutting, jumping, and pivoting maneuvers) without experiencing functional knee instability. The group at University of Delaware, led by author LSM, has devised a treatment algorithm and screening examination that distinguishes between highly active patients with different functional abilities early after injury, when treatment decisions are routinely made. Using these decision-making guidelines, patients may be prospectively classified as either good or poor candidates for nonoperative care. The dichotomous groups are referred to as potential copers and noncopers. Potential copers are nonoperative candidates identified by the screening examination who have the potential to compensate well for their injury [23, 25]. Noncopers are surgical candidates, as these individuals cannot return to high-level athletic activities after ACL injury because of continued episodes of the knee giving way [11, 14, 22, 64].

Classification cannot be predicted by a single clinical test or by demographic characteristics [14, 33, 34]. Daniel et al. [11] and Fithian et al. [22] found that the magnitude of knee laxity after ACL rupture was one factor that was predictive of a patient's ability to compensate for the diminished ligamentous knee stability. However, other studies have reported that the amount of anterior tibial translation is not predictive of functional abilities [33, 34, 40, 64]. Currently, identification of individuals who are most likely to succeed with nonoperative care is predicated on a series of inclusion and exclusion criteria and the results of a battery of clinical tests. For more than 10 years, one of the authors (LSM) has conducted clinical trials, long-term outcome studies, and laboratory investigations to evaluate the efficacy of the University of Delaware treatment algorithm and screening examination. After rigorous scrutiny, these decision-making guidelines have been established as an effective nonoperative treatment approach for managing highly active patients with acute ACL deficiency. The following section provides details of the treatment algorithm, screening examination, and rehabilitation protocol to facilitate implementation into the clinical practice of healthcare providers who regularly treat patients with ACL deficiency.

6.5 Treatment Algorithm and Screening Examination

6.5.1 Implementation of the Decision-Making Guidelines

Patient goals are an important factor when considering surgical versus nonsurgical management. Some individuals prefer to delay or avoid surgery. For instance, an athlete may want to finish the competitive season before having surgery, particularly if an upcoming game has significance. Furthermore, practice patterns outside of the United States are often quite different [38, 50]. In some countries, patients are counseled to undergo surgery only if nonoperative care has failed. For patients who are advised to have an ACL reconstruction, resources may be limited, and the patient can be placed on a waiting list before he or she undergoes surgery [32]. Counseling regarding appropriate activity participation in the interim would be useful in these instances. Hence, it is important for clinicians to consider each patient as an individual when making decisions regarding the ideal management strategy after ACL injury.

We recommend the decision-making guidelines for all patients with ACL deficiency who are regularly involved in International Knee Documentation Committee (IKDC) level I or II activities (>50 h/year of jumping, cutting, pivoting, or lateral movements) [20, 37]. Participation in the University of Delaware algorithm and screening examination was originally developed to be a short-term, that is, 6 months or less, approach to nonoperative management, as surgical management has been the standard of care in the United States. Even if they were asymptomatic, patients were advised to return to their orthopedic specialist for surgical management once they had completed their desired activities. However, some potential copers do not follow these recommendations. Hurd et al. [32] followed up with potential copers who remained ACL deficiency for more than 2 years. This cohort ($N = 25$) was able to remain active in high-level

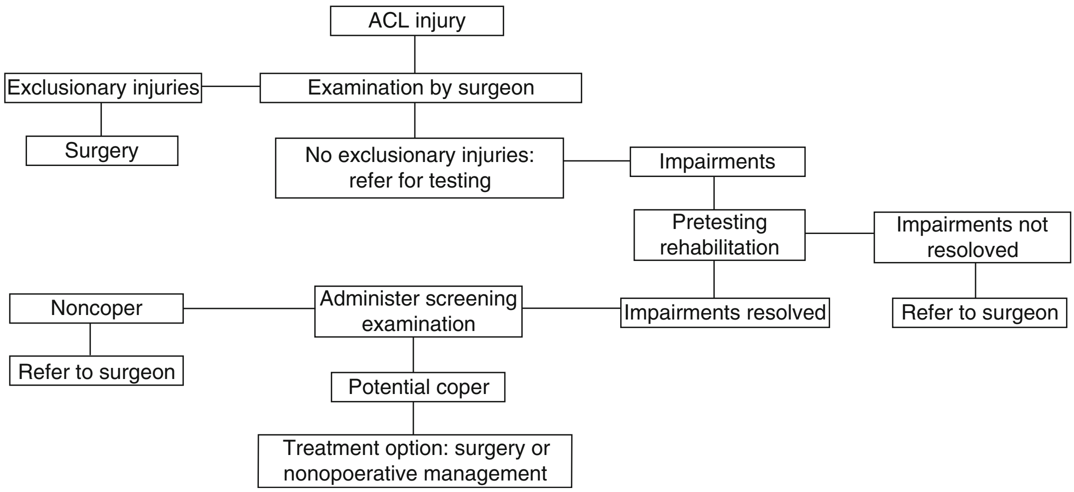

Fig. 6.1 University of Delaware patient selection algorithm for nonoperative versus operative treatment after ACL injury (From Fitzgerald et al. [25]. Reproduced with permission of the Orthopaedic and Sports Physical Therapy Sections of the American Physical Therapy Association)

sports activities and reported no compromise or symptom complaints with their daily function. These positive outcomes have prompted a shift in the authors' clinical practice: patients are instructed that, if they have no symptom complaints or compromise in activity participation, ACL reconstruction is optional. Validation of long-term, nonoperative outcomes for potential copers is currently under way.

6.5.2 Concomitant Injuries

Before participating in the screening examination and determining whether the patient can be classified as either a potential coper or noncoper, multiple criteria must be met. Evaluation for concomitant injuries is the first step in the algorithm to discriminate between surgical and nonoperative candidates [25, 33, 34] (Fig. 6.1). The patient presenting with grade II or greater concomitant posterior cruciate ligament (PCL), medial collateral ligament (MCL), lateral collateral ligament laxity, bilateral knee involvement, or the presence of any severe lower extremity or low back injury (e.g., nerve injury, fracture, dislocation) is not considered a candidate for nonoperative care. When time is not an issue or the patient desires to exhaust all nonoperative options, clinicians may consider treating the concomitant injury to facilitate participation in the screening examination. One example is a grade II MCL injury. Once the MCL has healed and there is no longer an increase in valgus knee laxity, the MCL injury does not preclude the patient from continued nonoperative ACL management consideration.

Additional concomitant injuries that exclude patients from participating in the screening examination may be identified with magnetic resonance imaging (MRI). These injuries include full-thickness articular cartilage lesions and potentially repairable meniscus tears [25]. If a patient experiences subsequent giving-way episodes in these instances, there is potential for the original injury to be extended. The rationales for having strict exclusion criteria based on the presence of concomitant injuries are the following: these individuals are at high risk for experiencing subsequent knee injury if nonoperative care is pursued [1, 11], the screening examination may not be safely completed, or a healthy contralateral knee is not available for comparison [33, 34].

6.5.3 Physical Impairments

Patients must meet the following rehabilitation criteria before they may participate in the screening examination: have no or minimal knee joint effusion; full, symmetrical knee active range of motion;

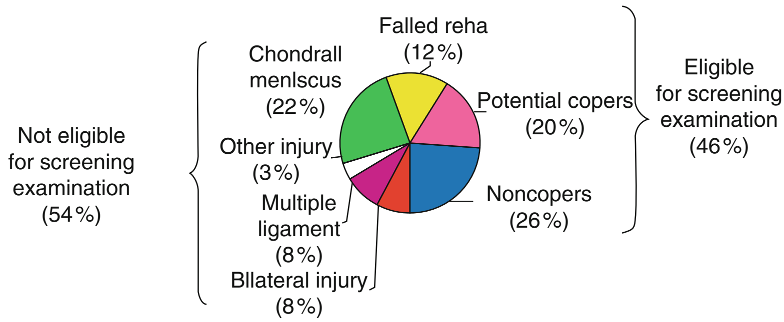

Fig. 6.2 Ten-year outcomes of the University of Delaware algorithm and screening examination

≥70 % quadriceps strength on bilateral comparison; and the ability to hop on the injured knee without pain while wearing a functional derotation knee brace [23, 33, 34]. Individuals who have any of the listed impairments should undertake supervised rehabilitation with the goal of completing the screening examination as soon as the impairments are resolved. Patients are referred to their orthopedic specialist if the rehabilitation criteria are not met within 4 weeks [33, 34].

It is currently unknown how an extended trial of rehabilitation (>4 weeks) for impairment resolution may impact patient outcomes. The rationale for a finite rehabilitation period was that many individuals in the United States who pursue nonoperative management are attempting to make a rapid return to high-level activities. An extended period of rehabilitation to resolve impairments may result in a missed opportunity to return to the desired activities. Consequently, nonoperative care is no longer advantageous in this instance. When timing is not an issue, clinicians may consider whether continued treatment to address impairments may be advantageous. It is possible, however, that an extended inflammatory response and inability to regain quadriceps strength may be a consequence of knee instability, suggesting these individuals are not good candidates for nonoperative care [33, 34].

Application of the treatment algorithm excludes a large percentage of patients from participation in the screening examination (Fig. 6.2). A systematic review of an entire population of highly active individuals with acute ACL deficiency revealed 54 % of patients were excluded from screening consideration secondary to either the presence of concomitant injury (42 %) or unresolved impairments (12 %) [34]. These results support the belief that ACL ruptures frequently occur in conjunction with other injuries. Furthermore, the large number of individuals not considered for nonoperative management demonstrates the treatment algorithm is by nature conservative; any factor that may contribute to future knee instability or extend the index injury must be considered as rationale for surgery as the treatment of choice [34].

6.5.4 Screening Examination

The screening examination consists of a battery of sequential clinical tests: unilateral hop testing, self-assessment questionnaires, and recording the number of giving-way episodes since the index injury [23].

Unilateral hop testing is conducted according to the protocol described by Noyes et al. [53]. It consists of the single-legged hop for distance, triple crossover hop for distance, straight triple hop for distance, and a 6-m timed hop. Patients perform two practice trials on each limb followed by two test trials. The two test trials for each limb are averaged, and a hop index is calculated for each test with performance of the injured limb calculated as a percentage of the uninjured limb. Patients wear a functional derotation knee brace on the injured limb throughout practice and testing [23, 33, 34].

Although all unilateral hop tests are performed as part of the screening examination, only the timed hop test is used for patient classification.

Potential copers must have a timed hop index of ≥80 % [23]. Out of the four hopping tasks, the timed hop is influenced the least by quadriceps strength [33, 34] and has been described as one of the less demanding hop tests [55]. It is, however, unique in requiring patients to hop repeatedly over a fixed distance (unlike the other hop tasks that require the patient to hop for a maximum distance). Hurd et al. [33, 34] suggested that the task demands—selecting and repeatedly performing a dynamic movement strategy—effectively challenge the neuromuscular control of patients with ACL injury. This is consistent with the theory that dynamic knee stability is more a consequence of coordinated muscle contractions than forceful muscle contractions [33, 34].

6.5.5 Patient Self-Assessment

The two self-assessment questionnaires that are completed immediately after unilateral hop testing are the Knee Outcome Survey-Activities of Daily Living Scale (KOS-ADLS) and the global rating of knee function [23]. Fitzgerald et al. [23] reported in preliminary work that patients tended either to underestimate or to overestimate self-reported scores if the hop tests were performed after the self-assessment surveys. Consequently, the authors of that article advocated that patients perform the hop tests first to give them an opportunity to self-evaluate their knee status after performing a physically challenging task, resulting in more accurate reporting of knee function [23, 33, 34].

The KOS-ADLS consists of 14 questions with 6 possible answers (each answer weighted from 0 to 5 points for a maximum of 70 points) and assesses knee function and symptoms during a variety of daily activities, such as ambulation, stair climbing, squatting, kneeling, and sitting. A higher score represents a higher level of function. The global rating of knee function is a single number between 0 and 100 and represents the patient's current knee function, including sports, with a score of 100 % representing preinjury function. Classification criteria for potential copers include a score of ≥80 % on the KOS-ADLS and a ≥60 % global rating score [23].

6.5.6 Knee Giving Way

Giving way is defined as buckling, or subluxation, of the tibiofemoral joint [23]. Only those episodes that occur during activities of daily living (ADL) are considered for patient classification. The rationale is that if recurrent episodes of giving way occur during daily tasks, the patient is at high risk for extended knee damage if they return to high-level activities without reconstructive surgery. For patients to be classified as a potential coper, they must have experienced ≤1 giving-way episodes since the index injury [23].

6.5.7 Classification

For patients to be classified as a potential coper and considered good candidates for a nonoperative return to preinjury activities, they must meet all criteria (timed hop score of ≥80 %, a KOS-ADLS score of ≥80 %, a global rating score of ≥60 %, and ≤1 giving-way episodes) [23]. Failure to meet a single criterion results in patient classification as a noncoper or poor candidate for nonoperative management. These patients are advised to return to their orthopedic specialist and be considered surgical candidates [32–34].

The screening examination is performed only once. There is currently no evidence to support repeated performance of the screening examination to provide noncopers the opportunity to improve their test scores and change their classification status. Likewise, individuals whose scores are "close" to but do not meet potential coper classification criteria should not be considered nonoperative candidates. In these circumstances, it can be challenging for the healthcare professional to instruct an athlete that his or her competitive season is over. However, consistent implementation and execution of the treatment algorithm, screening examination, and patient classification system are paramount to successful patient outcomes.

Table 6.1 Perturbation exercises and progression guidelines

	Rockerboard	Rollerboard/platform	Rollerboard
Sets/duration	2–3 sets/1 min each	2–3 sets/1 min each; performed bilaterally	2–3 sets/30 s – 1 min each
Direction of board movement	A/P, M/L	Initial: A/P, M/L Progression: diagonal, rotation	Initial: A/P, M/L Progression: diagonal, rotation
Application	Begin in bilateral stance for first session. Perform in single leg stance for remaining sessions	Subject force is counter-resistance opposite of rollerboard, matching intensity and speed of application so rollerboard movement is minimal. Leg muscles should not be contracted in anticipation of perturbation, nor should response be rigid co-contraction	Begin in bilateral stance for first session. Perform in single-leg stance for remaining sessions. Perturbation distances are 1–2 in.
Cognitive (early) phase (sessions 1–4)			
Treatment goals:			
• Expose athlete to perturbations in all directions			
• Elicit an appropriate muscular response to applied perturbations (no rigid co-contraction)			
• Minimize verbal cues			
Associative (middle) phase (sessions 5–7)			
Treatment goals:			
• Add light sport-specific activity during perturbation techniques			
• Improve athlete accuracy in matching muscle responses to perturbation intensity, direction, and speed			
Autonomous (late) phase (sessions 8–10)			
Treatment goals:			
• Increase difficulty of perturbations by using sport-specific stances			
• Obtain accurate, selective muscular responses to perturbations in any direction and of any intensity, magnitude, or speed			

A/P anterior/posterior, *M/L* medial/lateral

6.6 Rehabilitation

Potential copers who elect nonoperative management are advised to participate in a 10-session perturbation-enhanced rehabilitation protocol (Table 6.1) before returning to high-demand activities [33, 34]. Perturbation training is one type of neuromuscular exercise designed to improved knee stability after ACL rupture and involves the manipulation of an unstable support surface while the patient maintains his or her balance [24]. Additionally, the rehabilitation program includes cardiovascular exercise, muscle strengthening, agility and coordination training, and sport-specific skills [46]. Treatment frequency can range from twice a week to daily sessions, with the frequency dependent on symptom exacerbation and the patient's time constraints. Similar to the patient who has undergone ACL reconstruction, it is recommended that the patient with ACL deficiency pass all functional testing criteria before discharge and clearance for a full return to preinjury activities.

Perturbation exercise includes three conditions: rollerboard, rockerboard, and rollerboard with block (Fig. 6.3) [24]. Verbal cues such as "keep your knees soft," "keep your trunk still," and "relax between perturbations" are provided during training early in the program to provide patients with a framework for successful task completion. Each exercise condition promotes the recruitment of muscle groups to oppose the

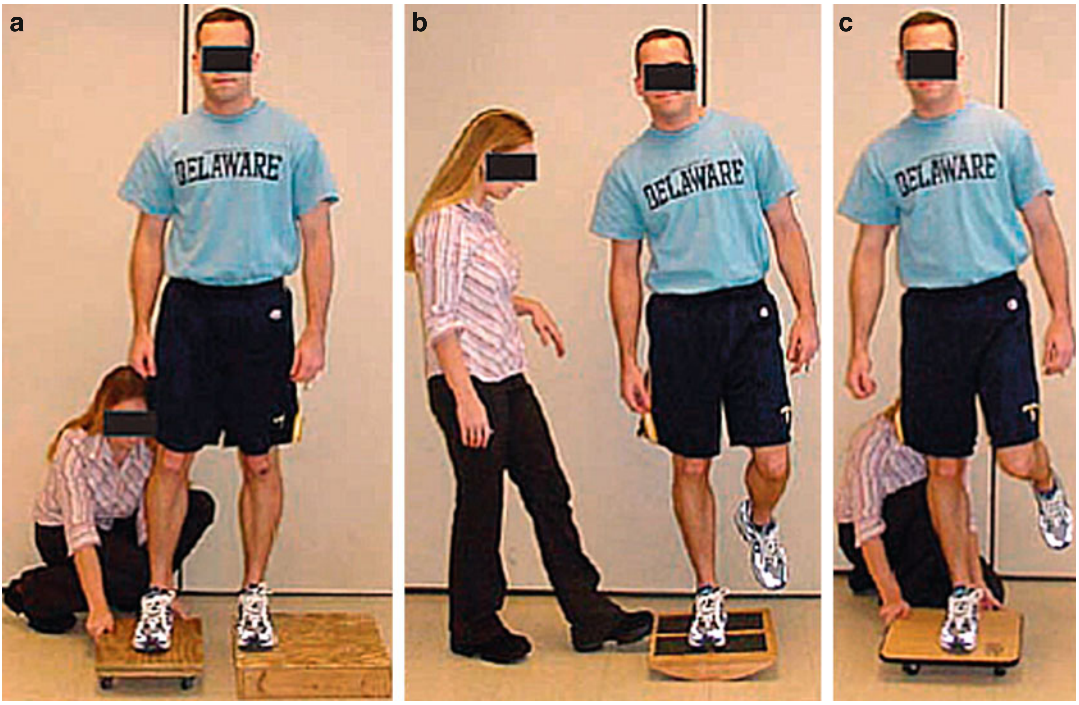

Fig. 6.3 Perturbation exercises. Rollerboard and block (**a**), rockerboard (**b**), and rollerboard (**c**)

perturbation. The focus of training is not on developing specific muscle activation patterns. Rather, patients are allowed to develop individualized patterns as long as the task is successfully completed, for example, maintain balance without rigid muscle co-contraction.

The perturbation-enhanced rehabilitation protocol consists of three phases. The first phase of the protocol, sessions 1–4, is the cognitive, or early, phase (Table 6.1). During this period, the patient is exploring and developing knee stabilization strategies. Clinicians can expect to see rapid improvements as the patient develops successful responses to the perturbations. Sessions 5–7 are part of the associative, or middle, phase and the second segment of the training protocol (Table 6.1). Knee stabilization strategies are refined during this rehabilitation stage. Additionally, sport-specific activities are incorporated into the perturbation exercise (i.e., kicking a soccer ball or passing a basketball), and patients are allowed to return to practice on a limited basis, that is, non-contact or part time. The final phase of the training protocol, sessions 8–10, is the autonomous, or late, phase (Table 6.1). Knee stabilization strategies are now automatic as the patient prepares for a full return to sports activities. Intensity, speed, and force of perturbations are advanced throughout the program [24, 25].

Muscle strengthening should be undertaken for all lower extremity impairments identified during initial evaluation. Muscle weakness of the quadriceps femoris complex is common after ACL rupture [25]. If the strength of the involved limb is <80 % of the contralateral limb, a high-intensity electrical stimulation or alternative protocol may be used to advance quadriceps muscle strength until this criterion is met [25, 63]. A combination of open and closed chain exercises may also be implemented with the goal of restoring full strength, with care taken to avoid exacerbation of any knee pain or effusion [25].

Cardiovascular training is incorporated to restore the patient's endurance [25]. Because endurance capacity is specific to the type of training that is performed, it is advised the type of endurance training be related to the patient's sport or work activity [25, 45, 65]. The majority of patients are involved in sports activities that include running. Consequently, a progressive treadmill program is the most common mode of cardiovascular exercise. When patients can run 15–20 min without pain or swelling, they may progress to level road or track running and finally to road or field hill running [25].

Agility and sport-specific training are implemented to allow the patient to adapt to quick changes in direction and prepare for return to sport demands [25]. During agility exercises, the patient wears a functional knee brace. Agility exercises are begun with single-direction movements, such as a lateral slide and shuttle run. They are progressed to cutting and spinning techniques with intensity advancing from half to full speed. Sport-specific drills are performed in the context of playing situations. For example, if the patient's goal is to return to basketball, they would perform plyometric jumping drills and practice dribbling skills, jump shots, and lay-ups [25]. These activities are initiated without being opposed by a training partner and then progressed to practice with one-on-one opposition (usually during session 7).

6.7 Outcomes

Hurd et al. [32, 33] prospectively characterized and classified the entire population of highly active individuals with ACL deficiency from a single orthopedic surgeon over a 10-year period. Of the 345 individuals who completed the screening examination, 42 % (n = 146) were classified as potential copers and 58 % (n = 199) as noncopers (Fig. 6.2). Although there were overall significantly more noncopers than potential copers within this cohort, these results indicate there are a large number of individuals who sustain an ACL injury who have the potential to succeed with nonoperative care. Seventy-two percent (63 of 88) of potential copers who pursued nonoperative management were able to return to their preinjury activities without symptom exacerbation and/or experiencing additional giving-way episodes (5 individuals experienced a giving-way episode during rehabilitation and were referred for surgery; 13 experienced a giving-way episode when attempting a return to sports; 5 individuals self-elected to mitigate their activity level; 2 were lost to follow-up) [32]. Eventually, 36 of 63 potential copers who had been successful with their nonoperative course returned to their orthopedist for ACL reconstruction [32]. There were 25 potential copers who had not undergone surgical reconstruction at the time of follow-up but were still active in high-level activities. Telephone interviews revealed these individuals were asymptomatic and had not compromised their activity level (KOS-ADLS X = 97 %; global rating X = 92 %). These results suggest there is potential for the algorithm and screening examination to identify candidates who may have long-term success with nonoperative care [32].

None of the potential copers who pursued nonoperative management and ultimately returned for surgery extended their original knee injury. One reason highly active individuals are counseled against nonoperative management after ACL injury is the increased risk for sustaining a meniscus tear or articular cartilage lesion from recurrent giving-way episodes and subsequently developing premature knee osteoarthritis. The authors consider potential copers to have failed nonoperative management if they experience a single additional giving-way episode. Therefore, the authors do not believe these patients are at greater risk for experiencing premature degenerative knee damage than individuals who undergo ACL reconstruction. The long-term, successful patient outcome is predicated greatly on early patient counseling and education. Because knee status may change over time, patients should be instructed to return to their physician or rehabilitation specialist if they experience any knee instability, effusion, or symptom exacerbation subsequent to discharge. The emphasis on "patient ownership" of the injury may reduce the likelihood that any changes in knee status that may contribute to early knee degeneration will be ignored.

Evidence supports participation in the perturbation-enhanced rehabilitation protocol before potential copers return to their preinjury activities. In a prospective randomized clinical trial, Fitzgerald et al. [24] assessed outcomes for ACL-deficient potential copers who participated in ten sessions of either standard (i.e., cardiovascular, agility, and plyometric exercises) or combined standard and perturbation exercise. Six months after completing rehabilitation, more potential copers from the standard group (7 out of 14) had failed in their attempt to return to preinjury activities than the perturbation group (1 out of 12), with failure defined as giving way of the knee, symptom exacerbation, or the inability to resume all activities [24]. Results reported by Hurd et al. [32] detailing outcomes of a 10-year prospective trial of the treatment algorithm and screening examination were consistent with Fitzgerald et al.'s [23] earlier work. Out of the 13 potential copers who failed in their attempt to resume preinjury activities without surgical intervention, 6 had not participated in the perturbation-enhanced rehabilitation protocol. Based on the collective results of Fitzgerald et al. [23] and Hurd et al. [32], the authors of this chapter strongly encourage all patients identified as potential copers who elect nonoperative management to do so only after participating in perturbation-enhanced rehabilitation [32, 33].

There is biomechanical evidence that corroborates differences in function after ACL rupture and supports the implementation of perturbation-enhanced rehabilitation for potential copers. Noncopers implement a stiffening strategy in a crude attempt to maintain knee stability after ACL rupture. These altered movement patterns include lower sagittal plane knee motion, knee moments, and higher muscle co-contraction on the injured limb in comparison to their uninjured limb and uninjured subjects [35, 60, 61]. In contrast, potential copers exhibit movement patterns intermediate to noncopers and uninjured subjects [8, 9]. Although these findings support the theory that potential copers have more advanced dynamic knee stabilization strategies than noncopers early after injury, it also supports implementation of additional rehabilitation. Chmielewski et al. [8] evaluated the gait patterns of ACL-deficiency potential copers before and after participation in the perturbation-enhanced rehabilitation protocol. The investigators reported potential coper movement patterns after training that were more like uninjured subjects, including an increase in sagittal plane knee excursion and reduced quadriceps-gastrocnemius muscle co-contraction [8]. Chmielewski et al. [8, 9] suggested that findings from this study were evidence for a biomechanical mechanism by which perturbation training acts as an effective intervention for promoting dynamic knee stability in this select population with ACL rupture. The authors are now investigating the effect rehabilitation has on movement patterns and functional abilities of noncopers.

Conclusions

If you want to predict the future of a given patient based on inferences from published evidence, then you should use only prospective studies that clearly define the population of interest. In the context of ACL insufficiency, retrospective sampling carries too much risk of transfer and treatment bias to allow for firm inferences on the future of a particular patient.

There is little evidence that knee pain and long-term risk of OA can be improved by surgical intervention. However, surgical intervention reduces knee instability, especially with higher levels of sports (i.e., level I and II). Similarly, risk of subsequent knee surgery and meniscal injury is reduced in patients undergoing ACL reconstruction.

It is clear that nonoperative treatment should not be confused with neglect. Patients can be rehabilitated following ACL injury, and clearly, there is a group of patients whose knees function well in level I and II activities without an intact ACL. In considering treatment, the clinician should strive to identify these potential "copers" and counsel them to optimize desired outcomes with a minimum of risk. The success rate (72 %) of the University of Delaware screening examination in returning highly active individuals to preinjury activities is far greater than those described in previous studies in which nonoperative care was based on patient self-selection (23–39 %) [1, 17, 62]. This disparity in patient outcomes suggests use of the treatment algorithm and screening examination described above is an effective clinical tool to discriminate between operative and nonoperative candidates, improving the probability of a safe, successful return to preinjury activities [32]. Given the differential patient response to ACL injury, implementation of these effective decision-making guidelines offers clinicians the opportunity to provide individualized patient care rather than a blanket surgical treatment strategy.

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7 The Stimulation of Healing of the Anterior Cruciate Ligament: Research and Clinical Relevance

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7.1 ACL Injury

Anterior cruciate ligament (ACL) injuries do not heal, and even with modern surgical treatments, long-term problems remain. Current estimates suggest an incidence of approximately 1 in 3,000 for ACL tears, and approximately 400,000 patients undergo treatment for ACL defects annually in the USA alone [13, 25]. Tears of the ACL cause pain and instability and predispose patients to osteoarthritis in the long term. Hence, all treatment options in the management of the torn ACL need to be evaluated both in light of their short-term effectiveness (as measured by pain, mechanical stability, and range of motion), as well as their ability to prevent osteoarthritis in the long term. The current gold standard in ACL treatment is reconstruction using either the middle third of the patellar ligament with patellar and tibial bone on either side or hamstring or quadriceps tendon. Allografts from cadavers are also available for use in multiple countries; however, availability is often limited, and there remains a small but real potential of disease transmission from the donor. Synthetic grafts are continuously being developed and tested; however, to date, most have failed in long-term trials due to inflammatory reactions to the synthetic material and eventual frank failure of the synthetic structure. Modern techniques of ACL reconstruction have consistently produced satisfactory results as far as restoring gross joint stability and relieving pain. However, recent studies have presented

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evidence of relatively high rates of osteoarthritis despite ACL reconstruction, even after controlling for other intra-articular damages caused by the initial trauma [10, 26, 48, 53].

7.2 Healthy and Healing ACLs

The purpose of a ligament or tendon is to withstand tensile forces. The composition and structural arrangement of these tissues is optimal for this purpose. Frank and Amiel were among the first to describe ligament and tendon structure as dense bundles of long type I collagen proteins with small additional contents of type III collagen and glycosaminoglycans [3, 12]. On the structural level, the fibers exhibit an undulating pattern, the so-called "crimp", which allows for stretching of the ligament [12]. This allows for a 6 % elongation of the ligament before resulting in permanent damage of the fibers within the ligament.

However, although it seems the terms tendon and ligament are used somewhat interchangeably, and despite the use of tendons as grafts to replace the torn ACL, it is important to note that there are distinct differences between these tissues. Ligaments have been reported to be more active metabolically, as suggested by higher cell numbers, higher DNA content, and more type III collagen [3, 12]. Tendons in turn contain more total collagen, but less glycosaminoglycans, which are important attractors of water. On the structural level, ligaments are less regularly arranged than tendons but have a greater degree of crimp (more waviness), allowing greater ease with normal range of motion (during which the non-isometric ligament needs to have some "give"). The significance of these differences for current and future clinical applications has not been fully understood.

Healing patterns of ligaments and tendons depend on a number of factors. It is a well-known conundrum that tears of the ACL will not heal, while tears of the medial collateral ligament heal spontaneously. Rotator cuff tendons also do not heal spontaneously, while tears of the Achilles tendon can be treated nonoperatively. Interestingly, the ACL and rotator cuff tendons are both intrasynovial, that is, they live within the joint, and it is likely that one of the reasons for their limited healing capacity is due to something in the intraarticular, or more precisely intrasynovial, environment. Wounded extra-synovial tissues (including the MCL and Achilles tendons) produce and sustain a fibrin clot within the gap between the torn ends of the ligament or tendon. The clot serves as both a scaffold for inflammatory cell attachment and as a source of stimulatory cytokines from platelet activation. Within this clot, the damaged tissue is absorbed, and new tissue is produced. In intrasynovial tissues, the formation of such a clot does not occur [28], a fact that is attributed to mechanical factors as well as biochemical factors such as the presence of plasmin within posttraumatic synovial fluid. Plasmin is an enzyme which actively degrades fibrin clots, and the presence of plasmin in the synovial environment may be the reason that after trauma, joints develop a hemarthrosis (runny, bloody fluid) rather than a giant fibrin clot within the joint space. Without the formation of the fibrin clot in the gap between the two ends of the torn ligament, there is no protected space or scaffold for surrounding cells to migrate into and remodel into a functional scar. Instead, for intrasynovial tissues, the tissue stumps are covered by proliferating synovial cells, and they eventually retract due to the production of smooth muscle actin-alpha in the matrix. As premature loss of the provisional scaffold in the wound healing process is likely a key mechanism in the failure of intra-articular tissues to heal, developing strategies to replace the lost provisional scaffold with a tissue-engineered substitute is of great interest. Developing a scaffold which has physical stability in the joint environment yet is able to simultaneously promote cell migration and proliferation, and extracellular matrix production is one of the most promising approaches in tissue engineering-augmented repair of the ACL [28, 33–35] and the rotator cuff [7, 17–19, 45].

In summary, one key mechanism behind the insufficient healing of the ACL is the lack of establishment of a stable provisional scaffold between the two torn ends of the ligament. The current solution to this problem is to replace the entire ACL with a tendon taken from elsewhere in the patient's knee or to use a donated tendon to replace the torn ACL. The success of this procedure may be limited by differences between tendons and ligaments as reflected in the "ligamentization" process. It is likely that this process plays a role in both failed ACL reconstructions and postoperative OA but to an unknown extent.

7.3 Stimulation

Given the fact that one key mechanism behind the failure of the ACL to heal spontaneously is the premature loss of the provisional scaffold, it seems logical to try to design a functional substitute for the missing fibrin clot. Among all biomaterials currently used in tissue engineering, collagen has a long-standing record as a biocompatible, biodegradable, and safe material for orthopedic applications and is the main constituent of the ACL [27]. Thus, such a biomaterial would be one candidate for a viable alternative scaffold to replace a fibrin clot. Furthermore, collagen can be applied as a hydrogel in and on the defect, thus filling the defect easily and completely [40]. Yet it is important to note that a fibrin clot is more than a mere scaffold for cellular migration. One of the most important intrinsic properties of such a clot is the release of growth factors and other cytokines that stimulate and regulate the inflammatory process that leads to tissue remodeling and finally defect healing. This fact must be considered in the design of a substitute material. Yet the addition of the correct combination of cytokines and their orchestrated release in a controlled manner is complicated. A simpler solution to this problem is the use of a platelet concentrate in connection with a collagen biomaterial. Platelets are activated by collagen and secrete an abundance of cytokines, thus acting as a natural growth factor delivery system [16].

One study furthermore suggested that the mix of cytokines released does not only stimulate cell growth but might also suppress inflammation [9]. The stimulatory effects of platelets are also being investigated for potential uses in bone healing [6, 24], cartilage [1] and meniscus repair [21], as well as treatment of degenerative disc disease [2, 37]. Harnessing the power of platelets could promote ACL treatments along two lines. On the one hand, platelet-collagen composites can be used as a source of growth factors to stimulate graft remodeling in ACL reconstruction. On the other hand, moving into the field of regenerative medicine, the orchestrated interaction of a collagen scaffold and a platelet concentrate could be used to enhance primary repair of the ACL, which, in contrast to replacement, would retain the native insertion sites and possibly even some of the midsubstance microstructure of the ACL.

7.4 Biologic Stimulation of ACL Reconstruction

An obvious question to ask is whether the use of collagenous biomaterials and/or platelet concentrates could enhance ligamentization and improve outcomes after conventional ACL reconstruction using a tendon graft. A number of investigators have used individual growth factors, including some of those released by platelets, to stimulate bone tunnel healing and graft remodeling after ACL reconstruction in animal models. Weiler et al. were among the first to publish results from a growth-factor-enhanced ACL reconstruction in a large animal model. Using a sheep model, they coated sutures with PDGF to create a carrier system [54, 55]. These sutures resulted in a release of roughly 60 μg PDGF per tendon graft. The treated sheep were followed for up to 24 weeks and compared to an identical ACL reconstruction without growth factor application. Weiler and colleagues did find alterations of the histological structure of the graft in response to the PDGF-laden suture and resulting improvement of biomechanics. In another study, Yoshikawa et al. used VEGF to try to improve the function of an ACL graft, also in the sheep model [56]. With the addition of VEGF, there was increased new vessel formation in the experimental group, but unfortunately, there was also reduced mechanical properties and increased laxity in the knees treated with ACL reconstruction and VEGF. In a related study in a porcine model, Vavken et al. demonstrated that the mechanical outcomes after ACL repair were dependent on the number of VEGF type 1 receptors on the surface of the ACL fibroblasts in vivo, where ligaments with higher numbers of VEGF receptors had improved mechanical outcomes [50]. Both these studies demonstrated that growth factors can have positive and negative effects on ACL healing and require great care in their use.

Six recent papers offer data on MRI assessment of graft maturation and ligamentization after ACL reconstruction enhanced with platelet-rich plasma (PRP) in humans. Four studies found significantly better results in the PRP group, with 100 % low-intense grafts in the platelet group but only 78 % in the control group ($p=0.036$) on a 6-month post-op MRI [39], significantly more homogenous grafts in CT assessment ($p<0.01$) [50], and earlier homogenization (by 48 %) of ACL grafts with the use of PRP [44]. Sánchez et al. [46] performed a histological assessment of ACL grafts treated with and without PRP and found a significantly better maturity index for ACL grafts treated with PRP (12 vs 14 pts, $p=0.024$), and more newly developed synovial tissue enveloping the PRP-treated grafts (77 % of cases) compared to the control grafts without platelets (40 %). These differences were statistically significant ($p=0.023$). However, no clear effect of PRP on tunnel healing has been shown in clinical trials so far, although, admittedly, most studies assessed tunnel healing at 6 months, which might be too late to observe difference between PRP-augmented and conventional ACL reconstruction [8, 52]. Vogrin et al., for example, report a higher level of bone-tendon interface vascularization, which is essential for bone remodeling, at 3 months, but not 6 months [52] (Table 7.1).

7.5 Stimulation of ACL Healing Using Biologic Scaffolds

ACL reconstruction is an excellent operation for patients – there is a high rate of patient satisfaction, return to sport. However, long-term studies show relatively high rates of posttraumatic osteoarthritis (as high as 75 % at 14 years after surgery) [53], and adolescent patients also have higher graft failure rates (as high as 20 % in some studies) [23]. A method which could stimulate repair of the ACL, rather than replacement of the ligament, would have several potentially important advantages. First, the complex insertion sites of the ligament could be maintained. The insertion sites of the native ACL are broad and cover more bone surface area than the cross-sectional area used for graft tunnels. Second, the ACL is known to have proprioceptive nerve fibers – repair of the ligament could potentially preserve these nerves and their function as the sensors for a dynamic feedback loop to the hamstring musculature. Third, as noted above, ligaments have an intrinsically higher crimp rate compared to tendons. Thus, getting ligaments to heal might preserve at least some of this high-crimp tissue and subsequently preserve the low-load behavior of the ligament tissue when the crimp is elongating and allowing relatively high strain to occur with little load. Each of these elements could potentially improve the function of the recovering ACL.

One possible way to do this would be to place a scaffold containing bioactive factors within the ACL rupture site. An effective scaffold would need to encourage ingrowth of surrounding cells, as well as encourage those cells migrating in to make collagen and other extracellular matrix proteins and form a functionally healing tissue. Recent studies have shown that cells from the human ACL can migrate into a scaffold made from bovine atelocollagen, and when they are there, they can express the gene for smooth muscle actin (SMA), which causes wound contraction [29–31]. ACL fibroblasts retain this ability also in ruptured ACL, where they exhibit even higher outgrowth rates [30]. The cells also remodel the collagenous biomaterial, which has been demonstrated to be a potential mechanism to introduce growth factor DNA to cells via retroviral infection with viruses in the biomaterial [43, 49]. The addition of a platelet concentrate to a collagen-based scaffold results in increasing proliferation and collagen production rates by the ACL cells [32]. Further analyses have shown that this effect is clearly attributable to platelets and not other remaining blood cells in the platelet concentrate [22]. The effects of other blood cells and individual factors in the clotting cascade on ACL fibroblast behavior are still somewhat elusive [14, 15, 20, 41, 43].

Table 7.1 Clinical studies of the use PRP to stimulate ACL reconstruction results

Authors	PRP	PRP location (volume)	Imaging: graft	Imaging: tunnel	Histology: graft
Vogrin et al. [52]	12×	Graft (4 mL) and both tunnels (1 mL)	…without a statistically significance between both groups	…enhances early revascularization in the interface…	
Figueroa et al. [11]	12×	Graft (4 mL) both tunnels (3 mL)	… with MRI at 6 months after reconstruction, we did not find any statistically significant benefit in the APC group in terms of integration assessment and graft maturation		
Nin et al. [38]	5×	Graft and tibial tunnel	…use of PDGF […] has no discernable clinical or biomechanical effect at 2 years' follow-up		
Silva et al. [47]	9×	Femoral tunnel (1.5 mL)		…use of PRP […] does not seem to accelerate tendon integration	
Orrego et al. [39]	9×	Graft (5 mL) and femoral tunnel (1 mL)	…enhancing effect on the graft maturation process…	…without showing a significant effect in the osteoligamentous interface or tunnel widening…	
Sánchez et al. [46]	3×	Graft (6 mL) and both tunnels			…resulting in more remodeling compared with untreated grafts…
Radice et al. [44]	9×	Graft (5 mL)	… a time shortening of 48%…		
Ventura et al. [51]	9×	Both tunnels	…transformation from autologous graft to new ACL was faster in the GF-treated group than in controls		

After characterization of the behavior of ACL fibroblasts seeded in a collagen-platelet composite in vitro, an initial animal study was done to assess the behavior of the collagen-platelet composite in a canine model of a stable central ACL defect [33]. This study showed good defect filling and a significant increase in the biomechanical properties of the ACL compared to the untreated group, which showed no improvement over the time course of the experiment. A later study compared treatment of a central defect in the ACL with defects in the MCL and the patellar tendon, which can be considered the natural gold standard of biological ligament and tendon healing [35]. This study confirmed the poor healing capacity of a central ACL defect but also showed that treatment with a collagen-platelet composite can produce results that are comparable to MCL or patellar tendon healing.

These early studies present evidence for the effectiveness of a collagen-platelet composite in ACL treatment in general, yet they build their results on central, partial defects while the clinical problem is a complete rupture. Thus, later studies used a complete transection model. Translation of an in vitro model into a potential clinical application requires animal testing. The choice of an appropriate model that mimics the situation in humans as intimately as possible is crucial to obtain valid results [4, 5]. For studies in ACL repair, a large animal should be used to recreate appropriate biomechanical stresses and to allow for suture repair. Secondly, the response to injury in the model ACL should be equivalent to the human ACL [4, 5]. Finally, the studied animal should exhibit similar growth rates and skeletal maturation to allow for testing of the effects of age. A porcine model satisfies these criteria. A direct comparison of primary suture repair with and without PRP to treat complete ACL transections in a porcine model revealed no differences in anterior-posterior knee laxity and stiffness and maximal tensile load of the remodeled tissue at 14 weeks [36]. These results prove that platelets alone are not sufficient to induce healing in a completely severed ACL. However, the addition of a collagen sponge together with the platelet concentrate (a collagen-platelet composite) produced significant increases in stiffness, load at yield, and maximal tensile loads at 4 weeks after the procedure [34]. This procedure resulted in 65 % of load at yield and 58 % of the maximal tensile load of an intact ACL at 4 weeks. Histological assessment of the treated ligaments showed hypercellularity and hypervascularity, suggesting still ongoing remodeling of the scar tissue at this time.

However, the more important question than comparison to healthy and transected ACLs is the direct comparison to an approved, clinically used gold standard to establish the relative effectiveness of ACL repair. Vavken et al. (unpublished data) compared ACL repair with bone-tendon-bone ACL reconstruction in a porcine model at 15 weeks. This study was in skeletally immature animals treated with immediate repair. In that study, it was noted that the bioenhanced ACL repairs had equivalent biomechanical outcomes to those seen in the ACL reconstructed group for immediate repairs done in this specific age group.

7.6 Clinical Relevance: Take Home Messages

- The data on clinical effectiveness of stimulated ACL reconstruction and ACL repair is still incomplete, and final, recommendations cannot be given (Level III data).
- Platelet-enhanced ACL reconstruction has shown improved outcomes on the microscopic level but failed to produce improvements in clinical outcomes. However, there is considerable heterogeneity in the available data and a lack of basic science data to support or refute with certainty the use of platelets in ACL reconstruction (no levels of evidence for basic science).
- The preclinical data for enhanced ACL repair is systematically and comprehensively collected and well documented. It supports the use of ACL repair based on relative effectiveness compared to ACL transection and ACL reconstruction. While these data support ACL repair, it is based on large animal models. Future testing in humans will help to establish the clinical effectiveness of ACL repair (no levels of evidence for basic science).

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ACL Primary Repair: What We Did, the Results, and How It Helps Today to Tailor Treatments to the Patient and the Pathology

8

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8.1 Introduction

In 1967, I was assigned as orthopedic surgeon and team physician to the United States Military Academy at West Point, New York. The population consisted of approximately 4,000 male cadets undergoing obligatory physical and military training as well as playing either a varsity or intramural sport each season. Knee injuries among the cadets and the staff were frequent.

Intramural tackle football was the biggest cause of serious knee injuries. I was mentored in my early days at the academy by some of the army's best: Colonel Anthony Ballard, Colonel Howard Abbott, and my partners: Lieutenant Colonel Joseph Rokous and Major Douglas Jackson. From the experience of those who preceded us, we agreed that there was "a syndrome" we called the "isolated tear of the anterior cruciate ligament" (ACL) which was usually characterized by a deceleration, noncontact event in which the participant heard and felt a pop, was unable to continue play, and developed a tense effusion over the next 12–24 h [1]. The effusion was always bloody upon aspiration, with only slight amounts of fat present. The physical examination usually showed a 3- to 5-mm positive Lachman test when compared to the opposite side. Further, the "natural history" over time was prejudicial to the active lifestyle required of the cadet and a future army officer. This was a serious epidemic, since approximately 75–100 of these events occurred annually. We therefore

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decided to explore the knee through a 2-in. anteromedial incision as soon as possible after injury and repair the torn ACL if possible (Fig. 8.1).

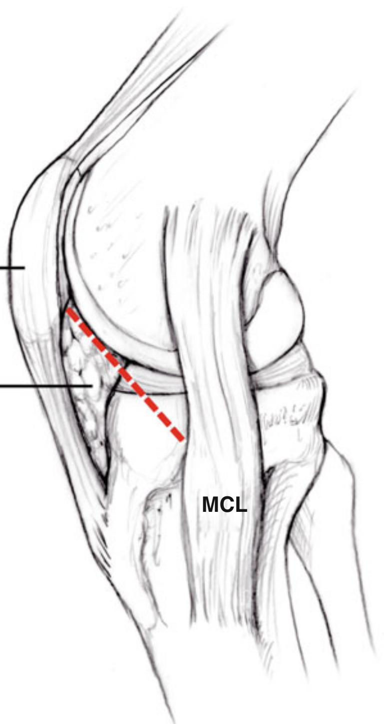

Fig. 8.1 Illustration of the medial knee depicting the medial collateral ligament (*MCL*), fat pad, patella, and 2-in. anteromedial incision (*red dotted line*) used to explore the knee to repair a torn ACL

One must remember that these were the days before arthroscopy and MRI, so the diagnosis was a clinical one made by history and manual examination. Surgery usually revealed a torn ACL, with little other demonstrable pathology. We felt that an acute tear of the ACL was usually amenable to primary repair. Interestingly, we were not naïve to the two bundles of the ACL and found that the tear was usually "z" shaped originating posterolaterally in the posterolateral bundle and exiting in the anterior distal portion of the anteromedial bundle (Fig. 8.2). A figure-of-eight suture was used to collect the fibers of the torn ACL and brought out through two lateral femoral condylar drill holes which were placed in the fresh raw femoral stump of the ligament (Fig. 8.3). Careful probing before repair insured there was little or no chondral or meniscal damage.

Approximately 10 % of the time our clinical diagnosis was in error. A subluxation of the patella could mimic an acute tear of the ACL, but in retrospect the hemorrhage occurred more quickly and was associated with significant fat in the aspirate. Sometimes, either we or the patient underappreciated a previous injury. In those instances, we typically found a tear of the residual ACL with a minor hemarthrosis and, frequently, a concomitant displaced bucket handle tear of the medial meniscus. We learned that the posterolateral bundle of the ACL contained the

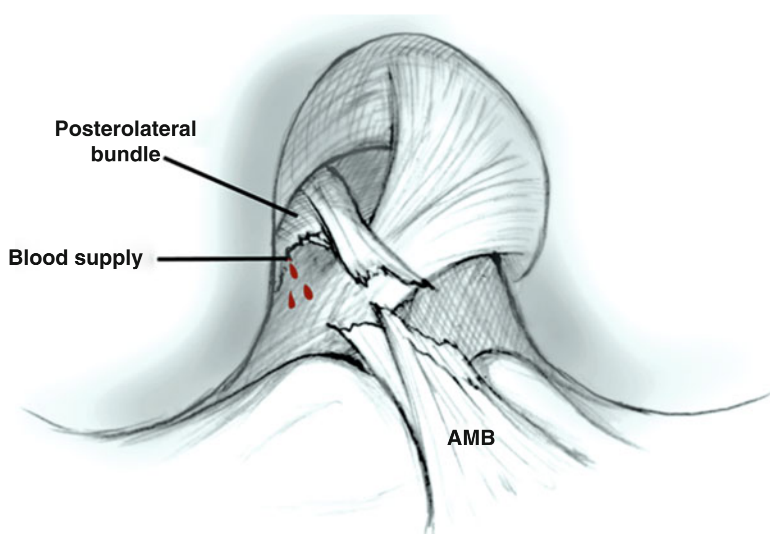

Fig. 8.2 Illustration of the typical "z"-shaped ACL tear originating posterolaterally in the posterolateral bundle and exiting in the anterior distal portion of the anteromedial bundle (*AMB*)

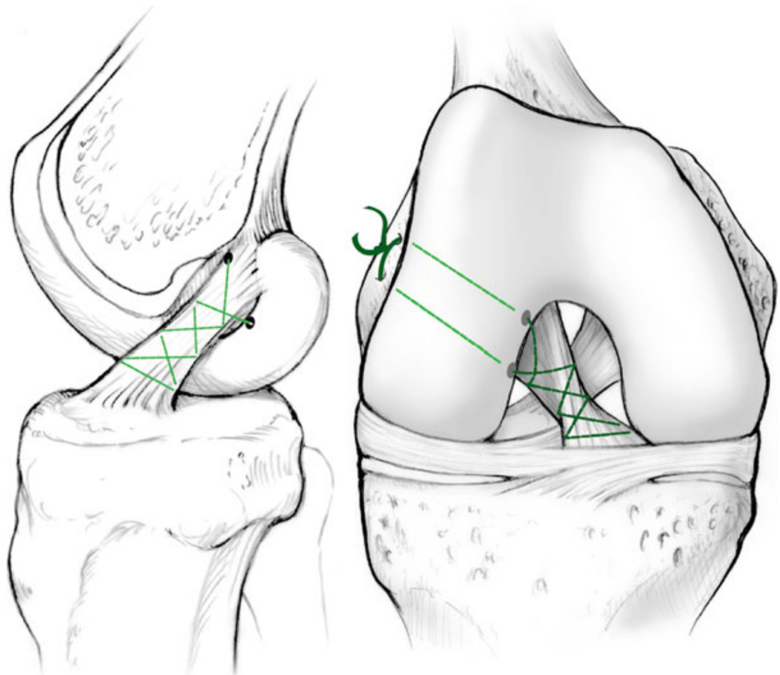

Fig. 8.3 Illustration depicting the figure-of-eight suture used to collect the fibers of a torn ACL and brought out of the two lateral femoral condylar drill holes

blood supply and was more critical to future function than the anteromedial band.

The postoperative care for these patients between 1967 and 1972 consisted of 3–5 weeks in a cast, crutches, and weight bearing to comfort. We were privileged to have access to the very best of rehabilitation personnel when the cast was removed [17]. We reported with confidence our 2-year results at the annual American Academy of Orthopaedic Surgeons (AAOS) meeting in Washington DC in 1972 [2].

As we became more confident in our results and our rehabilitation, we shortened the immobilization time and increased the level of allowed activity. Also, patients were allowed to return to sport earlier. I suspect this, and the passage of time prompted an increasing rate of reinjury and the necessity that we publish our 5-year follow-up, which did not support our enthusiasm or the results enjoyed at 2 years [1]. Essentially, at 5 years the patients fell into three categories. One-third had a good, satisfactory outcome, one-third required further surgery or significant limitation of required activities, and the final one-third were frank failures. Thus, there was little difference in our surgical results compared to the natural history as published by Noyes [8, 9]. We were greatly discouraged and were also challenged by the work of Marshall and Sherman, which reported much better results with primary repair [5, 11]. Interestingly, our 30-year follow-up of the original patients showed that the results at 5 years predicted the 30-year results – those that were good at 5 years remained so [14].

So what did we learn over the long run through this experience and how does it affect our judgment and treatment today? First, some general comments:

1. We gained confidence in our manual examination of the knee ligaments and in the pathology that we could expect to find based on the history as noted above.
2. The choice of "isolated tear of the ACL" was naïve and unfortunate and was so noted by Dr. Hughston (Hughston JC, 1972, personal communication). The knee is a symphony and sum total of its parts, and the secondary restraints are always stretched or violated when the ACL is torn. Frequently, and if protected, the secondary restraints will tighten as they heal, and sometimes the ACL will fall onto the PCL and heal as a Y-shaped ligament as described by

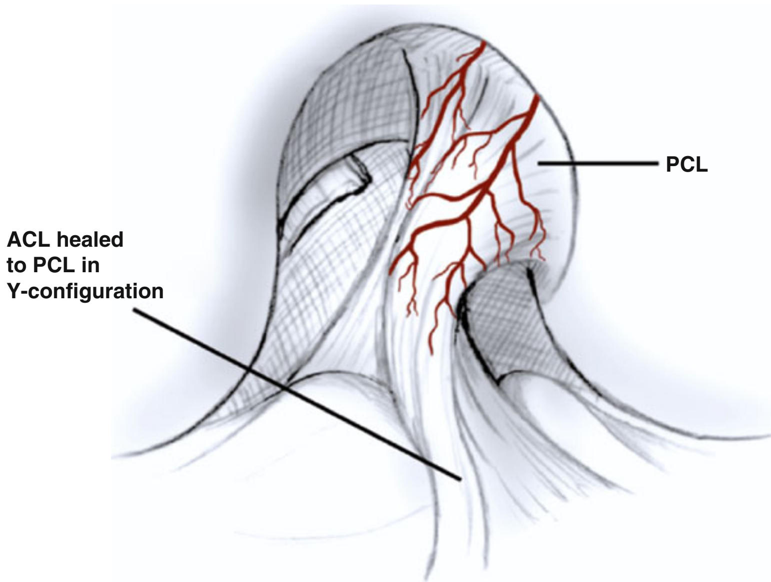

Fig. 8.4 Illustration depicting how an acute ACL tear can heal to the PCL in a Y-shaped configuration

Wittek [16] (Fig. 8.4). However, this was not enough support for the patients in our series to return to their active lifestyles.

The most important thing we learned was the importance of the role of the patient in the end result. In the beginning, we simply did not realize how unique our patient population was, nor did we realize how different the patient population of Marshall and Sherman was from our own. We did not appreciate that the cutting injury of contact sports was significantly more violent and associated with greater displacement and secondary injury than the slower twisting fall of the beginner skier.

It is important at this juncture to note Dr. Steadman's success with "healing response" [12, 13]. Both he and I are confident of the importance of this technique and the excellent results that can be appreciated in some patients. This is important, as the serious knee surgeon should examine his work and the results as to appropriately tailor the operation to the patient and the pathology. Most of Dr. Steadman's patients were skiers, many at the professional or near-professional level, and most committed to an intensive and extensive rehabilitation program.

Is this difference important? Absolutely, just as our patient population was unique and influential to the end results of our reported primary repairs, so has his patient population been different. Their professional experience and commitment to skiing, their muscle mass, their muscle memory, their rehabilitation, and postoperative bracing have all led to better results and the importance of the healing response in a select group of patients. Understanding the success of this approach in the hands of Dr. Steadman is just as important as understanding the causes of failure in our 5-year results if we are to apply our experience to patient selection in the future.

Coincident with this, I have always wondered if we had studied the satisfactory one-third of our patients as thoroughly as we did our failures what might have we come up with. To some extent I know. They were "smart" about their knees and the activities they chose. General Dwight D. Eisenhower, class of 1915 at West Point, though obviously not in our series, undoubtedly sustained an ACL injury while playing football as a cadet. He was troubled throughout his career by the residuals of this injury, and I was privileged to review his knee with him toward the end of his life. He had selected mostly staff officer assignments in his early career and only once noted fear of the knee giving way while performing his active duties – that was when he was wading ashore to meet the Free French in the early days of World War II in

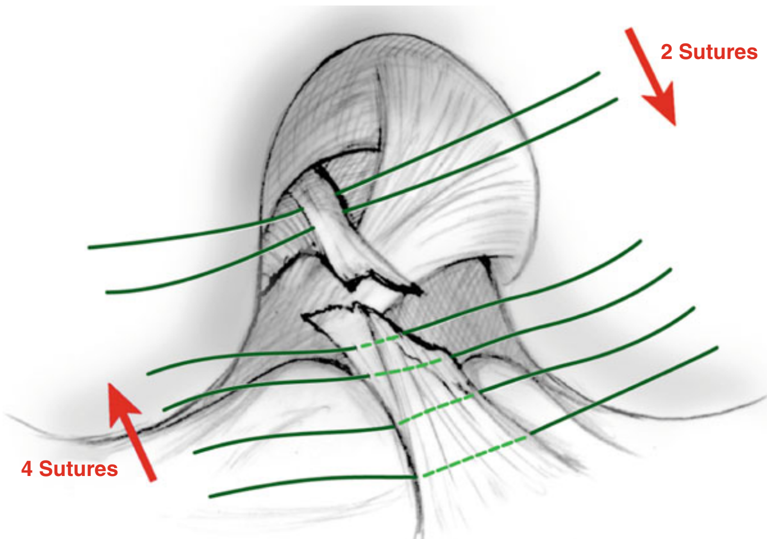

Fig. 8.5 Illustration depicting the multiple through-and-through suture technique of Marshall used to repair a torn ACL while preserving the blood supply

North Africa (Eisenhower DD, 1964, personal communication).

8.2 Surgical Technique and Pathology

As mentioned, we used a figure-of-8 absorbable suture to gather the bundles and pull them toward the femoral origin where the tear began. Dr. Marshall and I discussed the suture technique (Marshall JL, 1979, personal communication) as he felt his multiple through-and-through suture techniques were more preserving of the blood supply (Fig. 8.5), thus leading to better results through improved healing [6]. This point was never resolved as I felt our technique was more effective at drawing the fascicles together and encouraging their approximation to the femoral origin. By the time we had pondered this difference in depth, fortunately the problem was "solved" by bone patella tendon bone augmentation with interference fit fixation [4].

In retrospect as regards the surgical technique, I am amazed by several points. First, the limited incision gave us an amazing view of the joint providing we draped the patient to allow full range of motion and the assistant understood the requisites for retracting the fat pad, the medial collateral ligament, and the patella as appropriate. We did believe the fat pad should be respected and the incision was designed to insure this (Fig. 8.6). Further, there was no concern about the anatomic repositioning of the ligamentous stump because we operated early (usually within 24 h of the injury), and the fresh residual fibers of the cruciate ligament on the femur were quite identifiable.

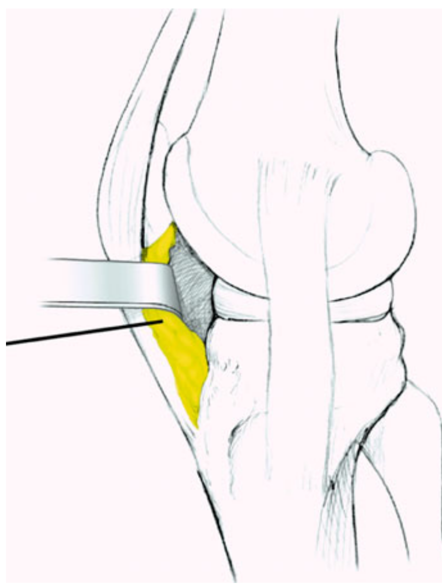

Fig. 8.6 Illustration depicting the limited incision providing a view of the joint with the fat pad retracted to avoid damaging it with the incision

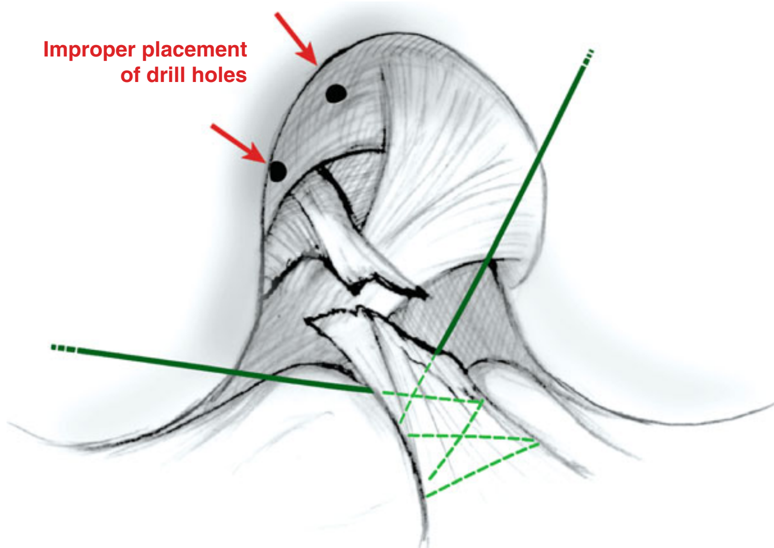

Fig. 8.7 Illustration depicting improper (nonanatomic) placement of the drill holes on the femur making patients more vulnerable to retear and reinjury

There are several other points relating to the pathology and the tear. As mentioned, most of the tears were "z" shaped beginning at the posterior femoral origin. The synovial sleeve was frequently intact, which served to mask the tear, particularly in its proximal portion.

Finally a complete midsection interstitial tear was unusual in the acute setting of a first-time injury. The tibial insertion was almost always intact and seldom was the ACL ligament torn in its entirety. It is important to note that, in our patient pool, there was usually 10–20 % of the ligament still intact, which provided a scaffolding and a direction to the repair. The residual intact ligament was usually a portion of the anteromedial band.

It is true that sometimes the ligament could not be adequately advanced to its origin, and thus the anatomic origin on the femur had to be compromised (Fig. 8.7). It was my opinion that these patients were more vulnerable to retear and reinjury. Rarely, in our experience, was the peel-off lesion from the femoral origin as sometimes seen in the ski injury. These were quite amenable to our technique of surgical repair, and I felt the results were reliable. Dr. Steadman's work on healing response supports this impression.

Our experience with primary repair of the adolescent injury was regrettably minimal. The pattern of tear and the population is once again different, and this experience would have been valuable. Dr. Kocher's work on adolescent ACL injuries may be beneficial in this regard [7].

A word about subacute or acute tears superimposed on a chronic partial tear. This occurred with relative frequency – perhaps 25 % of the time. The old healed injury, usually representing 10–25 % of the ligament, could be recognized by probing the ligament (Fig. 8.8). The fascicles were pale, lax, lacking turgor, and obviously stretched, weakened, and compromised. Yet they did represent an attempt by the body to heal itself, albeit in a hostile environment. Though these fibers were incorporated in the figure-8 sutures, it was felt that they compromised the quality of the repair and the end result since they obviously were not normal and represented scar tissue.

8.3 Discussion

Given the pathology and the improvements in every phase of knee surgery, is there a way to tailor the treatment to the patient and pathology so as to improve our current standards of care? I believe so.

First is the prelude and planning of the surgery. Does the history indicate a first-time acute injury? Was the injury slow and twisting as in

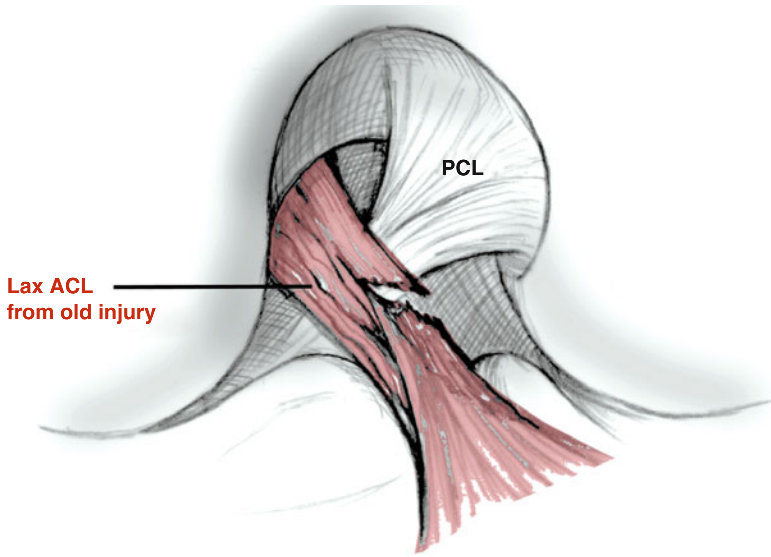

Fig. 8.8 Illustration of ACL lacking turgor and obviously stretched, weakened, and compromised due to an old healed injury

the beginner skier or violent as in the cutting sports (football, basketball, lacrosse, soccer, field hockey, or even gymnastics)? Thus the importance of a careful and thorough physical examination of the secondary restraints and an accurate grading of the pivot shift cannot be underappreciated. One would not elect to do a primary repair of the ACL on a patient who sustained a high-energy tear with a grossly positive pivot shift and an MRI that reflects bone bruising and injury to the secondary restraints. There is more laxity existent than may be appreciated.

Next is the consideration of the patient's age, expectations, vocation, avocation, and commitment to rehabilitation and return to sport. So often in later years as I understood these important variables, which so often determined the outcome of the surgery, did I realize the patient was in no way committed to sport, to rehabilitation, or even to a level of function that required a cruciate ligament. I had many patients in my later years that I chose to recommend nonoperative care to because I felt that the natural history would be quite satisfactory given their level of expectation and function. Primary repair or healing response are possible options for these patients, but with our techniques for reconstruction and meniscal repair, there is not the pressure to make a hurried decision or a decision based on incomplete evaluation. Better to start slow and formulate a plan that fits the patient exactly than to adopt a plan based on rote or erroneous assumptions.

The variables related to decision making for knee surgery have increased as our knowledge and experience have grown. Fortunately these variables can be learned from the written records and our mentors. How do these variables guide us in our future endeavors or vision?

Scaffolding and stenting are the key concepts to "regrow" or to encourage the ACL to heal; whether through primary repair or reconstruction, there must be a scaffold. Our scaffold of yesteryear was obviously not enough. Research today is promising of more effective scaffolding – whether it be autogenous, allograft, or prosthetic [3, 10, 15]. The future is promising for more efficient and effective surgery for ACL repair and replacement in the patient whose activity level and desires are requisite.

8.4 Summary

As mentioned in the very beginning, our original sin was to underestimate the demanding lifestyle of our captive patient population and the deleterious impact this active, competitive lifestyle had on our surgical results.

Do I feel there is a place for primary repair of the ACL today? Yes, though it is limited.

Whatever we can do to establish an anatomic ACL scaffolding to guide and encourage repair is worthy of consideration. This includes not removing residual ACL at the time of reconstructive surgery. There is almost always a residual band of anterior cruciate ligament that can serve to lend support, direction, and substance to the reconstruction. This should be preserved and integrated into the reconstructive technique.

Today, we are working to integrate the connection between the patient, the knee, and the surgical technique. The facts are known. The fallacy is usually in ignoring or not eliciting the details relative to the patients' pathology and needs that is at fault. We can improve our patient selection and our surgical technique if we communicate with the patient and complete our examination of the injured knee.

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9 Graft Choice in ACL Reconstruction: Which One and Why?

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Contents

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9.1 Introduction

Since the early 1980s, graft choice for anterior cruciate ligament (ACL) reconstruction has always been a subject of controversies among sports medicine surgeons. With time, mechanical strength of the grafts has been optimized and most of the fixation issues have been solved. However, harvesting morbidity of autografts and clinical outcome versus graft choice remains controversial subjects. Historically bone-patellar tendon-bone (BPTB) autograft has been the graft of choice. Then, the use of quadrupled hamstring tendons (HST) has known a large development mostly due to the ease of harvesting and less residual anterior knee pain compared to BPTB. Other options include the use of the central third of the quadriceps tendon (with or without bone plug) and allografts. Several meta-analyses comparing the outcome of ACL reconstruction according to graft type have reported conflicting results [32, 33, 42]. This explains why graft choice still remains a debated subject.

9.2 Biomechanical Considerations

The mechanical properties of the most commonly used grafts are listed in the Table 9.1.

The values are averaged from different publications [21]. One notices all these grafts exhibit a mechanical strength well above the native ACL

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and also a much higher stiffness. This originates in the collagen fiber orientations. They are parallel in tendons, while they are spiraled in the ACL.

9.3 Commonly Used Autografts

Contrary to a common belief, BPTB remains the most frequently used autograft [38], while hamstring and quadriceps tendon grafts are common alternatives (Table 9.2).

9.3.1 BPTB Autograft

BPTB autograft, which exhibits two bone plugs at each of its extremities, affords the most secure fixation, a low failure rate, and high rate of patient satisfaction. This is the graft of choice among team physicians dealing with high-level professional athletes [28]. However, it is associated with increased anterior knee pain and numbness with a greater incidence of extension loss and long-term osteoarthritis of the knee [29, 30]. Residual anterior knee pain can be decreased by filling the bony defects of the harvesting sites with bone paste recovered from the tibial tunnel drilling. Numbness can be prevented by saving the infrapatellar branch of the saphenous nerve during harvesting.

Table 9.1 Main mechanical properties of ACL tissue grafts

Graft	Ultimate strength (*N*)	Stiffness (*N*/mm)	Cross-sectional area (mm^2)
Intact ACL	2,160	242	44
BTB (10 mm)	2,977	620	50
Quadruple hamstring	4,590	861	53
Quadriceps tendon (10 mm)	2,352	463	62
Anterior tibialis tendon (single)	3,412	344	38
Posterior tibialis tendon (single)	3,391	302	48

9.3.2 Hamstring Grafts

Hamstring grafts are associated with less harvesting morbidity than BPTB, however, they exhibit a slighter degree of laxity, especially in females. Their harvesting weakens flexion strength of the knee and may account in the reported incidence of graft failure. They are usually fashioned in a quadrupled stranded graft using both gracilis and semitendinosus tendons.

9.3.3 Quadriceps Tendon

Quadriceps tendon has a low incidence of anterior knee pain and almost no residual numbness [15]. The skin of the distal thigh being very mobile, quadriceps tendon grafts can be harvested through a 4–5 cm long incision. It can be fashioned with or without bone plug. After harvesting, quadriceps deficit is temporary. Clinical outcome is excellent with residual laxity similar to BTB both in males and females, without extension deficit. It is still surprising this graft is not widely used for primary ACL reconstruction. However, for many, this is the graft of choice for ACL revision or posterior cruciate ligament reconstruction.

Table 9.2 Summary of the factors to be considered in ACL autograft selection [38]

Graft type	Anterior knee pain	Anterior knee numbness	Failure rate	Knee tightness	Residual weakness	Extension deficit	Patient satisfaction
BPTB	High	High	Low	High	Quadriceps muscle	High	High
Hamstring	Low	Low	Slightly higher	Slightly lower	Hamstrings	Low	High
Quadriceps	Low	Low	Low	High	Quadriceps muscle	Low	High

9.4 Allografts

Allografts avoid drawbacks of tendon harvesting, that is, skin incision, residual anterior knee pain, or numbness. In countries where legal issues are predominant, especially the United States (USA), allografts became the graft of choice for ACL reconstruction.

Currently, three kinds of allografts are available: chemically treated, irradiated, and/or fresh frozen. Due to their poor mechanical properties, chemically treated or irradiated allografts are gradually abandoned [23, 40]. Currently, fresh frozen allografts are the most widely used. Fresh frozen tibialis anterior or posterior tendons, Achilles' tendon with bone plug, and BPTB are the most widely used.

Tissue banks insure the proper donor selection as well as bacterial and viral screening. With the current infection control protocols, the incidence of viral or bacterial contamination is null. Graft quality is an issue and donor age must be known. Thus, the choice of the tissue bank remains a critical factor.

9.5 Graft Fixation Issues

Grafts with bone plugs are commonly fixed in the tunnels with interference screws either absorbable or metal. This method provides the highest strength and rigidity. However, there is concern that a too rigid construct may alter the full range of knee motion, and some surgeons prefer suspensory fixation with sutures tied on post or buttons with build in tissue loops.

Soft tissue graft fixation relies on numerous different methods: interference screws, suspensory devices, and cross pins. On the femoral side, suspensory devices with build in tissue loop, like the Endobutton® Continuous Loop, provides the strongest and stiffest fixation. With hamstring grafts, graft slippage at the tibial fixation site may occur explaining the slight increase in laxity compared to BTB.

9.6 What Is the Graft of Choice According to Evidence-Based Literature?

There are two types of scientific articles available in the orthopedic literature regarding graft choice. The first category corresponds to comparative series of one graft type versus another [1–4, 7–9, 11, 15, 20, 27, 29, 30, 36, 37, 40]. The second category are the meta-analyses [5, 6, 10, 12, 13, 18, 23, 24, 26, 34, 35, 39, 41, 43].

9.6.1 Comparative Studies

The results of ten studies [1, 14–17, 20, 24, 29, 30] are summarized in Table 9.3. Eight are randomized controlled trials (RCT) with level of evidence ranging from 1 to 3; two are non-randomized trials. Six are comparing the outcome of BPTB with HST autografts, one quadriceps tendon (QT) with BPTB, one allografts with autografts (regardless the graft tissue origin), and at last, one compares HST autografts with irradiated HST grafts.

Regarding the BPTB-HST comparisons, four studies found no difference for residual laxity and pivot shift. One found less laxity and pivot shift after BPTB. Three of the five studies which addressed the issue of harvesting site morbidity report a significant higher rate of pain, discomfort, or numbness after BPTB. Two studies conclude athletes returned to sports earlier and at a higher level after BPTB; this was not addressed by the other studies. Other interesting findings were: early open kinetic chain exercises increase residual laxity only after HST, BPTB slows down quadriceps strength recovery, and BPTB exposes to greater risks for early osteoarthritis

Other comparisons: QT versus BPTB [15] shows similar laxity outcome but significantly less pain after QT graft. Compared to autografts, using allografts does not increase the risk of postoperative infection [14]. Irradiated HST allografts results show more residual laxity compared to HST autografts [40].

9.6.1.1 Comments on the Comparative Studies

Most of the comparative studies BPTB versus HST do not find any difference between the two grafts for laxity or pivot shift; one favors BPTB. Most but not all of the studies report more harvesting site morbidity with BPTB, and two studies conclude return to sports was earlier and at a higher level after BPTB. QT grafts have a lower morbidity than PBTB and HST irradiated allografts result in higher residual laxity than HST autografts. The joint degeneration seems to be more frequently met after BPTB graft than after HS grafts.

Also, regardless the graft types (allograft vs. autograft) and graft source (BPTB, HST, etc.), some significant factors influence the outcome [22]: lower patient-reported outcome is strongly associated with obesity (BMI > 30), smoking, meniscectomy, and severe chondrosis at time of surgery. Also, a more vertical orientation of the graft influences the occurrence of a residual pivot shift test [31].

There are conflicting results between the various BPTB versus HST studies. This relates to different levels of evidence, surgical technique, follow-up duration, rehabilitation protocol, methods of evaluation, and all the studies do not address the same issues.

9.6.2 Meta-analyses Evaluation

The meta-analyses of randomized controlled trials performed to appropriate methodologic standards and reported according to the QUOROM statement represent the highest level of evidence [25]. Many meta-analyses on graft choice in ACL reconstruction have been recently published [5, 6, 10–13, 18, 23, 34–36, 39, 41, 43]. However, all of them do not reach the same conclusions, and several papers have been published to assess the statistical significance and clinical importance of differences [32, 33, 42]. The assessment of the quality of the meta-analyses as a potential source or explanation for differing results showed considerable differences in methodologic quality and quality of reporting only meta-analyses of graft choice for ACL reconstruction.

Poolman et al. [32, 33] in 2007 have identified 11 overlapping systematic reviews [5, 6, 10, 12, 13, 18, 34, 36, 39, 41, 43] . Three reviews favored BPTB for stability, and one favored HST. Six reviews favored HST to prevent anterior knee pain, and the rest were inconclusive. Only six reviews published systematic reviews on the same topic, and only two of these reviews cited all available systematic reviews that were available at that time. The quality of reporting ranged from 5 to 18 (median, 12; maximum score, 18). The internal validity ranged from 1 to 7 (median, 2; maximum score, 7). Formal sensitivity analysis was utilized infrequently. The highest-quality review favored HST grafts to prevent anterior knee pain and showed weak evidence that BPTB grafts yielded better stability.

About seven studies [5, 10, 12, 13, 34, 41], Vavken and Dorotka in 2009 [42] found that three of them favor HST, three favor BPTB, and one was neutral. Only two studies reported the rationale of repeating the meta-analysis. Furthermore, the levels of evidence among the included primary studies in these meta-analyses were rather low and vary among studies, especially with time. Also, there was variation in the numbers of studied end points, but all studies included stability. Methodologically, most meta-analyses were rather low quality. Assessment of publication bias was neglected completely, and only Biau et al. [5] tested study quality. Also, heterogeneity was rarely adequately considered. Finally, the validity of the methods used to pool data occasionally was unclear. Prodromos et al. [34] and Thompson et al. [41], for example, merely added numbers from the primary studies to obtain overall results. This, however, can lead to biased results owing to Simpson's paradox (i.e., the outcomes appear reversed when the groups are combined), particularly if the treatment allocation is not equal in all studies. Also, there seemed to be important differences in the surgical procedures, such as the type of fixation used. The studies by Biau et al. [5], Forster and Forster [10], and Goldblatt et al. [13] have the highest methodologic quality, but still presented conflicting conclusions. The qualitative assessment of studies showed differences only in the surgical procedures, suggesting

Table 9.3 Summary of ten prospective comparative trials

Authors	Year	Level of evidence	Comparison	Laxity	Harvesting morbidity	Others
Pinczeswski et al. [29, 30]	2002 and 2007	Prospective NRCT	BPTB vs. HST	No difference	HST: less harvest-site pain	BPTB: greater risks for early OA and ext loss
Jansson et al. [20]	2003	Prospective RCT	BPTB vs. HST	No difference	No diff in anterior knee pain	No diff for all scores
Aglietti et al. [1]	2004	1	BPTB vs. HST	No difference	More discomfort with BPTB, more tunnel widening with HST	
Maletis et al. [24]	2007	1	BPTB vs. HST	No difference	HST: better extension strength, fewer sensory deficits, fewer difficulty in kneeling	BPTB: greater number of patients returning to preinjury level
Heijne et al. [16]	2007	Prospective RCT	BPTB vs. HST	OKC at 4 weeks increases residual laxity after HST, not with BTB		Graft choice influences quad strength recovery more than timing of OKC
Han et al. [15]	2008	3	QT vs. BPTB	No difference	Less pain with QT	
Greenberg et al. [14]	2010	2	Allo vs. autografts	Not addressed	Not addressed	No diff in infection rate
Heijne et al. [17]	2010	Prospective RCT	BTB vs. HST	Less laxity and pivot shift w/BPTB	HST had not reached preoperative level in HS torque even 2 years after ACLR	BPTB returned to sports earlier and at a higher level
Sun et al. [40]	2011	2	HST: Auto- vs. irradiated allografts	More laxity with irradiated allografts		No functional difference

The follow-up of all the studies ranges between 2 and 10 years. The level of evidence is indicated according to what is mentioned in the original article
RCT randomized controlled trial, *NRCT* nonrandomized controlled trials, *OKC* open kinetic chain exercise

confounding by this variable [42]. The existing data suggested the most relevant answer is that a HST graft produces a better outcome, to a small extent, than a BPTB graft.

9.6.2.1 Meta-analyses Allografts Versus Autografts

Prodromos et al. published in 2007 a meta-analysis about the outcome of allografts versus autografts for ACL reconstruction [35] including HST and BPTB. Twenty RCT were included. They reported allografts had significantly lower normal stability rates than autografts. The allograft abnormal stability rate, which usually represents graft failure, was significantly higher than that of autografts: nearly three times greater.

Krych et al., in 2008 [23], have performed a meta-analysis of the outcome of allo-versus autologous BTB grafts from six published RCT. They found ACL reconstruction with BPTB autograft was favored over BPTB allograft for graft rupture and hop test parameters. However, when irradiated and chemically processed grafts were excluded, results were not significantly different between the two graft types.

Foster et al. in 2010 [11] have reviewed 31 prospective studies, level 1 or 2 comparing BPTB and HST allografts versus autografts. They could not identify an individual graft source that was clearly superior to the other graft sources. This led them to believe that, with currently available data, the graft source has a minimal effect on the outcome of patients undergoing ACL reconstruction.

9.7 Discussion

Many factors contribute to the final decision of which graft is used to reconstruct the ACL. As 85 % of surgeons are doing less than 10 ACL reconstructions per year, many use a single graft type for all patients [21]. However, factors as patient's age, life style, activity level, preexisting comorbidities, and associated injuries must be considered. According to the existing knowledge, there is no ideal graft. In Europe, HST grafts are widely used for their low harvesting morbidity. In the USA, allografts have the favor of most surgeons. However, surgeons must be able to adapt graft choice to the patient profile. It has been demonstrated that HST has a lower outcome in females and in patients with generalized hyperlaxity. Most of the publications regarding allografts do not recommend their use in young and competitive athletes due to a high failure rate. Nevertheless, in front of a failed ACL reconstruction, it is not always easy to separate what comes from the graft what comes from the surgical technique. One should not forget that most of the comparative studies and meta-analyses are based on ACL reconstruction performed with the transtibial endoscopic technique. The resulting non-anatomic placement of the graft strongly influences the objective outcome regardless the graft's type.

When my practice was in Europe, I was using about 95 % of HST for primary ACL reconstruction in adult patients, transportal, with a satisfactory outcome. Then, I moved to a country where a lot of male patients weighting 110–130 kg are playing recreational soccer five to seven times a week. They are not competitive or professional athletes. They are not particularly trained, do not warm up before playing, have a BMI between 35 and 40, and on the top of this, are often smokers. I started to use quadrupled stranded HST for ACL reconstruction with Endobutton CL in the femur and interference screw and screw post on the tibial side. With this technique I have got about 40 % of anatomical failure after 6–9 months. The HST graft either ruptured or stretched. I switched back to BPTB transportal, and the failure rate dropped almost to 0 %. My patients are Muslim and none of them has complained not being able to pray on the floor. I always saved the infra patellar branch of the saphenous nerve, I close the tendon defect, and I always graft the patella defect with bone paste. Thus, currently, as soon as the BMI is above 30, I do BPTB.

Another issue is the sports activity level. In this respect, the study of Pandarinath et al. presented at the 2011 AAOS [28] is exemplary. The authors have carried out a survey among team physicians dealing with professional athlete leagues in the USA (NBA, NFL, NHL, MLB) which concludes BPTB autograft is the graft of choice for ACL reconstruction in pro athletes. This choice is motivated by the strength of the fixation, faster rehabilitation, and earlier return to the field confirmed by the studies of Maletis et al. [24] and Heijne et al. [16].

In conclusion, there is no universal graft choice for ACL reconstruction. Surgeon must be able to select the most adapted type of graft according to the patient's profile. One type only cannot fit all. Graft choice is one factor among others which contribute to the success of ACL reconstruction. Graft positioning, fixation, rehabilitation, and secondary restrains insufficiency are also key factors.

9.8 Take Home Messages

There is no universal type of graft for ACL reconstruction.

- Level of evidence: 1
  HST and BPTB results in a similar favorable surgical outcome, reliably restoring knee stability
- Level of evidence: 1
  Allografts result in higher residual laxity but similar functional outcome
- Level of evidence: 1
  Irradiated allografts must not be used
- Level of evidence: 5
  BPTB has a higher incidence of harvesting morbidity
- Level of evidence: 3
  BPTB allows more aggressive rehabilitation than HST with earlier and higher return to sports than HST
- Level of evidence: 4
  Smoking, BMI > 30 are detrimental prognosis factors for HST

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Graft Healing in ACL Reconstruction: Can We Enhance It in Clinical Practice?

10

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10.1 Introduction

Surgical reconstruction of the anterior cruciate ligament (ACL) using tendon grafts is the current standard to treat the functionally ACL-deficient knee. The success of ACL reconstruction depends on a correct remodeling, reinnervation, and maturation of the graft used to replace the ACL. Remodeling and maturation of the graft affect

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directly the mechanical properties of the graft. Moreover, restoration of proprioception is equally as important as restoring mechanical stability of the knee. Restoration of proprioception is the result of reinnervation of the ACL graft.

Most of our knowledge on ACL graft healing comes from experimental studies in animal models. However, clinical human biopsy studies reporting "ligamentization"* and ligament insertion are scarce. This chapter reviews the literature and synthesizes our research on graft healing in ACL reconstruction. We will assess the graft healing at two locations: the intra-articular graft region and the intra-tunnel graft region. This topic is clinically relevant because patient management after ACL reconstruction using tendon grafts, especially postoperative rehabilitation protocols and timing of return to sports activities, will be greatly enhanced when we understand the "ligamentization" process and how we can enhance it in clinical practice. In this way, we will analyze the role of platelet-rich plasma in ACL graft healing in this chapter.

10.2 Experimental Studies in Animal Models: Basic Science and Clinical Implications

Many studies in animal models have shown that free tendon autografts, the most commonly used graft in ACL reconstruction, undergo a process of acellular and avascular necrosis although the collagen scaffold of the graft remains intact and unaffected and then it undergoes a progressive process of cellular repopulation, revascularization, and maturation after their implantation [4, 10, 20]. It is well-known that freezing and thawing destroy cells of the tendinous graft, although the framework of collagen remains normal [17]. Therefore, tendinous allografts would be the best experimental animal model to study the processes of recellularization, remodeling, and maturation of the grafts used to replace the ACL. Sanchis-Alfonso et al. [42, 43] have evaluated the processes of recellularization, remodeling, and maturation of cryopreserved tendinous allografts used to replace the ACL in a rabbit model using light microscopy, quantitative microscopy, and ultrastructural analysis. Moreover, they have analyzed the variables that could have an influence on these processes, such as preservation, or not, of the infrapatellar fat pad and graft tension [43]. However, we must note that there is currently no satisfactory animal model whose findings can be directly extrapolated to humans.

10.2.1 What Happens to the Graft at the Intra-articular Region from the First Week, Until the Graft Is Completely Mature? Clinical Relevance

The first week in our animal experimental model [42], we can see how the synovialization process begins at the point of the femoral anchoring of the graft. Histologically, the graft is acellular and avascular (Fig. 10.1). The second week, the synovialization process reaches the tibial anchoring. Histologically, we can see that the peripheral portion of the graft is repopulated by elongated cells having oval nuclei with euchromatin (active fibroblasts), oriented along the long axis of the graft (Fig. 10.2). The third week, the entire graft is covered by a thick, cell-rich connective layer with abundant blood vessels, and the entire tendon is repopulated by cells (Fig. 10.3). At week 6, the graft shows a marked proliferation of cells (hypercellularity) with a great functional activity and intense revascularization. This hypercellularity consists of mesenchymal cells and activated fibroblasts producing growth factors to initiate and maintain graft remodeling [45]. Finally, 3 months later, the allograft histologically resembles a normal ACL ("phenomenon of ligamentization") (Figs. 10.4 and 10.5). Cellular and vascular density return to values of the native ACL during the phase of ligamentization [45]. Moreover, there was no histologic evidence of any rejection responses during the postoperative period. Sanchis-Alfonso et al. [42] conclude that tendinous allografts seem

*It is well-known that tendons differ histologically from ligaments. In 1986, Amiel et al. [3] demonstrated that a tendon graft transplanted into the knee to replace the ACL remodels into a ligamentous structure very similar histologically to a normal ACL. They coined the term "ligamentization" to describe this phenomenon.

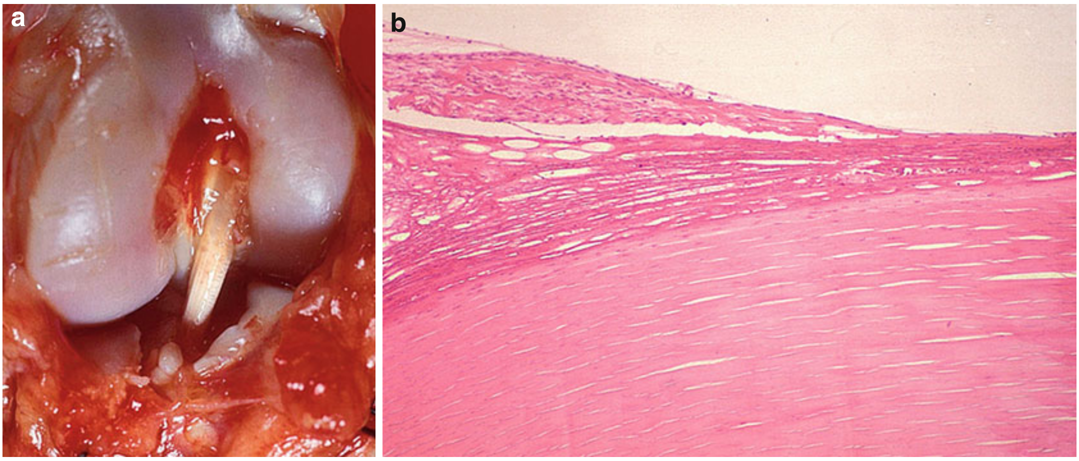

Fig. 10.1 First week. (**a**) Gross pathology. (**b**) Avascular and acellular graft

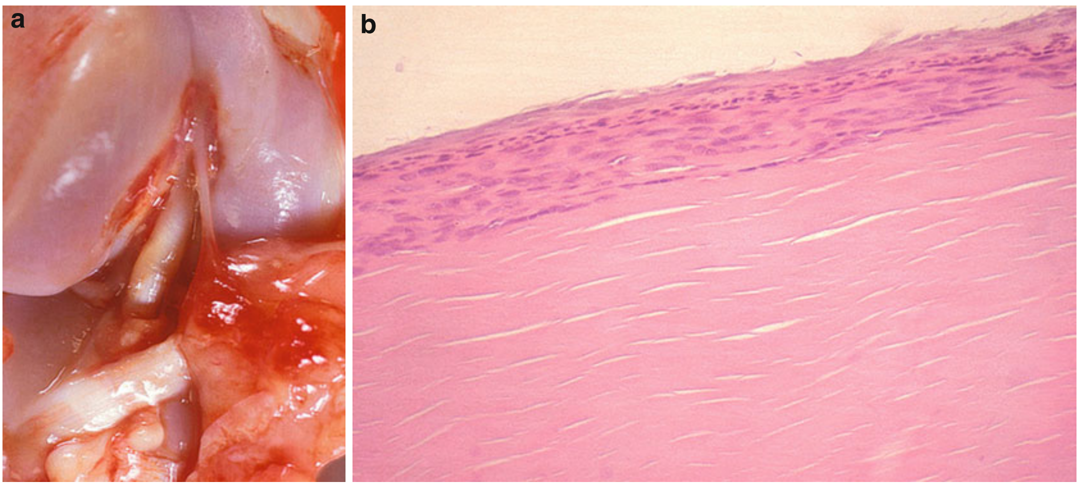

Fig. 10.2 Second week. (**a**) Gross pathology. (**b**) Peripheral portion of the graft repopulated with cells

to be a good graft from the biological point of view. Moreover, neither articular degeneration nor graft biodegradation is observed. Therefore, the tendon allograft provides a functional replacement for the removed ACL (Fig. 10.6).

10.2.2 What Is the Source of Recellularization of the Graft? Clinical Relevance

Sanchis-Alfonso et al. [43] have seen, within the allograft, some cells that at ultrastructural level contain features of cell damage, such as hydropic degeneration and autophagocytosis, which may lead to cell death (Fig. 10.7). That is the reason why they believe that these cells are not expected to participate in the recellularization process of the graft. Hence, the theoretical intrinsic source of the recellularization is not possible [43, 45].

Therefore, these authors postulate the extrinsic origin of recellularization [43]. Initially, the graft seems to be repopulated by cells from the peripheral synovial tissue, as can be deduced by the higher proliferative activity found at the synovial layer, compared with the graft itself using quantitative microscopy (Fig. 10.8). In this sense, Potenza and Herte in 1982 observed that the source

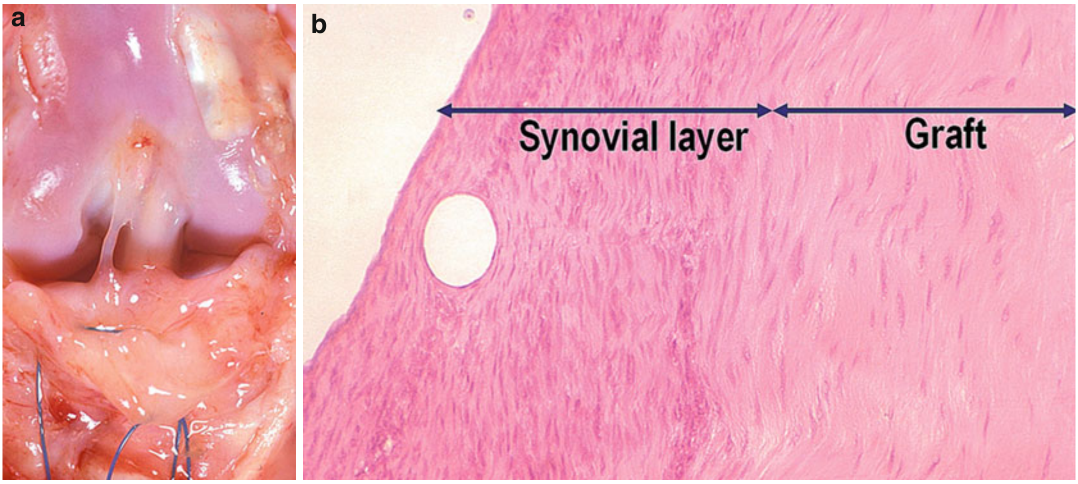

Fig. 10.3 Third week. (**a**) Gross pathology. (**b**) Entire graft repopulated by cells (Figure 10.3a - From Sanchis-Alfonso et al. [42]. Reproduced with permission from THIEME)

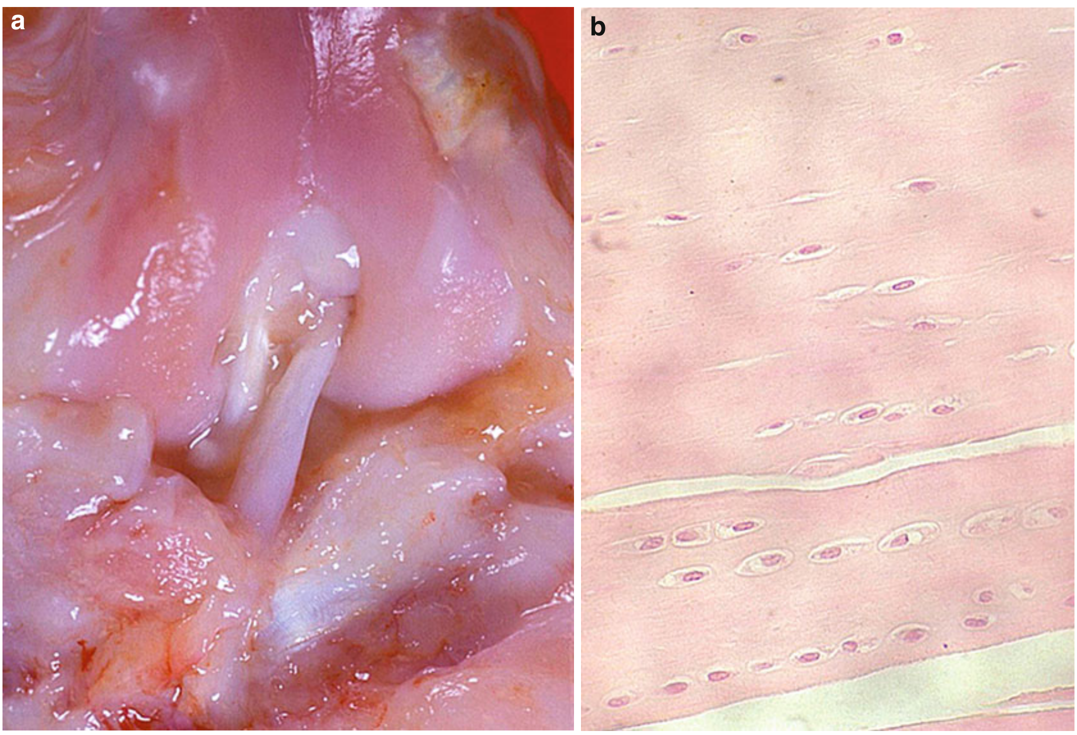

Fig. 10.4 Twelfth week. (**a**) Gross pathology. (**b**) The graft resembles a normal ACL (Figure 10.4a - From Sanchis-Alfonso et al. [42]. Reproduced with permission from THIEME)

of recellularization of acellular tendon allografts placed in the knee joint was the synovial cell of the joint – a highly versatile facultative fibroblast [37]. Thus, tendon revitalization theoretically does not require the presence of viable preexisting cellular elements. Thereafter, the peripheral zone loses activity in favor of the graft itself, as can be deduced by the decrease in the proliferative activity seen at the periphery, and the corresponding increment in the proliferative activity found

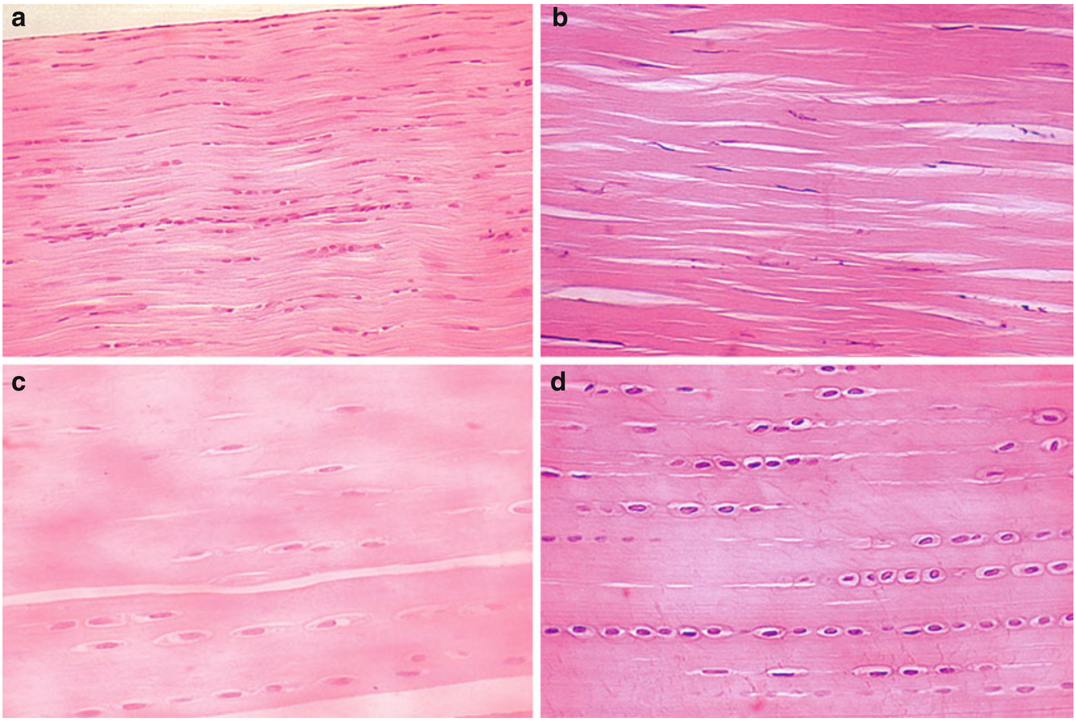

Fig. 10.5 Phenomenon of ligamentization. (**a**) Native tendon. (**b**) Cryopreserved tendinous allograft. (**c**) Allograft resembles a normal ACL. (**d**) Normal rabbit ACL

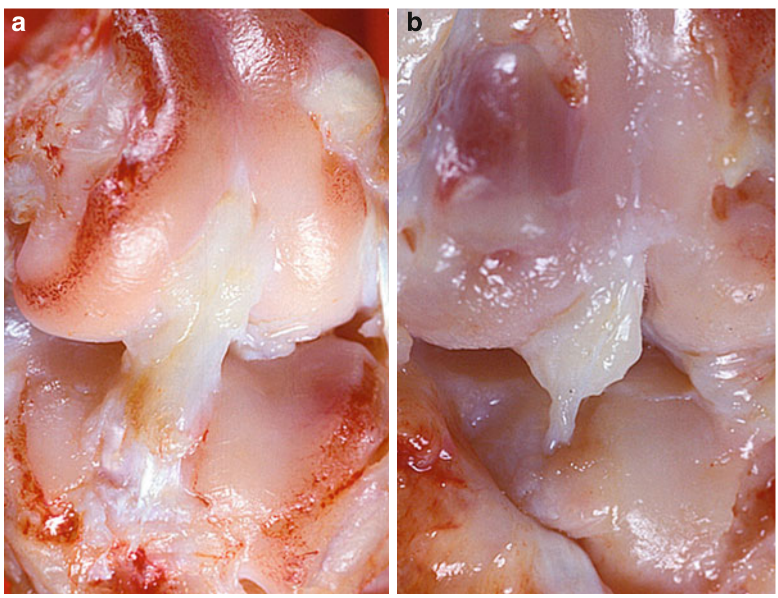

Fig. 10.6 (**a**) Six months. Gross pathology. Neither articular degeneration nor graft biodegradation is seen. (**b**) Six months. Gross pathology. Articular degeneration in a knee with graft deficiency

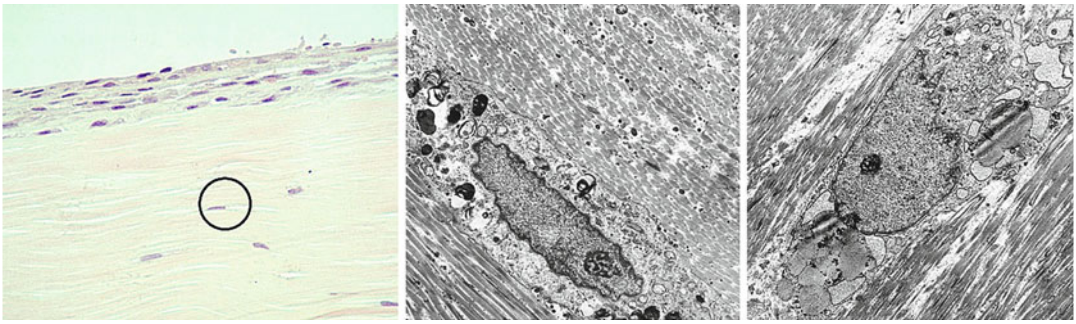

Fig. 10.7 Cells within the graft showing features of cell damage (*circle*). Intrinsic source of recellularization is not possible

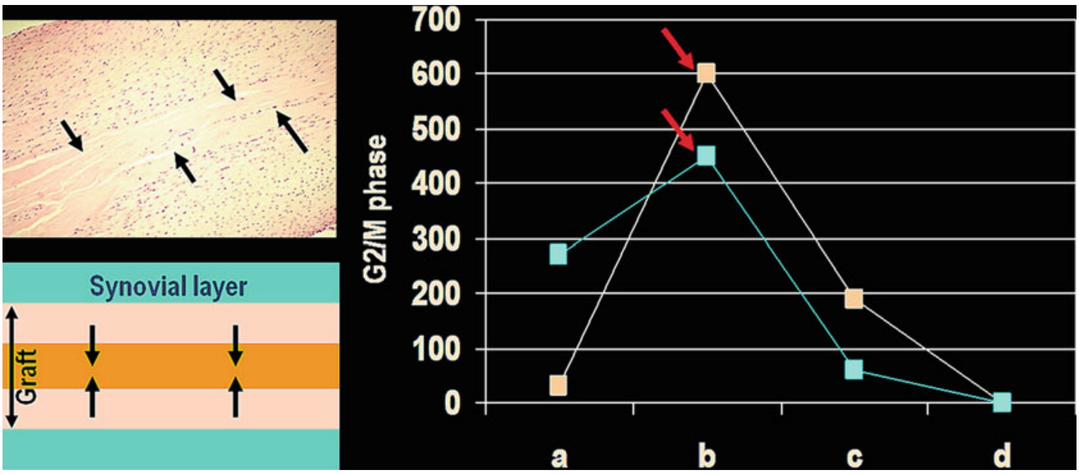

Fig. 10.8 Proliferative activity progression (peripheral zone – *blue*-, central zone – *pink*-). Phenomenon of creeping substitution

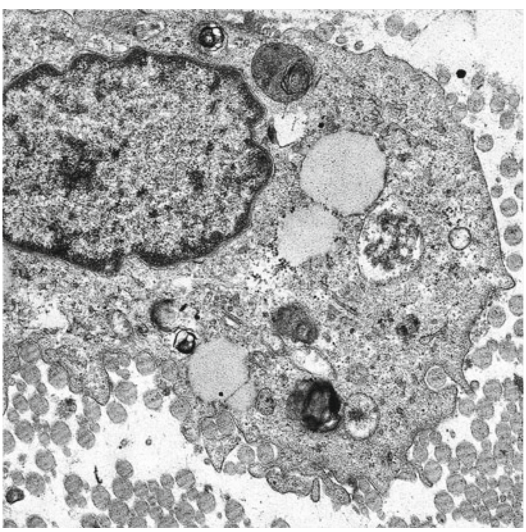

Fig. 10.9 Lysis of old collagen fibers by macrophages

in the graft (Fig. 10.8). At this stage, the source of recellularization is intrinsic, that is, the cells of the overlying stratum. Moreover, cells from the stump of the native ACL or bone marrow cells originating from drilling could be another source of cells [45].

In summary, the cell repopulation begins at the periphery and progresses to the center. During peripheral remodeling, the central zone of the graft remains acellular and compact (Fig. 10.8). Once the periphery of the graft has been successfully repopulated, the process progresses until the entire graft is completely restored. That is, during the remodeling process, the entire graft structure is not affected simultaneously, diminishing in this way the risk of rupture [43]. This is called the "creeping substitution" phenomenon.

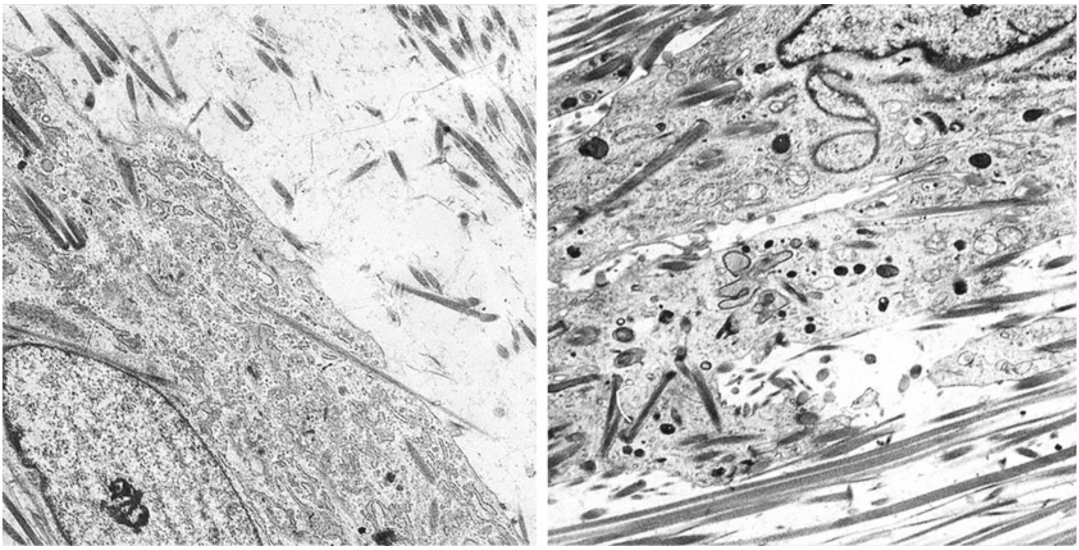

Fig. 10.10 Production of new collagen by active young fibroblasts

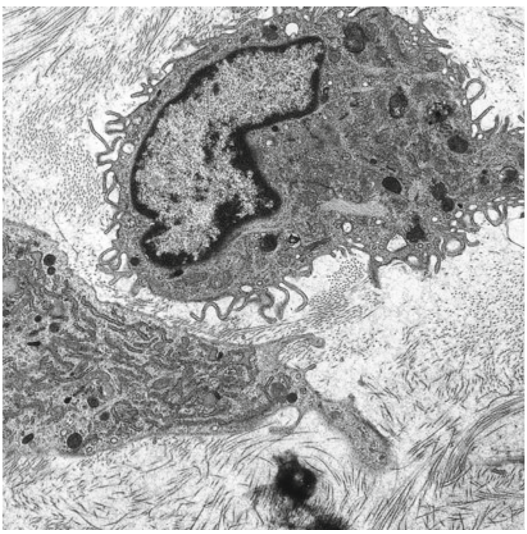

Fig. 10.11 Lysis of old collagen and production of new collagen are simultaneous and synchronic phenomena

Sanchis-Alfonso et al. [43] have demonstrated that during the remodeling process two phenomena occur: on one hand, lysis of the old collagen of the graft by macrophages (Fig. 10.9) and, on the other hand, production of new collagen by active young fibroblasts (Fig. 10.10). Both phenomena are simultaneous and synchronic (Fig. 10.11). This synchrony is crucial to preserve knee stability and graft tensile strength during the remodeling period. The maturation process progresses towards the center of the graft (Fig. 10.12). Finally, these cells modulate into fibrochondrocytes. This is called “polarized differentiation” (Fig. 10.13). The final result is a structure very similar histologically to a normal ACL (“phenomenon of ligamentization”) (Fig. 10.13).

The knowledge of the origin of repopulation cells has important implications. Given that cell repopulation of the graft is not by proliferation of donor cells, but by the introduction of recipient cells into the graft, rather than preserving the viability of donor cells, treatment with recipient cells before transplantation could facilitate remodeling into a normal ACL. Moreover, the importance of maintaining the blood supply to the autograft at the time of surgery would be questionable.

10.2.3 Reinnervation of the ACL Graft: Clinical Relevance

Aune et al. [6] have demonstrated immunoreactivity for neural markers in both rat and human ACL. This may indicate a proprioceptive function of this structure. Restoration of proprioception is equally important as restoring mechanical stability of the knee. Restoration of proprioception could be the result of reinnervation of the ACL graft.

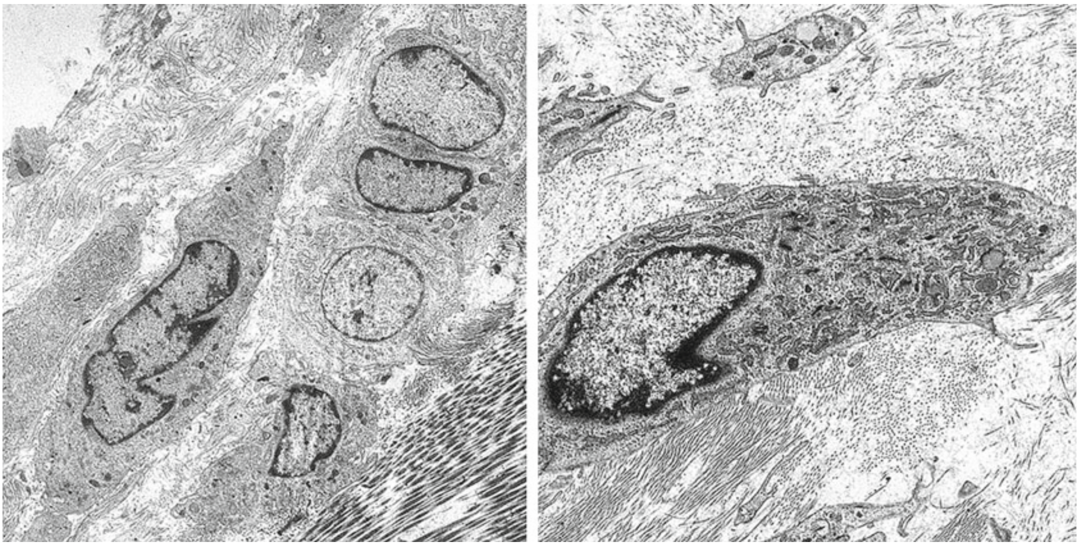

Fig. 10.12 Maturation process progresses towards the center of the graft

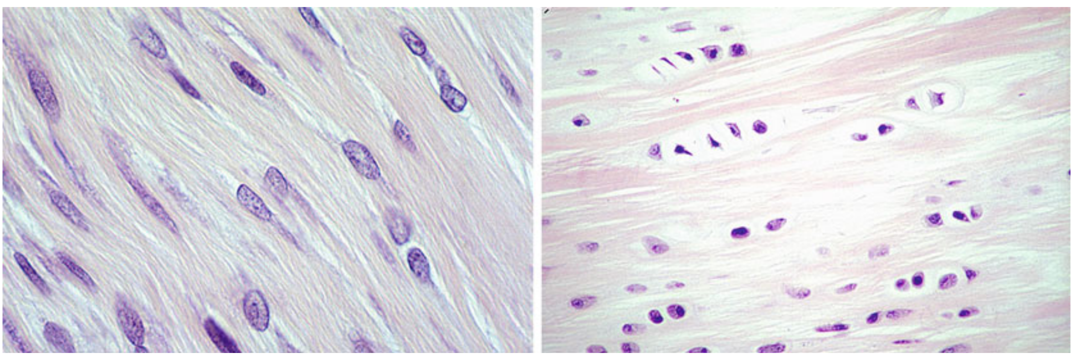

Fig. 10.13 Polarized differentiation: cells modulated into fibrochondrocytes

Aune et al. [6] have identified innervation in the ACL graft in a rat model. These findings are in agreement with those of Barrack et al. [7] who have demonstrated in dogs the reinnervation of the autografts used for ACL reconstruction by means of histology for neural elements and somatosensory-evoked potential technique.

10.2.4 What Variables Have an Influence on Recellularization, Remodeling, and Maturation Processes? Clinical Relevance

Many authors have shown the detrimental effects of the graft necrosis on the mechanical properties, strength, and stiffness of the graft when compared with the normal tendon or ACL during the first weeks of the graft after ACL reconstruction [34]. Failure of the graft may occur by rupture of its intra-articular part or from pullout from the bone tunnel. Consequently, accelerating the process of maturation could be crucial for a successful ACL reconstruction surgery. Therefore, it is very important to analyze the variables that could have an influence on the recellularization and maturation processes.

The first variable that we have analyzed is the preservation or not of the infrapatellar fat pad. Sanchis-Alfonso et al. [43] have observed that in those cases in which it was preserved, the recellularization process is faster and the

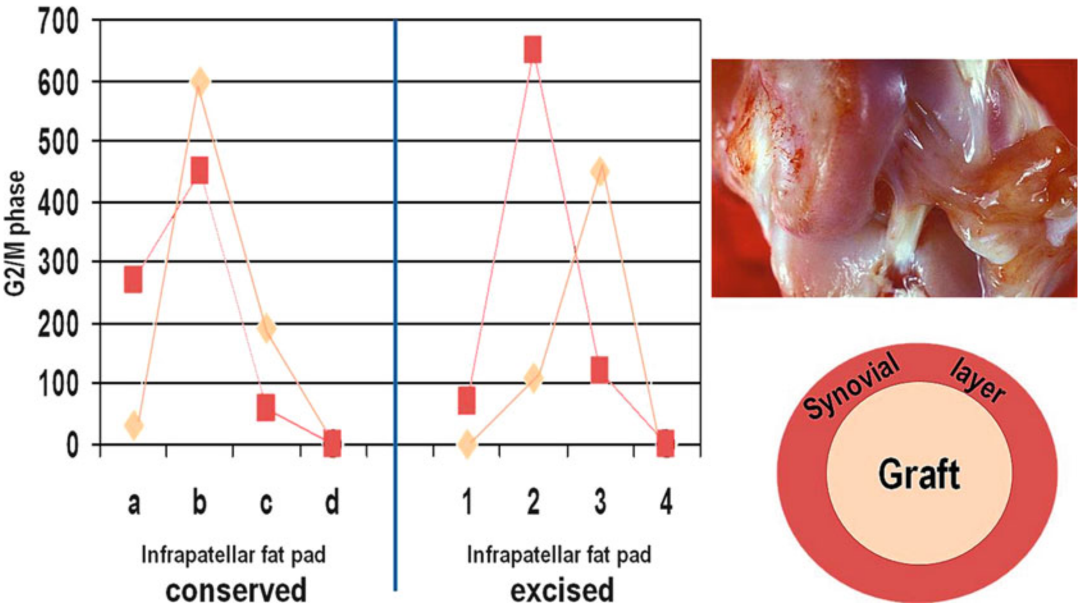

Fig. 10.14 Proliferative activity progression: infrapatellar fat pad conserved versus infrapatellar fat pad excised

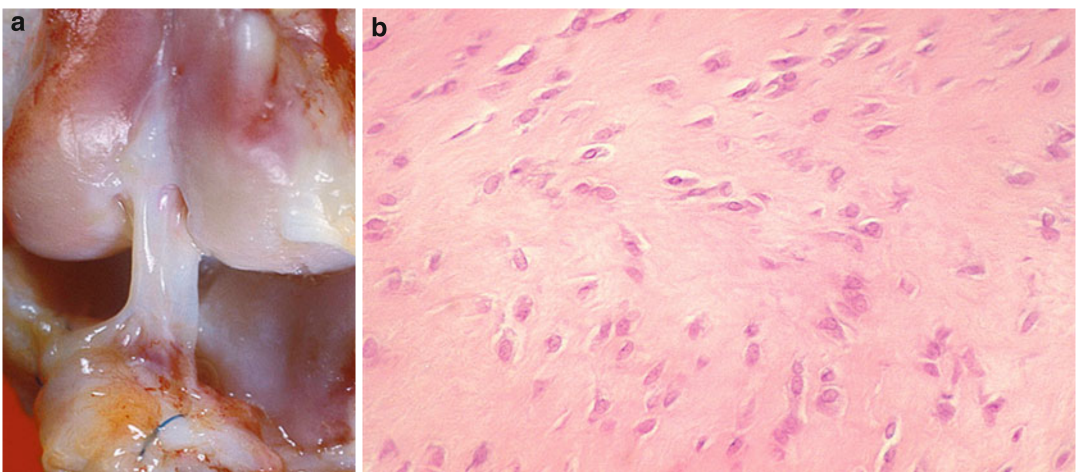

Fig. 10.15 (**a**) Gross pathology. (**b**) Incomplete graft maturation (3 months)

remodeling earlier than in those in which it was resected (Fig. 10.14). So, in the cases in which the infrapatellar fat pad was preserved, there would be a reduction in the period of weakness, diminishing the risk of rupture. Our data are in agreement with the prospective randomized study by Gohil et al. [19] who have demonstrated that minimal debridement of the synovium of the notch, the residual stump of the ACL, and anterior fat pad appear to speed up revascularization of grafts used to replace ACL. In theory, this might lead to an early return to maximum strength of the graft. But the infrapatellar fat pad has many more functions. In this sense, we have demonstrated that it initiates the repair process of the patellar tendon defect created after patellar tendon autograft harvest [44]. Moreover, infrapatellar fat pad is also the source of vascularization of the ACL grafts. Thus, the infrapatellar fat pad is not a waste tissue and, therefore, should not be resected when performing ACL surgery.

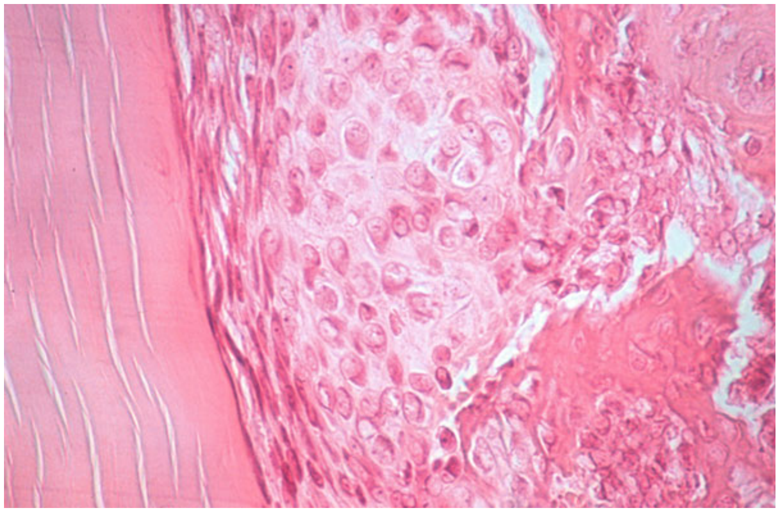

Fig. 10.16 Microscopic image of longitudinal section at bone tunnel level 1 week postoperatively. Acellular and avascular graft. Osteoid and mesenchymal cells

The second variable we have analyzed is anterior instability. Adequate graft tension is crucial for complete graft maturation [21, 29], hence, the importance of the isometric ligament placement. In the cases of anterior instability, we have demonstrated incomplete graft maturation (Fig. 10.15). In these cases, we have found hypercellularity, poor cellular orientation, hypervascularization, and immature cells (Fig. 10.15). Moreover, in the cases of anterior instability, we have observed degenerative changes.

10.2.5 Intraosseous Graft Healing in a Bone Tunnel: Clinical Implications

There are two types of entheses (transitional tissue between a tendon and the bone): (1) direct insertions (fibrocartilaginous entheses) that appears when the ligament enters the bone in a perpendicular direction such as the ACL insertion and (2) indirect insertions (fibrous entheses) when the ligament runs parallel to the bone inserting the ligament into the periosteum by Sharpey's fibers, such as the tibial insertion of the medial collateral ligament of the knee [32]. Direct insertions are composed of four zones: tendon, uncalcified fibrocartilage, calcified fibrocartilage, and bone [32].

Both direct and indirect insertions between graft and bone have been found after ACL reconstruction, although the presence of an indirect insertion has been more widely described [32]. Lui et al. [32] believe that this could be explained by the time of follow-up. Thus, in the papers with a short follow-up, the authors have found direct insertions. Sanchis-Alfonso et al. [42] in an experimental study using a rabbit model have observed that the graft is invaded by undifferentiated mesenchymal cells coming from the healthy receptor tissue host, being revitalized from the periphery towards the center (substitution by juxtaposition) (Fig. 10.16). The deepest portion of the tendon at the bone tunnel undergoes a process of resorption, while the proximal portion is occupied by fibrocartilage (Fig. 10.17). In the termino-terminal apposition zones, a process of endochondral ossification is observed. The final result is the formation of a physiological bone anchorage with three transitional zones: tendon, fibrocartilage, and bone (Fig. 10.18). In the case of a bone-patellar tendon-bone graft, the bone plug becomes anchored to the bony wall by appositional bone formation and the bone plug becomes necrotic as new bone forms [53]. Moreover, we must remember that the length of the tendon portion of the bone-patellar tendon-bone autograft is usually greater than the intra-articular ACL length, therefore, we must consider also in this type of graft the tendon-to-bone

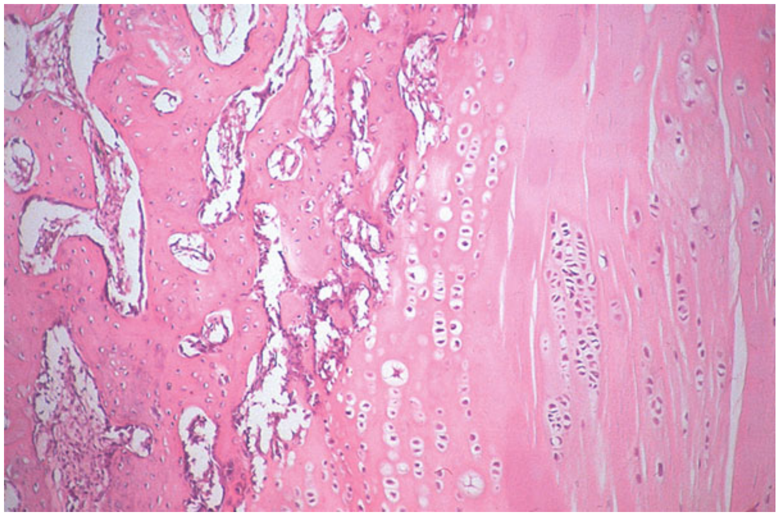

Fig. 10.17 The deepest portion of the tendon at bone tunnel undergoes a process of resorption while the proximal portion is occupied by fibrocartilage

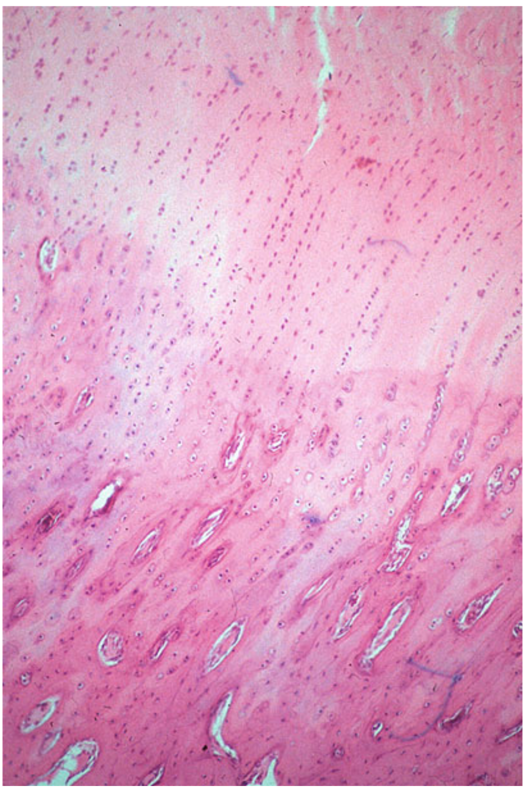

Fig. 10.18 Anchoring at 3 months resembling the normal ligament to bone attachment

healing because some of the tendinous portion of the graft usually remains in the portion of the tunnel opening into the joint.

Yamazaki et al. [50] using biomechanical and histological evaluations demonstrated that a long graft length (15 vs. 5 mm) within the bone tunnel does not result in an additional increase of anchoring strength and stiffness of the graft in ACL reconstruction. In both groups, the perpendicular collagen fibers connecting the tendon to the bone tunnel wall were observed only in the narrow area located close to the intra-articular tunnel outlet. Therefore, surgeons need not be overly concerned about graft length within the bone tunnel. Moreover, Yamazaki et al. [49] have demonstrated that graft-tunnel diameter disparity of up to 2 mm have not an adverse effect against intraosseous healing of the tendon graft after ACL reconstruction using pull-out strength studies. Therefore, surgeons need not be overly concerned about minor graft-tunnel diameter disparities.

The incorporation of the graft within the bone tunnel is crucial for a successful outcome after ACL reconstruction. Solid healing of the tendon graft in the bone tunnel is crucial to allow for more aggressive and earlier rehabilitation and a rapid return to full activity. To enhance graft-tunnel healing, manipulation of the biologic environment at the healing tendon-bone interface using tissue-engineering approaches, including the use of growth factors (v. gr. bone morphogenetic protein-2), mesenchymal stem cells, and enveloping of tendon graft with periosteum which has osteogenic capacity (periosteum graft augmentation), have been tested on animal models. These biological solutions have shown promising results in terms of enhancement of bone-graft healing rate, although it should be confirmed with randomized trials [15, 53].

10.2.6 Intraosseous Graft Healing in a Bone Tunnel: Bone Tunnel Enlargement: Clinical Implications

Cameron et al. [11] have demonstrated high concentrations of nitric oxide, Interleukin-1b, IL-6, and TNF-a in the synovial fluid for several weeks after ACL rupture. Moreover, Zysk et al. [54] have demonstrated a significant increase in IL-6 concentrations following ACL reconstruction. It is well-known that Interleukin-1 b, IL-6, and TNF-a stimulate osteoclastic activity and, therefore, are factors associated with bone resorption [24]. According to Hoher et al. [22], the synovial fluid with high levels of these cytokines "bathes" the osseous tunnel leading to inhibition of bone formation and possible osteolysis. This is in agreement with the work of Berg et al. [9] who demonstrated in a rabbit animal model that the tunnel healing was slower or incomplete at the articular portion of the tunnel in contrast with the regions of the tunnel farther from the joint and less exposed to synovial fluid. Rodeo et al. [39] had similar findings, greater tunnel widening at the articular aperture as well as a greater concentration of osteoclasts proximally in the tibial tunnel. Junkin and Johnson [26] have observed that preservation of the ACL tibial stump results in a significant decrease in arthroscopy fluid leak through the tibial tunnel decreasing the bathing event that will lead to a decrease in cytokine-mediated osteolysis and tunnel enlargement.

10.3 Clinical Studies in Humans Reporting Ligamentization: What Happens to the Human Graft?

As we have seen, numerous animal studies reporting ligamentization have been undertaken [3, 4, 10, 17, 20, 32, 39, 42, 43]. However, these findings should not be extrapolated directly to the human knee due to the complexity of the human ACL anatomy, surgical techniques, postoperative rehabilitation protocols, and testing conditions.

There is little information regarding the phenomenon of "ligamentization," in the human ACL after a clinically successful reconstruction, and the level of evidence of the papers published is low [12]. The concept of "ligamentization" described in animal models is also applicable to humans although important differences have been revealed. The first important finding revealed in the human studies is that the tendon autograft does survive in the intra-articular environment, being, at one point in time, histologically viable along with nourishing vascularization and with no signs of important necrosis [12]. There is no consensus on the origin of the neovascularization, but it is thought to be the Hoffa fat pad and the synovium. However, since the biopsy is an invasive procedure potentially deleterious on the graft, these biopsy studies provided information from the peripheral region of the graft and not from the core graft. In contrast with that, Delay et al. [13] studied an entire ACL-graft specimen during an autopsy and found areas of deep necrosis. Moreover, the timeline of biologic events occurring during the remodeling activity has been proven to be substantially different between animals and humans, being slower in humans. The time required by the human graft to become undistinguishable from a native ACL is still controversial.

Marumo et al. [33] demonstrated that the phenomenon of ligamentization occurs in the successfully reconstructed human ACL within 1 year after surgery (level of evidence 2). Moreover, they have found that after ACL reconstruction using autografts, the biochemical characteristics of the graft resembled those of the native ACL [33]. Falconiero et al. [16] conclude that by 12 months after ACL reconstruction with autografts, the graft resembles a normal ACL. However, because no statistical differences were noted in vascularity and fiber pattern after 6 months following ACL reconstruction, the authors conclude that significant graft maturity may occur before 12 months. This could allow early postoperative return to full activity and support proponents of accelerated rehabilitation programs following ACL reconstruction with autografts. On the other hand, Abe et al. [1] observed during second-look arthroscopic evaluation that the graft presented a gross similarity to the original ACL at approximately 1 year postoperatively. Their ultrastructural study suggested that the grafts were still immature even at 1 year postoperatively. Collagen fibrils of these grafts were of uniformly small diameter compared with normal patellar tendon and ACL. These findings are in agreement with those of Zafagnini et al. [51, 52] who analyzed the remodeling process of hamstring tendon graft and bone-patellar tendon-bone graft. They demonstrated that up to 10 years, while histologically the graft architecture was similar to a normal ACL in terms of numbers and multidirectional aspects of the fibrils, the mean diameter and bimodality distribution of the fibrils were not reached. Interestingly, they found that from 48 months onward, the neoligamentization process seemed to cease with no further change. Moreover, Rougraff et al. [40] observed that the process of ligamentization takes as long as 3 years to complete. Recently, Janssen et al. [25] showed that the remodeling process of human hamstring tendon grafts after standardized ACL reconstruction with an accelerated rehabilitation protocol was prolonged for up to 2 years after ACL reconstruction.

In summary, although the healing phases observed in animal models (necrosis, recellularization, revascularization, and ligamentization) have been found in humans, they cannot be directly applied to humans because the intensity of graft necrosis and neovascularization observed in animal models has not been seen in humans [45]. Moreover, there is an agreement that cellular repopulation and neovasularization of the tendon graft does occur after ACL reconstruction, although the exact source remains controversial. Clearly, it would be important to better understand the remodeling process of the human ACL graft and to have the possibility of performing core biopsy studies. A deeper understanding of the graft biology would have multiple clinical implications, especially the possibility to advocate an early aggressive rehabilitation during the first postoperative months to achieve a quicker return to sport activity without an increment of failure rates. Moreover, as suggested by Zaffagnini et al. [52], other factors such as the biomechanical environment determined by the surgical technique must be considered due to the need for proper stimulation to induce cell function transformation. It is well-known that necrosis and neovascularization lead to an important deterioration of the mechanical properties of the ACL graft [45]. Therefore, the small amount of necrosis and neovascularization observed in humans could explain why early aggressive rehabilitation during the first three postoperative months does not result in an increase of failure rates.

10.3.1 Does Fibrin Clot/Platelet-Rich Plasma Have a Role to Play in ACL-Graft Healing?

Enhancing the healing of the tendon graft to the bone and at intra-articular level and, therefore, decreasing the time to maximal tensile strength of the graft is crucial to facilitate an early, aggressive, and safe rehabilitation and to reduce the recovery time, which is measured by many as the ability to return to sports activities for athletes.

Fibrin clots have been widely used to enhance meniscal repairs in humans [27]. The fibrin clot supplies growth factors that promote cellular infiltration and healing [27]. It also acts as a scaffold for the reparative process [27]. In this sense, in an attempt to enhance the biological healing and maturation process during ACL reconstruction, some authors (see Chap. 21) add a fibrin clot to the graft. During surgery, 50–60 ml of blood is collected from the patient and then slowly stirred in a beaker until a clot has formed (after approximately 5 min). In soft tissue grafts, parts of the fibrin clot are sutured into the proximal and distal ends to enhance healing inside the tunnel. Eventually, in double-bundle reconstruction, the fibrin clot is placed between both bundles intraarticularly, just before fixating the anteromedial bundle on the tibial side.

Platelet-rich plasma (PRP) can also be used. PRP is essentially similar to a fibrin clot but contains more abundant growth factors [23]. Some preliminary findings suggest a potential effect of PRP on intraligamentous regeneration in humans at an intra-articular level. In an MRI study, Radice et al. [38] recently demonstrated a 48 % reduction in the time required to achieve a complete homogeneous graft signal when PRP was used for surgical ACL augmentation. Sánchez et al. [41] showed, in a biopsy study with low level of evidence, that the application of a particular platelet-rich plasma preparation rich in growth factors (PRGF) during ACL surgery using hamstring results in a better tendon graft "ligamentization." Moreover, the use of PRGF has also been advocated to speed up healing at the region of the osseous tunnel. Regarding the healing of the graft at the bone level, the results seem to be not so promising. In the context of the hamstring tendons technique, Orrego et al. [36] showed an enhancing effect on the graft maturation process as evaluated by MRI signal intensity, but no significant effect of the platelet concentrate on the osteoligamentous interface or tunnel widening evolution was observed. Similarly, Silva et al. [46] used PRP after hamstring ACL reconstruction, but knee MRI performed after 3 months failed to show an acceleration of tendon-to-bone integration. However, some limitations, such as the low number of patients for each group and the possible insufficient sensitivity of MRI in detecting small changes in the fibrous interzone, decrease the relevance of the results obtained in this study. In the context of bone-to-bone integration, the use of PRP to enhance the graft attachment is to be considered with caution because of the unclear usefulness of PRP on bone-graft integration. In fact, the effects of PRP on osteointegration are controversial, and some studies have even showed a negative effect on bone healing and regeneration [5, 48]. Vavken et al. [47] in a systematic review (level of evidence III) analyzed the effect of platelet concentrates on graft maturation and graft-bone interface healing in ACL reconstruction in humans. They concluded that the addition of platelet concentrates to ACL reconstruction may have a beneficial effect on graft maturation and could improve it by 20–30 % on average but with substantial variability. They believe that platelet concentrates accelerate graft recellularization and remodeling. However, the current evidence shows that platelet concentrates have a very limited influence on the intra-tunnel graft region healing and no significant difference in clinical outcomes. Moreover, it has been demonstrated (see Chap. 7) that growth factors can have positive and negative effects on ACL healing and require great care in their use.

In conclusion, at this time, the therapeutic role of PRGF in ACL reconstruction remains unclear. The administration of PRGF should be performed with caution and only in high-level trials to evaluate the safety and efficacy of it use.

10.3.2 Remnants of the Ruptured ACL as a Possible Source of Reinnervation of the ACL Autologous Graft

The presence of mechanoceptors in the native ACL is a widely documented finding because of the importance of restoring proprioception for a successful ACL reconstruction. In this regard, Barret [8] noted that after surgery, the clinical ligament stability levels correlated poorly with patient's satisfaction and the overall functional outcome. However, it was the proprioception of the knee that correlated with both function and satisfaction. This concept focuses the attention on the sensitive rather than mechanical proprieties of the ACL, suggesting alternative strategies to improve the outcome of ACL reconstruction. An interesting topic in this background is the potential property of the remnants of the ruptured ACL to reinnervate the ACL autologous graft.

Georgoulis et al. [18] investigated the presence of neural mechanoreceptors in the remnants of the ruptured ACL as a possible source of reinnervation of the ACL-autograft. They concluded that in patients with an ACL remnant adapted to the PCL, mechanoreceptors exist even 3 years after injury. A majority of these receptors have been reported to be located within the distal aspect of the ACL near the tibial insertion [28]. Dhillon et al. [14] evaluated the proprioceptive potential in ACL remnants, reporting a significant relation between injury duration and persistence of mechanoceptors and proprioceptive fibers, showing higher proprioceptive potential when the injury is more recent. Furthermore, they also reported the stump length and its adherence to PCL as strong predictors of higher proprioceptive potential. It is plausible that with degenerative changes, the proprioceptive potential of the injured stump decreases, making the delayed treatment of ACL lesion dangerous from the proprioceptive and mechanoceptive point of view and affecting the outcome of the reconstruction. Adachi et al. [2] reported a positive correlation between the number of mechanoceptors in ACL remnants and the joint position sense just before ACL reconstruction, suggesting proprioceptive benefits from a higher number of mechanoceptors and indicating a remnant preserving approach in the ACL reconstruction surgery would be beneficial. Finally, Ochi et al. [35] reported the presence of sensory neurones both in ACL remnant and the graft using somatosensory-evoked potentials (SEP). Furthermore, the voltage of the SEP of the reconstructed ACL was almost identical to that of native ACL. This finding suggests the propriety of the reconstructed ACL to provide information regarding deformation of the ligament, contributing to proprioception and joint stability.

If we accept that restoration of proprioception is the result of reinnervation of the ACL, ACL-remnant stumps are likely to be of some proprioceptive benefit after an ACL injury due to the retention of proprioceptive function which may contribute to a successful outcome. Lee et al. [30] observed that native ACL tibial stump preservation improves revascularization and reinnervation of the graft. The presence of the proprioceptive nerve fibers in the remnant of the ACL may provide a source for the reinnervation of the graft and restoration of normal proprioception. They also reported significant difference in functional outcome and proprioception between patients with more or less 20 % of tibial remnant, in spite of no significant difference in terms of mechanical stability, postulating that better result of ACL reconstruction is related to a more intact tibial remnant [31].

State of the art, controlled, randomized studies comparing the quality and quantity of mechanoreceptors in the reconstructed ACL with and without preservation of the ACL remnant have not been performed. However, one might assume that retention of the normal mechanoreceptors may accelerate the process of graft reinnervation, improving the rehabilitation process, recovery, and outcomes.

10.4 Take Home Messages: Future Research

From our chapter, we have drawn the following conclusions:

- Tendinous grafts seem to be a good graft from the biological point of view. When the graft is placed in the anatomical and environmental milieu of the ACL, it undergoes a process of "ligamentization."
- The cells responsible for this metamorphosis are of extragraft origin.
- Infrapatellar fat pad should not be resected when performing ACL surgery.
- Graft tension and isometric ligament placement are important for the formation and reorganization of the transplanted connective tissue.
- There is a disparity between the biological processes of graft healing described in animal versus human models. Further research is required to accurately describe the timelines for graft healing in humans and to relate the timelines for healing to functional capacity and a safe return to sport.
- At this time, the therapeutic role of PRGF in ACL reconstruction remains unclear. The administration of PRGF should be performed with caution and only in high-level trials to evaluate the safety and efficacy of it use. Growth factors can have positive and negative effects on ACL healing and require great care in their use.

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Is Double-Bundle ACL Reconstruction Necessary?

11

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Contents

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11.1 The Impetus for Changing to the Double-Bundle ACL Technique

The surgical technique for anterior cruciate ligament (ACL) reconstruction has evolved through the years, and the results with using various graft sources, such as a hamstring tendon graft, patellar tendon graft, or allograft, have varied considerably. An open technique for ACL surgery using an ipsilateral patellar tendon graft was the gold standard for ACL surgery in the 1980s. Stability was predictably obtained, but lack of knee range of motion and donor site morbidity was common enough for surgeons that they sought other graft sources and different surgical techniques. There was a shift to arthroscopically assisted ACL reconstruction, but knee stiffness and donor site morbidity problems persisted.

During the same time that arthroscopically assisted ACL reconstruction was becoming more common, there was an emphasis in healthcare to provide outpatient surgery whenever possible. This change led to even more rehabilitation problems because patients had to travel home after surgery and then they had to travel again the next few days after surgery to attend rehabilitation sessions. What physical therapists then had to deal with during the first few weeks of rehabilitation were patients who had a large hemarthrosis in their knees, poor leg control, and a lot of pain, which caused more donor site morbidity and knee range of motion complications.

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Surgeons initially used hamstring grafts for older, less active patients, and they observed that rehabilitation was easier than with the patellar tendon graft, although stability was harder to achieve. As new fixation devices became available, surgeons began using hamstring grafts for patients of all ages because they wanted to reduce donor site morbidity and make rehabilitation as easy as possible after outpatient ACL surgery.

Initially, femoral graft placement with arthroscopically assisted ACL reconstruction was done through a tibial tunnel, but this led to many grafts being placed too far anteriorly in the intercondylar notch because the deep position where the tunnel needed to be placed was difficult to reach with a transtibial approach. This technique often left patients with an intact graft but with more laxity than desired. The lack of ability to achieve stability reliably with hamstring grafts was one of the reasons the double-bundle ACL technique was introduced. However, inferior stability also led surgeons to adding a medial portal with the arthroscopically assisted approach to be able to place the femoral tunnel in a more ideal location deeper in the intercondylar notch.

The same change in surgical approach for the femoral tunnel was made with the double-bundle ACL technique that has evolved since the 1980s and 1990s. Some early comparative studies between single-bundle and double-bundle surgery showed little or no differences in results between the two surgery types [1, 7, 14–16, 27, 30]. However, the concern with these comparison studies was that the double-bundle surgeries were not performed anatomically correct, as the femoral tunnels were drilled through the tibial tunnel, causing imperfect position of the femoral tunnels. Thus, the procedure has changed to where it is recommended that the femoral tunnel be drilled from a medial portal to provide a more "anatomic" tunnel placement [26, 31].

The long transition from surgeons predominantly using patellar tendon autografts for ACL reconstruction in the 1980s to predominantly using hamstring grafts currently is an example of how surgeons tend to find surgical answers to problems. My approach has been to continue to use the patellar tendon autograft, which I believe is the best graft source available, and work to determine the best possible rehabilitation program to achieve excellent stability and minimize donor site morbidity and postoperative complications [20].

11.2 Double-Bundle ACL Techniques Compared with Single-Bundle Techniques with Patellar Tendon Graft

Anatomy studies showed that the fibers of the ACL function differently depending on location, with the anteriomedial (AM) portion becoming more taut with knee flexion and the posterolateral (PL) portion becoming more taut with knee extension [2, 8].

All of the double-bundle ACL techniques include drilling two distinct tunnels on the femur that has a 1–3-mm bony bridge between the bundles. The native ACL has a small elevated ridge of bone near the middle of the ACL insertion site, but there is no complete bony bridge that separates two distinct bundles of the ACL. Therefore, the "anatomic" double-bundle surgical technique is not completely anatomic, but it may be an improvement upon a single-bundle approach when the femoral tunnel is drilled transtibially.

I have been performing ACL reconstruction using patellar tendon autograft since 1982 with over 6,000 ACL reconstructions. I use a mini-open ACL technique where I can directly see the anatomical landmarks and place both the tibial and femoral tunnel precisely at the anatomical landmarks. The patellar tendon graft has triangular bone plugs on each end and the tendon and is 10 mm wide and, on average, 5 mm thick (range 4–11 mm; Shelbourne KD, 2012, unpublished data). This 10-mm × 5-mm graft is larger than the patient's normal ACL in most cases, so a notchplasty is usually performed to allow this graft to fit.

The intercondylar notch is normally filled with the posterior cruciate ligament (PCL) and the ACL, with the PCL encompassing about 60 % of the notch [5]. I drill the 10-mm tunnel so that the medial edge of the tunnel is located just lateral to the PCL and the inferior edge is located about 1 mm from the posterior wall of the notch

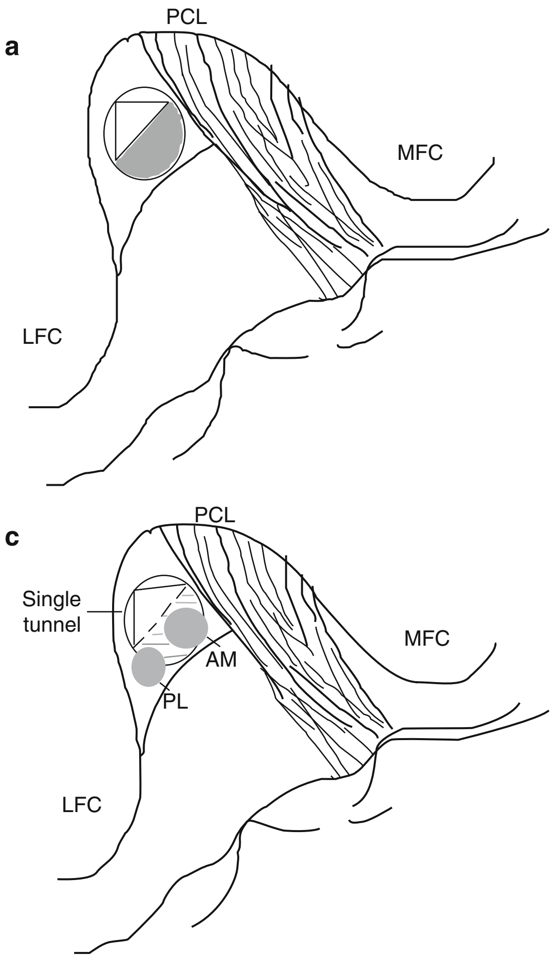

Fig. 11.1 This illustration shows the knee flexed about 90° and rotated about 45° counterclockwise from vertical. (**a**) The 10-mm-wide femoral tunnel is drilled so that the medial edge of the tunnel is located just lateral to the PCL and the inferior edge is located about 1 mm from the posterior wall of the notch. The tunnel is filled with the bone block (*triangular piece*), and the ligamentous portion is shown in *gray shading*; (**b**) with a double-tunnel procedure, two tunnels are drilled along the ACL footprint with about a 3-mm gap between tunnels, and the posterolateral (*PL*) tunnel usually created slightly smaller than the anteriomedial (*AM*) tunnel. (**c**) The single 10-mm tunnel is shown superimposed upon two tunnels frequently used for a double-tunnel ACL technique, and it shows that the single tunnel covers most of the area. *LFC* lateral femoral condyle, *PCL* posterior cruciate ligament, *MFC* medial femoral condyle, *PL* posterolateral tunnel, *AM* anteromedial tunnel

(Fig. 11.1a). The tibial bone plugs are triangular in shape, and the patellar end of the graft is placed in the tibial tunnel at the level of the joint line. The remainder of the graft is taken up in the femoral tunnel so that the bone plug is deep into the femoral tunnel and the ligamentous graft lies posteriorly in the tunnel.

When a double-tunnel procedure is performed, two tunnels are drilled along the ACL footprint with about a 3-mm gap between tunnels, and the PL tunnel usually created slightly smaller than the AM tunnel (Fig. 11.1b) [29]. Double-bundle sizes of most hamstring grafts are two round bundles of 4–7 mm in diameter [6]. Figure 11.1c shows the single 10-mm tunnel superimposed with the two tunnels frequently used for a double-tunnel technique, and this figure shows that the single-bundle technique with a patellar tendon graft covers the ACL footprint for the AM bundle and part of the footprint that is usually used for the PM bundle of a double-bundle technique when the tunnel is drilled through a medial portal. The 10-mm-wide and 5-mm-thick patellar tendon autograft reproduces the native ACL more anatomically correct than the double-tunnel soft tissue graft because it does not have the complete bony bridge gap between the two constructs of the ACL.

11.3 Will Double-Bundle ACL Techniques Provide Better Long-Term Results Than Single-Bundle Techniques?

Many surgeons switched from using a patellar tendon autograft because it is more difficult to rehabilitate the donor site from the graft harvest. The use of hamstring tendon grafts helped surgeons reduce complications with the donor site but the stability that was reliably achieved with the patellar tendon graft was more difficult to achieve. The change from using the patellar tendon graft to other graft sources led to decreased stability and then to new surgical techniques to include the double-bundle surgical approach.

It is believed that, if better rotational stability is achieved with ACL reconstruction, patients would have less osteoarthritis (OA) in the long term after surgery, but this theory has not been verified. Improving rotational stability, with the hope of reducing the incidence of OA in the long term after surgery, has been the motivation behind performing double-bundle ACL reconstruction. My concern with the use of double-bundle ACL reconstruction is that, if some surgeons have difficulty with performing a single-bundle technique properly, will they not then have more difficulty with double-bundle technique?

Also, we need to ask whether these changes with different graft sources and surgical techniques have led to better results. Stability is the main outcome being considered in the short term, and less evidence of OA is the main outcome being considered in the long term. The thought is that the double-bundle procedure provides better stability than the single-bundle technique. However, is there any evidence to show that obtaining better stability will achieve the goal of preventing OA?

Changes with ACL surgery need to be made with a specific focus on where we are failing patients, and the question is, "Are we failing patients with a single-bundle ACL technique using the PTG?" It is true that some patients do develop OA after ACL reconstruction, but have we been able to determine what factors cause the OA? Each surgeon needs to know his or her own success rate with surgery, and the only way to accomplish that goal is to obtain long-term follow-up on patients, and this is something that very few surgeons do as a routine. It is difficult to know what aspect needs improving without a systematic follow-up of results. As surgeons, we tend to always try to find a surgical solution to our patients' problems, and this is done many times without the surgeon really knowing what factors are important.

Some of the causes of OA in the long term after ACL reconstruction have been studied in depth and are quite obvious. Patients who undergo partial or total meniscectomy or have existing articular cartilage damage in the knee have been found to have a higher incidence of OA after surgery [11–13, 17–19, 21, 22, 25]. These factors are difficult to control, and we may not be able to prevent the OA that develops from existing meniscal and articular cartilage damage.

I have continued to use the patellar tendon autograft because bone-to-bone healing occurs quickly and the graft provides reliable stability and allows for unrestricted rehabilitation. The patellar tendon graft is a more reliable graft for stability than hamstring grafts or allografts, especially for young competitive athletes and women [3, 4]. The average age of patients undergoing ACL reconstruction in my orthopedic practice is 21 years old. Thus, I choose to continue to use the patellar tendon autograft because I believe that my patient population needs to receive the best graft possible to achieve stability so they can return to high-level sporting activity.

Analysis of our data in the 1980s showed us that knee stability was not a problem but that obtaining full knee range of motion was a problem. We found that delaying surgery after the acute injury to allow the knee to become calm and obtain full knee range of motion before surgery drastically reduced the complication rate of ROM problems after surgery. We also found that introducing exercises to obtain full knee extension immediately after surgery along with elevation, cold, and compression to prevent a hemarthrosis was key [20]. Most importantly, these improvements in our rehabilitation through the years did not result in less knee stability. Furthermore, as patients were more comfortable with their knee earlier in the rehabilitation process, they returned to functional activities and sports sooner. The earlier return to sports did not cause a higher reinjury rate after surgery [23, 24].

Many rehabilitation programs prescribed for surgery with soft tissue grafts and allografts recommend bracing, limiting knee ROM in the early post-op period, and delaying the return to activities. These rehabilitation restrictions may lead to deficits in knee extension and/or knee flexion that can affect the long-term results of ACL surgery. Shelbourne and Gray [22] found that the most important factor related to lower subjective scores at a mean of 14 years after surgery was a knee extension deficit >2° or flexion deficit >5°. Furthermore, patients who had meniscectomy or articular cartilage damage also had statistically significantly lower scores if they also had ROM deficits. In another study that evaluated the radiograph ratings of patients at a mean of 10 years after surgery, Shelbourne et al. [25] found that patients who obtained normal extension and flexion after surgery and then maintained it through final follow-up had a statistically significantly lower prevalence of OA (39 %) versus patient who had less than normal ROM throughout follow-up (53 %).

There have been some prospective randomized studies comparing various results between single-bundle, nonanatomic double-bundle, and anatomic double-bundle ACL reconstruction. Although some of the studies found that rotational stability was improved with anatomic double-bundle ACL reconstruction compared with single-bundle ACL reconstruction, the differences between the two surgical procedures have been minimal for other outcome objective and subjective variables measured [9, 30].

Almost all of the comparison studies of single-bundle versus double-bundle ACL techniques used hamstring grafts for both types of procedures. Only a few studies exist that compare a single-bundle ACL reconstruction with a patellar tendon autograft to a double-bundle ACL reconstruction [10, 28], and this is the true comparison that needs to be made.

Ishibashi et al. [10] performed an intraoperative evaluation of anteroposterior laxity and rotational stability at various degrees of knee flexion and found no difference between anatomic double-bundle ACL reconstruction and single-tunnel ACL reconstruction with patellar tendon autograft. Tsuda et al. [28] compared a "lateralized" single-bundle ACL reconstruction with a PTG with double-bundle ACL reconstruction with hamstring grafts. The location of the "lateralized" placement of the femoral tunnel was in the 10 or 2 o'clock position. The results showed no differences in KT1000 arthrometer measurements, pivot-shift tests, or Lachman tests between groups. Furthermore, there was no difference between groups for IKDC objective grade at final follow-up.

11.4 Summary

I do not believe that the double-bundle ACL reconstruction technique is needed to provide superior stability in the knee because excellent anteroposterior and rotational stability can be achieved with a single-bundle ACL reconstruction with a patellar tendon autograft. The trend away from using the PTG was due to donor site problems that surgeons were having difficulty solving. An extremely effective rehabilitation program for ACL reconstruction with PTG is available that provides for excellent range of motion, strength, and function after surgery, but it does require a commitment by the surgeon to educate their patients and rehabilitation staff in order to be effective. Whatever ACL technique or graft source is used for surgery, rehabilitation to achieve normal knee range of motion needs to be emphasized in order to achieve the ultimate goal of patient satisfaction and lower incidence of OA in the long term.

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12 ACL Injuries in Skeletally Immature and Adolescents Patients: How Can We Improve the High Rate of Poor Outcomes?

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12.1 Introduction

Currently, it is estimated that 400,000 anterior cruciate ligament (ACL) surgeries are performed annually in the USA. About half of those patients are children and adolescents [26, 66]. The most common injury patterns are midsubstance tears or tibial eminence avulsions. Treatment of a tibial eminence avulsion is done with closed reduction and immobilization (Meyers and McKeever types I and II) or refixation with sutures, pins, or screws (type III) and will not be discussed in this chapter.

Treatment of midsubstance tears in skeletally immature patients has the same goals as treatment in adults, namely, to create a stable knee and minimize the progression of further joint damage. The most important difference between the skeletally immature patient and the adult is the potential for physeal arrest and the length of time any secondary cartilage or meniscal changes will affect the patient. In the growing skeleton, transphyseal ACL reconstruction can potentially damage the growth plate and lead to growth disturbances. Furthermore, the consequences of posttraumatic osteoarthritis 15 years after injury in a 40-year-old patient are very different than those for a patient who tears his/her ACL during adolescence. The 40-year-old who is 55 when the osteoarthritis becomes evident is likely to be a candidate for a knee replacement if necessary, but this option is less likely to have long-term success in the 29-year-old patient who had an ACL tear at age 14. These factors

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have to be considered when choosing a treatment for a skeletally immature patient with an ACL tear.

12.2 The Physis

Children and young patients with a significant amount of remaining growth are at risk of growth deformities if the physis is injured by trauma or surgery. Skeletal maturity is usually reached at approximately 13–15 years of age in female and 16–18 years in male individuals. Its progression can be assessed and documented using the method described by Tanner and Davis [62], using physiologic signs of outer sexual development, or radiographically using X-ray images of the hand and wrist, the pelvis, or the knee. During skeletal growth, 65 % of the lower leg length derives from the distal femoral and proximal tibial growth plates. Tunnel placement in ACL reconstruction potentially jeopardizes both of these growth plates and could lead to leg-length discrepancy and angular deformities if the damage is eccentric. This potential risk has historically discouraged orthopedic surgeons from performing transphyseal surgical ACL reconstruction in skeletally immature patients. For the purpose of our research, we define disturbed growth as a leg-length discrepancy (LLD) of more than 1 cm and/or angular deformities of more than 3°, both side to side.

A number of large animal studies have assessed the risk of leg-length discrepancy and angular deformities after physeal damage as it would potentially occur in transphyseal ACL reconstruction. These studies suggest that the risks of growth disturbance can be minimized by adherence to several basic principles. Risk factors for physeal disturbance, in animals, include posterior tunnel placement [54, 55], a high tunnel diameter to physeal surface area ratio [20, 21, 24], excessive graft tensioning [14], incomplete tunnel filling by the graft [52, 59], and graft fixation across the physis [11]. If these factors are considered and avoided, the risk of growth disturbances can be reduced to below 1 %, as reported in two recent meta-analyses [26, 66]. Surgeons should familiarize themselves with these risk factors before considering a surgical intervention in a skeletally immature patient.

12.3 Conservative Treatment

Because of the potential risk to the physes, conservative treatment until skeletal maturity has been considered the first-line treatment for immature patients with ACL tears for a long time and is still favored by many [26, 66]. It has been favored because it was assumed that surgical treatment, i.e., transphyseal ACL reconstruction, would expose immature patients to an undue risk of growth plate damage, resulting in limb-length discrepancy and/or angular deformities.

Conservative treatment typically consists of limited weight bearing with or without a brace for up to 8 weeks, combined with physical therapy to regain and maintain muscle strength. Appropriate training consists of isometric exercises initially and is gradually progressed to closed kinetic chain exercises for approximately 2 months. Thereafter, moderate sports participation, such as conditioning sports, indoor cycling or swimming, should be encouraged. Pivoting sports should be avoided until definitive treatment, which is usually ACL reconstruction after skeletal maturity [2, 61, 66, 69]. Some investigators advocate return to pivoting sports with a brace after 1 year of physical therapy [61].

It is important to clearly express that conservative treatment can only slow down the degeneration of the knee joint. Conservative treatment has no effect on ACL healing and no effect on concomitant injuries such as cartilage damage and/or meniscus tears. All these defects will deteriorate over time. Hence, it is not surprising that essentially all studies on conservative management of ACL tears report long-term consequences such as chronic instability with repeated giving way, failure to return to sports, meniscal damage, and early osteoarthritis [2, 5, 6, 19, 22, 25, 26, 39, 40, 43, 47, 61, 66, 68, 69].

A recent meta-analysis of 476 patients followed for 53 ± 12 months on average showed a high proportion of unstable, symptomatic knees with chronic degenerative changes in all three tissues – ACL, meniscus, and articular cartilage – leading to discontinuing conservative treatment and converting to surgical stabilization in 50 % (range 17–88 %) of all cases [66]. While it is not clear whether meniscal and cartilage damage is caused by a treatment failure or is the cause of the treatment failure, it is obvious that the outcomes of conservative treatment in the skeletally immature population, even with adequate bracing and rehabilitation, are poor at best and that this treatment option should be considered a last resort.

12.4 Surgical Treatment

Surgical treatment of ACL tears in immature patients has two main categories: transphyseal and physeal sparing. Transphyseal ACL reconstruction in immature patients is performed similarly to ACL reconstruction in adults, with care taken to minimize tunnel size, completely fill the tunnels with graft, and avoid posterior tunnel placement in the femur and excessive graft tension and fixation across the physes. Since injuries to the growth plate from transphyseal tunnel placement have been a concern, a number of physeal-sparing techniques have been developed that aim at either intra-articular but extraphyseal placement of the graft or extra-articular/extraosseous knee stabilization.

12.4.1 Transphyseal ACL Reconstruction

Intra-articular, transphyseal ACL reconstruction in immature patients is performed similarly to transphyseal reconstruction in adults [13]. To date, 31 studies have presented findings for ACL reconstruction with at least one transphyseal tunnel. These studies report results in a total of 479 patients aged 14 ± 1 years and followed for 42 ± 19 months on average [3, 4, 6–9, 12, 14, 16–19, 22, 23, 30–35, 38–41, 47, 50, 51, 53, 58, 61].

The same grafts that would be used in adults were used in these studies, including hamstring grafts (doubled, tripled, quadrupled), quadriceps tendon, fascia lata, and patellar tendon. Gebhard et al. in 2006 published a direct comparison of four different grafts (hamstrings $n=28$, patellar tendon $n=16$, fascia lata $n=12$, and quadriceps tendon $n=12$) in a multicenter study including 68 patients at Tanner stage 1–3 and 28 patients at Tanner stage 4–5 [17]. After an average follow-up of 33 months, Tegner activity score, Lysholm, IKDC, and KT-1000 were assessed. While all four groups showed a significant improvement after reconstruction, there were no significant differences across the groups for IKDC, Tegner activity score, or KT-1000.

In looking at the entire group of the 31 published studies of transphyseal ACL reconstruction in immature patients, including almost 500 individuals, only 3 angular deformities and 2 limb-length discrepancies of more than 10 mm were observed, or a risk of roughly 1 % [66]. The authors' experience includes two cases of valgus deformity in pubescent patients. Ten patients had MRI results consistent with physeal narrowing but without angular or limb-length deformities. A different meta-analysis of 55 studies, including 935 patients of 13 years of age on average, showed a slightly higher risk for growth disturbances (LLD of more than 1 cm) of 1.8–2 % with transphyseal reconstruction [15]. However, when interpreting such data, it should be remembered that 77 % of the normal population have a leg-length discrepancy of up to 7 mm and 7 % of 12.5 mm or more. Other studies have gathered causes for leg-length differences after ACL reconstruction and identified graft fixation devices or bone plugs leading to bony bars across the lateral distal femoral physis (54 % of angular deformities) or fixation devices crossing the tibial physis resulting in physeal arrest (27 % of angular deformities) [27] as the most common causes, before tunnel placement and tunnel diameter [27]. Risk factors for physeal damage have been outlined earlier in this text.

The clinical outcomes after transphyseal ACL reconstruction in immature patients are consistent with those in adult patients. The likelihood of normal knee function (IKDC grades A and B) is about 85 % [15], and Lysholm scores and OAK scores of 95–98 can be expected [26, 66]. Return to activity ranges from 92 to 94 %, and a side-to-side difference in anteroposterior laxity of less than 3 mm can be seen in roughly 94 % of patients [17, 26, 66]. However, rerupture rates of 4–10 % have been reported for immature ACL reconstruction [15], and graft failure rates in the long term can vary between 25 and 41 % [64, 65]. Furthermore, long-term follow-up studies have shown the rate of posttraumatic osteoarthritis despite ACL reconstruction to be as high as 41–75 % over 10–14 years [64, 65].

12.4.2 Physeal-Sparing ACL Reconstruction

Physeal-sparing ACL reconstruction aims at surgical stabilization of the knee without damaging the growth plate. This is usually accomplished by placing the graft in the epiphyses, proximal to the tibial growth plate and distal to the femoral growth plate, or by using extraosseous stabilization techniques.

12.4.2.1 Physeal-Sparing, Transosseous ACL Reconstruction

There is data for 56 patients from five scientific papers undergoing physeal-sparing, intra-articular, transosseous stabilization [20, 21, 42, 47, 49, 57]. The average age of the patients in this group was 13 ± 2 years; all patients were followed for 47 ± 14 months on average.

Such procedures can be done with a soft tissue graft [3, 20, 21] or a patellar tendon graft [56, 57]. The tibial tunnel is placed under fluoroscopic control in the epiphysis using a guide wire and a cannulated drill (6–8 mm) [3, 20, 21]. The femoral tunnel exit site is chosen to lie distal to the femoral physis. Graft fixation is achieved with an EndoButton proximally and staples or a screw and post distally.

While such procedures have been reported to have both a good clinical outcome and a low risk of growth disturbance, there are a few potential risk factors that may jeopardize the physis. Listing such risk factors without any ranking, tunnel placement is usually eccentric, which is a known risk factor for physeal damage in ACL procedures [66]. The distal fixation with staples can result in an epiphysiodesis, and the graft lying parallel and on top of the growth plate can cause a similar effect [66]. Furthermore, drilling through the epiphysis parallel to the growth plate can potentially cause physical damage from compression, heat, or friction that would lead to growth plate disturbances. As mentioned above, Frosch et al. calculated the risk ratio for growth deformities for physeal-sparing versus transphyseal ACL reconstruction to be 0.34 in favor of transphyseal ACL reconstruction having a lower risk [15]. If the abovementioned facts are to be considered, this risk ratio can be substantially reduced, but if not, the growth plate might suffer more damage from such "physeal-sparing" procedures than it would from transphyseal placement, despite best intentions.

Apart from the potential for growth disturbances, the clinical outcome of physeal-sparing intraosseous ACL reconstruction is excellent. The final follow-up scores for the population described above were 98 for the OAK score and 96 for the IKDC score, on average. The average side-to-side difference in AP laxity compared to normal knees was 1.5 mm.

12.4.2.2 Extraosseous Stabilization Techniques

Alternative physeal-sparing approaches are extraosseous techniques. The best-known technique is a "combined intra- and extra-articular, physeal-sparing, extraosseous reconstruction" pioneered by Micheli [42]. In this technique, the iliotibial band (ITB) is incised, tubularized, and brought to the over-the-top position by wrapping it around the lateral femoral condyle. At this position, it is sutured to the condyle for additional fixation and inserted into the knee through the posterior capsule. From there, the ITB is brought to the front of the tibial ACL footprint, led through a groove placed underneath the intermeniscal ligament, and sutured to the periosteum or attached to the tibial cortex with staples. This configuration creates an extra-articular, anteroposterior stabilization between Gerdy's tubercle and the lateral femoral condyle as well as an intra-articular stabilizer against AP translation and rotation.

Data on 106 patients treated with this procedure, 12 ± 1 year of age on average, are available [10, 17, 19, 29, 39, 42]. The average follow-up is 47 ± 21 months [66]. No growth deformities were seen in these patients. Lysholm scores at the latest follow-up ranged from 94.3 to 97.4, with no instabilities. One direct comparison of extraosseous stabilization with transphyseal ACL reconstruction reported no difference in functional outcomes at 32 months [17]. Although this treatment was historically considered a temporizing procedure, it has functioned as a definitive reconstruction for the vast majority of patients who have had this performed [28, 29].

An alternative procedure uses a semitendinosus-gracilis autograft left in situ at the tibial insertion and passed underneath the anterior horn of the medial meniscus to be attached to the femur [10]. While it resulted in no growth deformities and good clinical scores, none of the nine patients of the original study population returned to sports without bracing.

12.4.3 Surgical Treatment of the Very Young Patient: Tanner I and II

Of particular interest is the management of ACL tears in the very young patients, such as Tanner stages I and II, which typically corresponds to a chronological age of 11 years or younger. As of 2011, data are available on the treatment of 93 such patients, ranging from 10 to 12 years of age, treated with all three surgical techniques described above: transphyseal ACL reconstruction; physeal-sparing, transosseous stabilization; and extraosseous stabilization.

Liddle et al. [32] followed 17 patients for 44 months after transphyseal ACL reconstruction with a quadrupled hamstring graft producing 15 excellent and 1 good result and two complications (1 rerupture, 1 superficial wound infection). One patient developed a 5° valgus deformity without functional disturbance. Bollen et al. [9] report on five adolescent males treated with transphyseal ACL reconstruction and followed for 35 months. No growth disturbances were seen, and all the patients returned to their preinjury level of activity. Streich et al. [61] directly compared 12 patients treated nonoperatively with 16 patients treated surgically with semitendinosus-gracilis grafts, followed for 70 months. At the final follow-up, no angular deformities or leg-length discrepancies (≥15-mm side-to-side differences) were observed. Unsurprisingly, the surgical group had significantly better clinical outcomes. Within 2 years after the initial injury, 7 out of the 12 nonoperative patients (58 %) proceeded to surgical stabilization.

Guzzanti et al. treated eight preadolescent patients with physeal-sparing ACL reconstruction and followed them for 70 months [21]. These patients reached an OAK score of 97 on average and a side-to-side difference in KT-2000 AP laxity of 1.8 mm.

Micheli et al. used his "combined intra- and extra-articular, physeal-sparing, extraosseous reconstruction" IT band stabilization technique for 17 prepubescent patients with ACL tears [42]. Eight patients were assessed after reaching skeletal maturity at an average follow-up of 67 months. All patients reported subjectively stable knees and also had good stability as measured objectively by KT-1000 testing. No leg-length discrepancies or angular deformities were found. The average Lysholm score for all patients at final follow-up was 97.4. Kocher et al. extended this treatment group to 44 patients, followed to 5 years postoperatively on average [29]. Again, no leg-length discrepancies or angular deformities were seen. Two patients had to be revised because of graft failure at 5 and 8 years postoperatively. For the remaining patients, the mean IKDC score was 97; the mean Lysholm knee score was 96.

12.4.4 Future Treatment Directions

Recent evidence from large ACL registries and meta-analyses has shown that, in adults, ACL reconstruction is associated with high long-term rates of osteoarthritis, despite initially excellent results for pain and instability. While there are no long-term studies looking at this problem in immature patients, it is rather likely that they will suffer from the same fate. Thus, researchers have started to investigate potential alternative or supplementary procedures.

Steadman et al. report results in 13 skeletally immature patients with proximal ACL injuries (complete midsubstance tears were excluded from this study) at 69 months postoperatively for a "healing response" procedure. This procedure consists of microfracture of the notch at the site of the femoral ACL attachment and reapproximation of the ACL stump with further surgical fixation. This is combined with postoperative restriction of mobility [60]. They report the results were good, with five patients having a negative pivot shift and 23 % having a significant reinjury requiring ACL reconstruction.

Others have suggested using platelet concentrates in conjunction with ACL reconstruction to enhance graft maturation and tunnel healing. Unfortunately, there are no data for this procedure in skeletally immature patients, but a recent meta-analysis of 380 adult patients from eight papers showed a beneficial effect on graft maturation but no effect on tunnel healing or clinical outcomes [67]. However, in younger patients, enhanced graft maturation might translate into better clinical outcomes.

Murray and coworkers have developed a method of biologically enhanced primary repair building on a collagen-platelet composite, which is discussed in more detail in Chap. 7. Briefly, they have shown promising results in a series of large animal studies [44, 45, 63]. Recently, it has been demonstrated that this treatment produces equivalent results to bone-tendon-bone ACL reconstruction in a large animal model. Moreover, this procedure has been shown to be particularly well suited for immature and adolescent patients, because of a stronger biological response at younger ages [36, 37].

12.5 ACL Injury Prevention

Earlier in this chapter, we have outlined the treatment options for ACL tears in skeletally immature patients. While the described surgical treatments result in good and excellent clinical results in the midterm, the long-term outcomes are characterized by a considerable risk of graft failure and premature osteoarthritis. New treatments might mitigate this situation but are not clinically available yet. Hence, the current best option for managing ACL tears is their prevention.

Earlier studies have shown that approximately 80 % of all ACL tears in adolescent patients are noncontact injuries and quadriceps-active, valgus stress incidents. Typical reasons for such incidents are a too narrow stance during landing or an overly erect stance during direction changes with knees and hips close to full extension (particularly in young women). Based on such knowledge, various ACL tear prevention programs have been developed that aim at improving motion patterns, proprioception, and neuromuscular responses.

Two recent meta-analyses have assessed the effectiveness of such programs in reducing the injury rate for noncontact ACL tears. Abernathy et al. assessed the effectiveness of strategies to prevent adolescent injury in sports in general, including a subgroup of knee and ACL injury, and found evidence for effectiveness of preseason conditioning, functional training, education, balance, and sport-specific skills but no evidence for effectiveness of protective equipment such as braces [1]. [49] focused on programs for noncontact ACL injury prevention specifically. In their meta-analysis of nine controlled trials, they calculated a pooled risk ratio (RR) of 0.38 in favor of intervention programs versus untreated controls, showing a significant reduction of the risk of noncontact ACL ruptures in the prevention group. They also report a substantial difference in this effect across genders, with females showing a RR of 0.45 and males a RR of 0.15. According to their statistical evaluation, the number needed to treat, i.e., the number of adolescents that need to receive training in order to avoid one ACL tear, was 38, which is fairly small considering that such prevention programs would be used for whole teams or high-school classes.

Conclusions

ACL tears in skeletally immature patients are an important clinical problem because of their high and still growing incidence and the increased likelihood of chronic secondary damages such as early-onset osteoarthritis and growth disturbances. Management of ACL tears in such a population should consider these risks. Conservative treatment, which has been considered the first-line treatment to avoid physeal damage, should be avoided if possible since the evidence shows that such treatment results in continuing instability and severe damage to the knee, including destruction of menisci and cartilage.

Transphyseal ACL reconstruction can be done even in the youngest patients (Tanner I and II), and if a few simple principles are considered, the risk of growth disturbance remains well below 1 %. Physeal-sparing placement of ACL grafts is possible but could, despite best intentions, lead to even more growth plate damage than transphyseal placement. Extraosseous stabilization has shown excellent results, but follow-up data beyond 5–8 years is scarce. Despite the impressive clinical results and a low risk of growth disturbances, surgical ACL reconstruction has less impressive long-term results, with approximately half of all adolescent patients suffering from a failed graft or onset of osteoarthritis one to two decades after the initial injury. This is particularly troublesome in adolescent patients, who are still very young two decades after injury. Finally, it should be noted that the true incidence of physical complications in skeletally immature patients after ACL reconstruction is likely to deviate from what is published since there is a general reluctance to publish complications out of concerns for medicolegal consequences and impacts on professional reputation.

New treatment options aiming at biological regeneration of the ACL are being developed. Such treatments have shown promising results in large animal studies and are of special interest for immature patients because young patients have a higher healing potential for ACL injuries. It is in our patients' interest to encourage participation in ACL injury prevention programs, which have been shown to be effective – only 38 adolescents have to participate in such programs to avoid one extra, noncontact ACL tear. In addition, these programs are inexpensive and relatively easy to implement on a large scale.

12.6 Take Home Messages

- ACL injuries in adolescents can be minimized by education and training in neuromuscular training programs, with one ACL tear being prevented for every 38 students who participate in such programs.

Level of evidence: II

- Once an ACL injury has occurred, early stabilization of the knee is warranted, particularly for active children and adolescents, who remain at high risk for secondary meniscal and cartilage injury if they are even mildly active with an ACL-deficient knee.

Level of evidence: II

- Transphyseal reconstruction can be performed with minimal physeal risk if certain guidelines are followed. Surgeons unfamiliar with these principles and risk factors run a considerably higher risk of causing long-term complications.

Level of evidence: II

- There are also physeal-sparing operations available for very young patients that have produced good and excellent results in the short and intermediate term (5–8 years).

Level of evidence: II

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Indications for Ancillary Surgery in the ACL-Deficient Knee

13

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13.1 Introduction

The anterior cruciate ligament (ACL) is frequently injured, and its reconstruction is among the most commonly performed orthopedic procedures. While modern reconstructive techniques frequently alleviate symptoms and allow a return to an active lifestyle, excellent results are not universal. Instability is the most frequent reason for revision ACL reconstruction. Johnson et al. classified the etiology of postoperative instability as technical error, failure of graft incorporation, or recurrent trauma [26]. However, poor outcomes following ACL reconstruction are also associated with arthrofibrosis, extensor mechanism failure, progression of degenerative disease, and infection [9, 19, 25].

The goal of this chapter is to explore the role of ancillary procedures in improving outcome following ACL reconstruction. We will address the rationale, indications, and evidence for the addition of lateral extra-articular tenodesis, valgus-producing high tibial osteotomy, tibial deflexion osteotomy, and meniscus preserving procedures to ACL reconstruction.

13.2 Lateral Extra-articular Augmentation

13.2.1 Rationale

Rupture of the ACL is associated with increased anterior tibial translation and anterolateral rotatory

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instability, limiting the ability of patients to participate in cutting and pivoting activities [62]. Such instability can also lead to damage to other intra-articular structures and hasten the development of osteoarthritis [33, 39, 46]. Various surgical techniques have been developed to restore stability to the ACL-deficient knee. Currently, intra-articular reconstruction of the ACL is the gold standard, with patients frequently returning to sports with good medium- to long-term results [29, 50, 54]. However, a subset of patients still experience instability following reconstruction.

Augmentation of an intra-articular ACL reconstruction with a lateral extra-articular reconstruction has been suggested as a method of improving rotational stability in these patients [21, 30, 43]. The high incidence of anterolateral capsule injuries associated with ACL ruptures suggests that such augmentation would be useful [52, 57]. The extra-articular position of the graft provides a longer lever arm than an intra-articular graft, facilitating rotational control. Further, the addition of a lateral extra-articular graft has been shown to decrease forces on intra-articular ACL grafts [18].

13.2.2 Indications

The decision of whether to add an extra-articular tenodesis to an intra-articular ACL reconstruction is complex and is hampered by a paucity of clinical evidence. As described above, the primary function of a lateral extra-articular graft is to decrease translation of the lateral compartment associated with anterolateral rotatory instability. Lateral extra-articular augmentation is thus most useful in patients with an explosive pivot shift characterized by significantly increased anterior tibial translation in the lateral compartment. This excessive lateral compartment anterior tibial translation may be poorly controlled by an intra-articular graft alone [30]. Patients whose instability pattern is characterized primarily by increased direct anterior tibial translation will likely not benefit from augmentation as it is likely that this pathologic motion will be well controlled with an isolated intra-articular reconstruction. Similarly, patients with rotational instability characterized by posteromedial or posterolateral rotatory instability will not benefit from the addition of this procedure. In fact, lateral extra-articular augmentation in patients with posterolateral instability may tether the tibia in a posterolaterally subluxated position.

Because extra-articular augmentation also serves to decrease stress on an intra-articular ACL graft, it may also be considered in patients who plan to return to collision sports that expose grafts to excessive loads such as rugby or American football [18, 43]. It is also useful to add this lateral procedure in cases of revision ACL reconstruction as it has long been noted that objective control of laxity is worse in revision cases [9, 59]. This course of action may be especially beneficial in patients in whom recurrent trauma was the reason for failure of the primary reconstruction and patients with significant meniscal loss.

13.2.3 Evidence

The role of lateral extra-articular augmentation of intra-articular ACL reconstruction procedures remains controversial. Two in vivo studies have demonstrated that the addition of lateral augmentation to a single-bundle intra-articular ACL reconstruction decreases anterolateral tibial rotation by decreasing anterior tibial translation in the lateral compartment [6, 37]. Clinical studies are split on the effect of augmentation in cases of primary ACL reconstruction (Table 13.1). While some authors have noted no advantages of lateral augmentation [5, 51, 56], others have demonstrated increased stability with augmentation in more active patients and those with significant lateral compartment translation preoperatively [20, 21, 30, 43]. It must be stressed that all clinical studies to date have been retrospective and nonrandomized, leading to preoperative differences in the two groups in most cases. Improved stability with the addition of lateral extra-articular augmentation in revision cases was demonstrated in a large multicenter study [11] as well as a recent in vivo study by Colombet [10].

Table 13.1 Studies evaluating the addition of lateral extra-articular reconstruction

Author and year	Level of evidence and study design	Patients	Intra-articular graft	Method of augmentation	Findings
Roth et al. (1987) [51]	Level III Retrospective comparative study	43 augmented 50 nonaugmented	BTB autograft	Biceps femoris tendon transfer	No difference in subjective outcome score, Lachman, KT-1000, or pivot shift at 2 years post-op
Strum et al. (1989) [56]	Level III Retrospective comparative study	43 augmented 84 nonaugmented			No difference in outcome score or instrumented anterior tibial translation at 4 years post-op
Noyes and Barber (1991) [43]	Level III Retrospective comparative study	40 augmented 64 nonaugmented	BTB allograft	Iliotibial band tenodesis	Augmentation yielded lower failure rates, decreased anterior tibial translation, and improved Cincinnati knee score at 3 years post-op
Goertzen and Schulitz (1994) [21]	Level III Retrospective comparative study	32 augmented 26 nonaugmented	Doubled semitendinosus autograft	Iliotibial band tenodesis	Augmentation yielded improved Lysholm scores, increased isokinetic strength, and decreased anterior tibial translation on KT-1000 at 1 year postoperative
Barrett and Richardson (1995) [5]	Level III Retrospective comparative study	32 augmented 38 nonaugmented	BTB autograft	Iliotibial band tenodesis	No difference in subjective outcome score, anterior tibial translation with KT-1000, Lachman, or pivot shift
Lerat et al. (1997) [30]	Level III Retrospective comparative study	60 augmented 50 nonaugmented	BTB autograft	Quadriceps tendon graft	Augmentation yielded decreased lateral compartment translation and decreased incidence of pivot shift at 4 years post-op
Giraud et al. (2006) [20]	Level III Retrospective comparative study	29 augmented 34 nonaugmented	BTB autograft	Quadriceps tendon graft	Augmentation yielded decreased incidence of pivot shift at 7 years post-op. No difference in subjective IKDC scores or anterior tibial translation were noted

13.3 Valgus-Producing High Tibial Osteotomy

13.3.1 Rationale

The addition of a valgus-producing high tibial osteotomy (HTO) to an ACL reconstruction is theoretically advantageous in two distinct situations. The first situation is early medial compartment osteoarthritis in the setting of ACL insufficiency. These two conditions frequently coexist several reasons. First, instability associated with ACL injury can hasten the development of osteoarthritis [33, 39, 46], likely due to pathological joint loading [31]. Second, the medial meniscus is commonly injured in patients with ACL deficiency, either associated with the initial trauma or due to increased stress on the meniscus as it is loaded excessively in the ACL-deficient knee. Loss of meniscal tissue significantly increases risk of osteoarthritis [39, 41]. Third, ACL deficiency increases the risk of chondral injury, further increasing osteoarthritis risk [14]. In patients presenting with a chronic ACL rupture, early arthritis, and varus malalignment, isolated ACL reconstruction risks precipitating the progression of the arthritis [16]. In patients with genu varum and medial compartment arthritis, a valgus-producing HTO can slow the progression of arthritis in the medial tibiofemoral compartment for a number of years [12, 58]. It is logical that HTO is also useful in combination with ACL reconstruction when early arthritis and instability coexist in the same knee.

The second situation in which the addition of a valgus-producing HTO to an ACL reconstruction may be useful is in cases of coronal plane instability. Noyes et al. classified varus ACL-deficient knees as primary, double, or triple varus [45]. Primary varus refers to varus tibiofemoral joint alignment. Double varus refers to primary varus associated with opening of the lateral compartment, indicating insufficiency of the lateral structures. Triple varus refers to double varus with associated recurvatum and external rotation indicating posterolateral corner insufficiency. The varus thrust associated with double and triple varus leads to additional stress on intra-articular ACL grafts that can be mediated with the addition of a valgus-producing HTO [4, 45].

13.3.2 Indications

Simultaneous reconstruction of the ACL and valgus-producing HTO is indicated in patients with ACL deficiency associated with primary varus deformity and early-stage medial compartment osteoarthritis as well as patients with double or triple varus. When considering the addition of an HTO for early-stage osteoarthritis, one must remember that these patients represent a select group on a continuum. At one end of the continuum lie patients with ACL deficiency as well as primary varus alignment but no evidence of osteoarthritis. As long as double or triple varus is absent, these patients can be treated with an isolated ACL reconstruction [27]. On the other extreme lie patients with significant osteoarthritis and complete joint space loss. In this situation, ACL reconstruction is not indicated. Treatment of the osteoarthritis is the primary goal, either through isolated HTO or total knee arthroplasty [14]. Patients in the middle, with ACL deficiency and early osteoarthritis without complete joint space loss, can benefit from combined valgus-producing HTO and ACL reconstruction (Fig. 13.1). The procedure has been recommended in patients less than age 40 or 45 [2, 7, 14, 24, 28].

13.3.3 Results

Data regarding the results of combined valgus-producing HTO and ACL reconstruction are limited to case series. Early results at up to 1 year postoperative have demonstrated improvements in patient-oriented outcomes scores and high rates of return to recreational sports [2, 24, 63]. Several studies with 2- to 5-year follow-up have demonstrated maintenance of pain relief and continued control of anterior tibial translation at follow-up [4, 40, 45]. A recent case series with 12-year follow-up demonstrated progression of

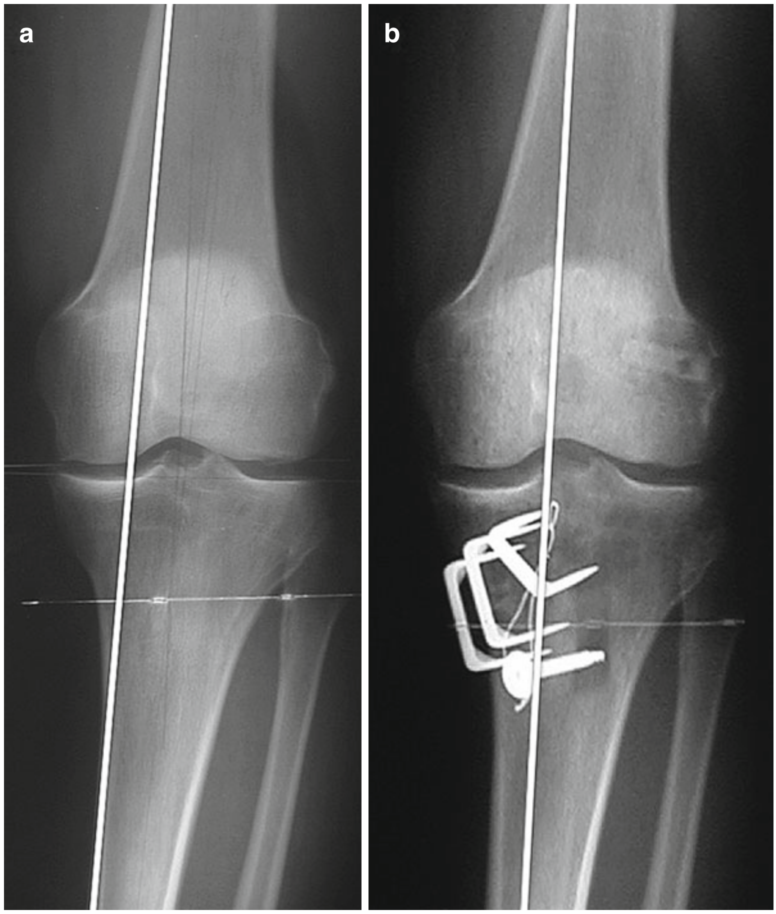

Fig. 13.1 (**a**) Pre-operative and (**b**) postoperative anteroposterior radiographs of a left knee with ACL deficiency and early medial compartment degenerative disease treated with simultaneous valgus-producing HTO and ACL reconstruction. The mechanical axis of the limb (*white line*) has shifted from the medial compartment to near the center of the knee following the HTO

osteoarthritis by at least one grade in only 17 % of the knees [7].

13.4 Tibial Deflexion Osteotomy

13.4.1 Rationale

Although the ACL is the primary restraint to anterior tibial translation, the contribution of other anatomic structures cannot be ignored. These include the posterior horn of the medial meniscus (see Sect. 13.5), the medial and lateral capsuloligamentous structures, and osseous anatomy. The role of osseous anatomy in stability has garnered more interest recently as authors have noted that bony morphology contributes to the magnitude of the pivot shift following ACL tear [38]. It has long been noted that increased tibial slope is associated with increased stress on the ACL [36] and increased anterior tibial translation following ACL injury [14, 32].

13.4.2 Indications

Because increased tibial slope is associated with increased stress on ACL grafts, we recommend addressing tibial slope with a deflexion osteotomy in cases of 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 and a tibial slope greater than 13° (Fig. 13.2) [14, 42]. These cases are generally associated with early degenerative change and frequently meniscal pathology that allows excessive anterior tibial translation.

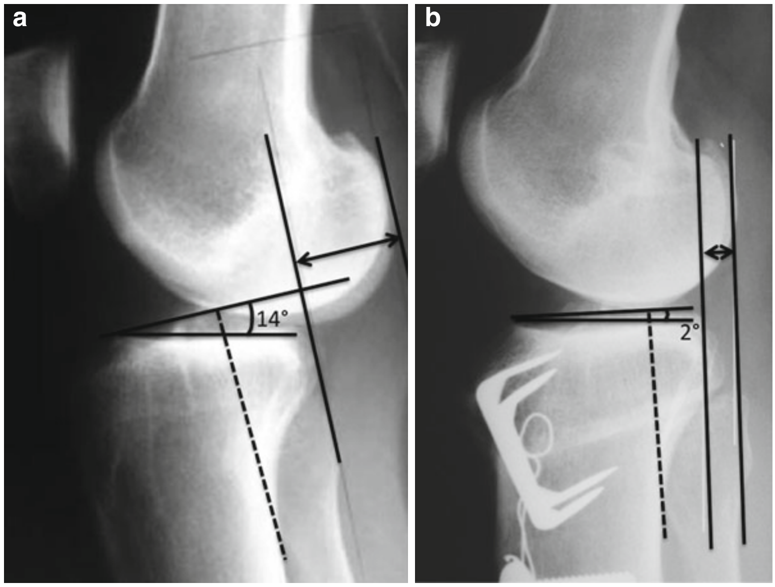

Fig. 13.2 (**a**) A lateral plain radiograph of a right knee with an ACL tear. Significant anterior tibial translation is noted (*double-headed arrow*) as well as increased tibial slope of 14° relative to the long axis of the tibia (*dashed line*). (**b**) A lateral plain radiograph of the same knee following revision ACL reconstruction associated with tibial deflexion osteotomy. Anterior tibial translation has been reduced (*double-headed arrow*), and tibial slope has decreased to 2° relative to the long axis of the tibia (*dashed line*)

13.4.3 Results

There is little data available on the outcome of tibial deflexion osteotomy performed in association with ACL reconstruction. Dejour et al. retrospectively evaluated a series of 22 knees with chronic anterior laxity and excess tibial slope (average 16.5°) [13]. They performed deflexion osteotomy in all patients and associated ACL reconstruction in 18 patients. They noted improved results in the patients in whom both procedures were performed. Good outcome has also been reported in a case of bilateral congenital absence of the ACL treated with ACL reconstruction and tibial deflexion osteotomy [15].

13.5 Addressing Meniscal Lesions

13.5.1 Rationale

Meniscal injury associated with ACL reconstruction is a common occurrence, and meniscectomy is among the most common surgical procedures performed in the first year following ACL reconstruction [34]. Loss of meniscal tissue is concerning for several reasons. First, the posterior horn of the medial meniscus is an important secondary restraint to anterior tibial translation in the ACL-deficient knee [3], and its absence significantly increases anterior tibial translation as well as the severity of the pivot shift [14]. Cadaveric studies have demonstrated that meniscal loss significantly increases the loads experienced by ACL grafts [47] and decreased the effectiveness of grafts in controlling anterior tibial translation [53] and the pivot-shift phenomenon [48]. Second, meniscectomy is a major risk factor for osteoarthritis (OA) of the knee [1, 22, 35]. The reasons for increased rates of osteoarthritis are likely related to both increased cartilage contact stress due to the loss of meniscal tissue as well as increased shear forces due to abnormal joint loading and motion [14].

13.5.2 Indications

Because of the dire consequences of meniscal loss, all efforts should be made to preserve meniscal tissue. Traditionally, longitudinal tears in the red-red and red-white zones have been considered amenable to repair [55]. However, advances in fixation techniques, scaffolds, and biologics have extended indications for repair to root avulsions and certain radial tears, especially in younger patients. When surgical repair of a meniscal tear is not possible, minimal resection required to restore stability should be performed.

In spite of efforts to preserve meniscal tissue, subtotal meniscectomy is sometimes unavoidable. In these cases, one can consider other techniques to mitigate poor results. Meniscal allograft has long been felt to offer advantages in such patients, particularly in younger patients without significant degenerative disease [44]. Newer meniscal scaffold techniques can be utilized to address segmental meniscal defects or loss of the entire meniscus [60]. The goals of both procedures are to address both the abnormal joint loading and loss of stability associated with meniscal loss.

13.5.3 Results

As expected for reasons related to both load transmission and knee stability, rates of osteoarthritis have been demonstrated to increase in concert with the amount of meniscal resection [8, 23]. Similarly, meniscal repair has been shown to reduce osteoarthritis risk compared to partial meniscectomy. In a prospective cohort study with 4.5-year follow-up, Aglietti et al. demonstrated significantly lower rates of osteoarthritis following meniscus repair compared to partial meniscectomy in a patient population undergoing ACL reconstruction [1].

The results of meniscal allografts available in the literature are generally limited to case series. In a large, recently published meta-analysis, ElAttar et al. analyzed 1,136 meniscal allografts reported in 44 series [17]. They noted an overall improvement of Lysholm scores from 44 to 77 and improvements in Tegner activity score from 3 to 5. The preponderance of studies did not note progression of joint space narrowing, although follow-up in most studies was relatively short. The majority of the results of meniscal replacement scaffolds are reported as case series and biomechanical studies, many of which show promise but lack in outcome data [61]. One notable exception is the collagen meniscus implant described by Rodkey et al. [49]. In a randomized control trial, they noted that patients in the collagen meniscus group with chronic injuries regained significantly more of their preinjury activity level than did patients in the control group at a mean of 5 years postoperative. They also noted increased meniscal tissue at second-look arthroscopy than was noted at the initial meniscal resection. They did not evaluate the effect of the graft on knee stability, and follow-up was too short to evaluate the effect of the implant on the development of osteoarthritis. More work will need to be done to delineate the role of these implants in the treatment of meniscal pathology.

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 failed surgery as well as progression of degenerative disease remains unacceptably high. Ancillary procedures including lateral extra-articular reconstruction, valgus-producing HTO, tibial deflexion osteotomy, and procedures related to meniscal preservation and restoration may provide routes for improving results. Further work, including development of new techniques and well-designed prospective studies evaluating results, is necessary to improve and verify the utility of these procedures.

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Outpatient ACL Surgery: Is It Safe?

14

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14.1 Introduction

ACL reconstruction (ACLR) is one of the most commonly performed procedures in orthopedic sports medicine. Over 200,000 primary ACLRs are performed annually in the United States with good or excellent clinical outcomes in 75–95 % of these patients [20, 31]. Over the past 30 years, the surgical techniques of ACLR have evolved from inpatient, open, extra-articular procedures to outpatient, endoscopically assisted, intra-articular surgery. During this time period and particularly in the early 1990s, advances in a variety of other perioperative factors contributed to a safe and successful transition from inpatient to outpatient ACLR, including improvements in perioperative pain and nausea management, increased awareness of cost effectiveness, and improved patient satisfaction following outpatient surgery. The experiences of the senior surgeon throughout this transition have been well documented over the past two decades, with encouraging results [9, 11, 14, 26, 37, 39].

Outpatient ACL surgery is a routine, safe, and cost-effective experience. The benefits of outpatient ACLR were evident early on, from an increase in patient satisfaction to a decrease in hospital costs [3, 11, 39], and have been reported by numerous authors in the literature [1, 8, 23, 24]. At our institution, all ACLRs are performed in an outpatient surgery center, first opened in 1993. The purpose of this chapter is to review the historical transition of ACLR from inpatient to

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outpatient surgery, with a focus on pertinent advances in surgical technique, perioperative management of complications, and cost savings that have allowed this transition to occur. With the evolution to outpatient surgery came numerous questions and concerns, many of which will be discussed in this chapter.

14.2 Advances in Surgical Technique

Over the past 30 years, advances in surgical technique have played a prominent role in guiding the transition from inpatient to outpatient ACL surgery. Throughout the early 1980s, ACLR was typically performed via an open arthrotomy, combining intra-articular and extra-articular techniques. Incisions were generous in both length and exposure of the knee joint, and all patients were admitted to the hospital for several days for pain control and perioperative management. In the mid-1980s, however, the popularization of knee arthroscopy led to the first significant technique-based transition in ACLR, as surgeons evolved from arthrotomy-assisted approaches to two-incision, arthroscopy-assisted ACLR. This change led to improved patient outcomes and knee function scores and decreased postoperative morbidity [2]. From 1986 to 1991, in the senior surgeon's experience, nearly all ACLRs were performed in the main operating room using an arthroscopic-assisted, two-incision technique using bone-patellar tendon-bone (BTB) autograft without extra-articular augmentation. One incision was made over the anterior tibia for drilling of the tibial tunnel from outside in, and a second incision was made over the lateral aspect of the lateral femoral condyle for drilling of the femoral tunnel from outside in. During this time, patients were routinely hospitalized on average 3 days postoperatively for management of pain and nausea and the use of continuous passive motion (CPM) machines and physical therapy.

Bach and colleagues published both short-term (2–4 years) [5] and intermediate-term (5–9 years) [7] results in clinical outcome studies of patients who underwent this two-incision technique between 1987 and 1991, demonstrating good to excellent results. At a minimum 5-year follow-up, over 90 % of patients had clinically stable knees on examination (Lachman, pivot shift), 95 % had objectively stable knees (KT-1000 arthrometer testing), and 94 % had subjective satisfaction with the operative result. Functional tests, including vertical jump, single-leg jump for distance, and single-leg timed 6-m hop, averaged less than 2 % difference compared to the contralateral side, with a 2 % reoperation rate [7].

In the early 1990s, a second significant technique-based transition occurred. As biomechanical research began to elucidate the functional anatomy of the ACL and surgeons became more proficient with the arthroscope, ACLR evolved from a two-incision, arthroscopic-assisted ACL technique to a single-incision, endoscopic-assisted ACLR. This procedure, initially performed at our institution in 1991, utilizes an obliquely oriented transtibial approach in an effort to place a lateralized femoral tunnel within the intercondylar notch [18]. From 1991 to 1993, ACLRs were performed by the senior surgeon using the single-incision rather than the two-incision technique, and a majority of patients were routinely admitted to the hospital postoperatively for a minimum of 23 h (mean 1.6 days). The evolution to single-incision ACLR led to smaller incisions, greater cost savings, decreased hospital time, and reductions in perioperative morbidity. Further, it allowed for earlier, more aggressive rehabilitation regimens, helping to reduce the incidence of postoperative flexion contractures and stiffness [2, 18]. With this transition, it quickly became apparent that patients had less discomfort and desired to be discharged home on an earlier basis.

In March 1993, the Rush Surgery Center (Rush SurgiCenter, Ltd.) opened at our institution, creating an environment ideal for providing ambulatory, outpatient orthopedic procedures. In 1994, the senior author performed his first outpatient ACLR in the SurgiCenter, signaling a key shift in patient care. Importantly, the transition to an outpatient surgery center did not compromise knee stability, clinical results, early perioperative complications (pain, nausea, hospital admissions, emergency room visits), or future reoperations for symptomatic flexion contractures. In a retrospective clinical follow-up study analyzing the single-incision endoscopic-assisted technique at the outpatient SurgiCenter, Bach et al. reported a greater than 90 % success rate for knee stability by physical examination and 95 % by objective quantification (KT-1000 arthrometer testing) using patellar tendon autograft after 2 years [6]. Functional tests showed 4–6 % differences in side-to-side comparisons for functional testing, and there was a 5 % reoperation rate for minor motion problems (flexion contractures, re-tears). Further advancements in rehabilitation protocols with an emphasis on early knee extension decreased the reoperation rate to 2 %. Ninety-three percent of patients reported they were “mostly” or “completely” satisfied with their experience, and 95 % would recommend the procedure to others [6].

Additional clinical follow-up studies have evaluated subgroups of ACLR patients over the age of 35 [28], male versus female [14], skeletally immature patients [30], revision ACL patients [15], and primary allograft ACL patients [4], all with good to excellent clinical results following surgery performed at an outpatient surgery center. The single-incision, endoscopic-assisted transtibial technique has now become our preferred approach to ACLR, as well as nationally and internationally for nearly 20 years, and was a major contributor to the successful transition from inpatient to outpatient ACL surgery.

14.3 Advances in Management of Common Postoperative Complications

While the transition from inpatient to outpatient ACLR theoretically increases the risk for compromise of patient safety via inappropriate or improper management of postoperative complications such as pain, nausea, vomiting, hemarthrosis, and arthrofibrosis, the literature suggests otherwise [2]. In the senior author’s experience of more than 1,700 ACLRs performed on an outpatient basis since 1993, return-to-hospital rates are <0.5 % (either clinic or emergency department) for complaints of urinary retention, intractable nausea, uncontrolled pain, or other perioperative complications [2]. Nevertheless, there is potential for perioperative complications to be encountered in the outpatient setting, and an increased focus on the preemptive management of these issues has helped make ACLR safe in the outpatient setting.

14.3.1 Perioperative Pain Management

In addition to surgical technique, improvements in perioperative pain management have allowed for the safe evolution from inpatient to outpatient ACLR. For optimal outcomes and prevention of pain-related complications in outpatient surgery, it is essential that patients have adequate pain control at the outpatient facility and maintain this level of analgesia during the acute postoperative period. Therefore, close and effective teamwork with the anesthesia team is mandatory. While several anesthetics and postoperative analgesic protocols have been developed to facilitate rapid recovery, most depend heavily on the use of regional anesthesia and oral analgesics as part of a multimodal approach [10]. As opposed to pain pumps [patient-controlled analgesia (PCA)] previously used for inpatients before the transition, outpatient pain protocols aim to preserve normal physiologic parameters and psychomotor skills in the immediate postoperative setting, helping to reduce known complications such as arthrofibrosis resulting in knee stiffness.

In the early 1990s, advances in anesthesia, including the development of improved short-acting general anesthetics such as Diprivan (propofol; Stuart Pharmaceuticals, Wilmington, DE), allowed for easier recovery and fewer anesthesia-related complications after ACLR [29]. Intramuscular Toradol (ketorolac tromethamine; Syntex Laboratories, Inc., Palo Alto, CA), a nonsteroidal anti-inflammatory, was also found to contribute to reduced early postoperative discomfort [25, 27]. Further, cold therapy, corticosteroids, local anesthetics, and regional blocks alone or in combination have all been shown to be beneficial in redirecting postoperative pain [12, 13, 16, 39]. Collectively, these advances in analgesics and anesthesia contributed to a rapid, safe, and smooth transition from inpatient to outpatient ACLR.

At our institution, we routinely use general anesthesia intraoperatively with intravenous short-acting anesthetics such as propofol (Diprivan), which is associated with few postoperative side effects (Table 14.1). Importantly, the use of IV opioids should be kept to a minimum to reduce opioid-related adverse events and prolonged recovery periods in the outpatient center [10]. In some situations, depending on specific patient factors increasing the risk for general anesthesia or concomitant factors that may increase the length of surgery, femoral nerve blocks may be given using bupivacaine (0.25–0.5 %) or ropivacaine (0.2–0.5 %), which can provide analgesia for the surgery and postoperative period. Since the transition to outpatient surgery, however, the use of femoral nerve blocks for straightforward ACLRs is rare, with an estimated prevalence of <1 % of all ACLRs at our institution.

Another integral part of our multimodal approach to pain control in the perioperative period is the use of injectable local anesthetics and cryotherapy. At our institution, preemptive analgesia is used by injecting 1 % Xylocaine with epinephrine (1:200,000) and 0.25 % Marcaine intraincisionally and intra-articularly at the beginning of the procedure as well as postoperatively [10]. Cryotherapy is used to decrease swelling and pain following ACLR. Cold therapy reduces local inflammation via production of local vasoconstriction and decreases pain via reduction in nerve conduction velocity [12]. Despite conflicting findings in the literature regarding its efficacy, we routinely use cryotherapy units in our patients, as continuous-flow cold therapy has the capacity to reduce bleeding, edema, and a local inflammatory mediator response [10].

Patients are discharged with oral narcotics such as hydrocodone (30 tablets, no refills). The average patient uses a total of 12 narcotic tablets and is completely off narcotics by 5–7 days after surgery.

Table 14.1 Perioperative protocol used for outpatient arthroscopic knee surgery

Preoperative holding unit
Midazolam HCl 1 mg IV 30 min before surgery
Anesthetic
Propofol 2–2.5 mg/kg induction, maintenance 75 ug/kg to 160 ug/kg and nitrous oxide (66 % nitrous and 33 % oxygen)
Sufentanil (narcotic) 12.5–25 ug
Rocuronium bromide (muscle relaxant) 0.6–0.8 mg/kg
Prior to surgical start
Cefazolin 1 g IV (or 2 g if >70 kg)
Bupivacaine (0.25 %) and epinephrine (1:300,000) – half maximal dose (based on body weight) injected intraincisionally
Dilute epinephrine (1:1000) solution in arthroscopic fluid (1.5 mL per 5 L bag of fluid)
Conclusion of surgery
Ketorolac 30 mg IV
Bupivacaine (0.25 %) and epinephrine (1:300,000) – remaining half of maximal dose injected intraincisionally and intra-articularly
Cryotherapy
Drop-lock postoperative knee brace to maintain extension / hyperextension
Recovery room
Morphine sulfate IV supplementally if needed
Midazolam IV supplementally if needed
Cryotherapy
Physical therapy (day of surgery)
One session: review gait training, prone hangs, straight leg raising, active ROM, cryotherapy and brace instructions
At discharge
Hydrocodone prescription (30 tablets; 1–2 tablets PO q 4–6 h PRN)
Discussion regarding additional use of celecoxib or ibuprofen for postoperative discomfort
Cryotherapy
POD 1: office visit
Clinical knee examination → aspirate PRN if moderate hemarthrosis (use pain and motion to guide decision-making)
Remove postoperative dressing and replace steri-strips
Apply new dressing
Reinforce ROM goals: complete extension and flexion to 90° by 10 days

Patients are instructed to use anti-inflammatories such as ibuprofen or celecoxib for "breakthrough" pain or postoperative discomfort, which helps reduce inflammation as well.

Outcomes using similar pain protocols have demonstrated excellent results. Tierney and colleagues reported results of 227 patients undergoing arthroscopic-assisted ACLR using either BTB autograft (169 patients) or BTB allograft (58 patients) during a 27-month period [36]. Their protocol employed a general anesthetic administered with the intent of same-day discharge, infiltration of the skin and joint with bupivacaine, a cold compressive dressing, and the use of both Toradol and a schedule III narcotic (acetaminophen with codeine or with propoxyphene) for postoperative pain control. At an average follow-up of 10 months, they had zero readmissions in the immediate postoperative period and no short- or long-term postoperative complications, concluding this technique is safe and effective for outpatient ACLR. At our institution, the senior author has performed over 1700 outpatient ACLRs using the pain protocol outlined in Table 14.1 since 1993 with minor variations throughout the years, with less than five emergency room evaluations and zero readmissions for pain control postoperatively.

14.3.2 Nausea/Emesis

Postoperative nausea and emesis can be a major challenge in the postoperative period, and the use of prophylactic measures preoperatively can help decrease postoperative complications in the outpatient setting. In the preoperative holding area, patients are routinely screened for risk factors such as motion sickness or nausea/emeses related to previous anesthesia [10]. If there are positive risk factors, this complication can usually be prevented by the use of a transdermal scopolamine patch (1.5 mg), assuming no contraindications [38], or by administering an HT-3 blocker such as ondansetron (Zofran) in the perioperative setting [10]. In the presence of multiple risk factors, a polypharmaceutical approach to this complication has been advocated, including the use of steroids (dexamethasone, 5–10 mg intravenous intraoperatively). Finally, to reduce the risk of nausea/emesis and optimize rapid recovery, it is important to minimize the use of IV opioids during surgery.

14.3.3 Arthrofibrosis

Before the transition to outpatient surgery, continuous passive motion (CPM) machines were routinely used in patients undergoing ACLR for 3 days prior to discharge [2]. By 1990, with the evolution of accelerated rehabilitation protocols [32], we altered our protocol such that patients were allowed to come out of the CPM machine every two hours to lock their knee brace in complete extension. Further, with the transition to a single-incision endoscopic technique in 1991, patients were routinely discharged on the first day after surgery, and rates of arthrofibrosis subsequently decreased [2]. For this reason, we completely abandoned the use of CPM machines postoperatively as we transitioned to outpatient ACL surgery. While helping to achieve flexion postoperatively, the CPM did not provide for improvements in extension, which is the most common reason for patients requiring additional surgery secondary to symptomatic knee flexion contractures and arthrofibrosis [2]. Our reoperation rate for symptomatic knee flexion contractures has ranged between 0 and 2 % annually since 1993 using our current protocol with an accelerated rehabilitation protocol and no CPM [18].

14.3.4 Hemarthrosis

Similar to the use of CPM machines, placement of an intra-articular drain was a normal part of our protocol in the late 1980s to help reduce the incidence of postoperative hemarthrosis. During the early 1990s with earlier discharge from the hospital, however, we had increasingly abandoned the use of postoperative drains, and by the time we started outpatient surgery, drains were no longer a part of our protocol. Interestingly, the elimination of drains did not result in an increased need to perform knee aspirations postoperatively, and the incidence of repeat arthroscopy for surgical resection of arthrofibrosis and knee flexion contractures failed to increase as well [2].

Nevertheless, postoperative hemarthrosis remains a known complication after any knee surgery, with a reported incidence of up to 5–10 %

after ACLR [2]. Therefore, after all outpatient ACLRs, we routinely examine patients in the office on the first postoperative day for a dressing change, clinical evaluation, and aspiration if needed (Table 14.1). During this visit, we also remove and replace steri-strips to help avoid traction blisters. Since the introduction of this postoperative visit, the incidence of postoperative traction blisters from steri-strips has been dramatically reduced, but the rate of knee aspirations has remained the same (~5 %).

14.3.5 Deep Venous Thrombosis/ Pulmonary Embolus

The value of a tourniquet during ACLR is to minimize bleeding and provide a clear field for arthroscopic and/or open visualization during the procedure. However, several studies have demonstrated an increased risk of complications with tourniquet use in lower extremity surgeries, such as nerve and muscle injuries [22], limb swelling [33], increase in pain [19], deep venous thrombosis (DVT) [19], and pulmonary emboli (PE) [17]. While findings in the literature are contradictory with regard to the safety of tourniquet use in ACLR and reduction of pain postoperatively [21, 34], the increased risk of DVT with tourniquet use has been clearly documented in lower extremity surgery, particularly with prolonged tourniquet times [19, 35]. Using our standard arthroscopic-assisted ACLR technique described above, we are able to adequately visualize intraoperatively without tourniquet usage via the following guidelines: using a dilute epinephrine solution within the arthroscopic fluid solution (1.5 mL of 0.001 % epinephrine per 5 L bag of fluid), maintaining a systolic blood pressure less than 110 mmHg, and using arthroscopic electrocautery as needed. We inflate the tourniquet in fewer than 3 % of our cases, thereby reducing the risk of DVT and/or PE and possibly minimizing postoperative pain as well. In our experience with more than 1,700 patients with ACLRs since the transition to outpatient surgery, one patient was diagnosed with a nonfatal pulmonary embolus, and one patient was found to have a DVT postoperatively.

14.4 The Influence of Patient Satisfaction

Another important factor spurring the evolution to outpatient surgery is the improvement in patient satisfaction scores. For example, in a randomized clinical trial of 40 patients undergoing primary ACLR, Krywulak and colleagues randomized patients into inpatient versus outpatient groups and used a validated testing measure (visual analogue questionnaire) to assess patient satisfaction [24]. Inpatients stayed overnight in the hospital and were discharged home the next day, while outpatients were discharged home on the day of the procedure. The mean overall satisfaction score of the outpatient group was significantly higher than that of the inpatient group (85.1 vs. 78.2, $p=0.015$), while there were no significant differences in postoperative pain, nausea, rate of readmission, and complications. At our institution, based on the senior authors' personal experience, patients appear less anxious about having a surgical procedure in the SurgiCenter as opposed to the main hospital operating room. In general, our ACLR patients' subjective perception of the outpatient surgical setting, procedure, and experience has been uniformly positive.

14.5 Cost Containment

From an economic perspective, the evolution from inpatient to outpatient ACLR has led to considerable cost savings. In a retrospective study comparing surgical charges of patients undergoing ACLR between 1989 and 1993, Nogalski et al. analyzed the difference in charges between patients undergoing the two-incision technique and a single-incision endoscopic-assisted ALR, both using patellar tendon autograft [26]. They noted a statistically significant difference in hospital days (2.8 vs. 1.57, respectively, $p=0.0001$), total hospital charges ($15,063 vs. $13,520, $p=0.0001$, incorporating 8 % inflation), operating room/hospital ward charges ($p=0.0001$), pharmacy charges ($p=0.035$), and physical therapy charges ($p=0.001$). If one compared, however, a 2-day hospitalization charge for two-incision versus single-incision techniques, there was no significant difference, suggesting that time to discharge was the single most important factor underlying charge reductions between the two groups [26]. Therefore, before the SurgiCenter opened in 1993, our institution initiated a “23-hour observation” policy in which there was a different charge strategy for patients who could be discharged from the hospital within this time period.

In 1996, Novak and colleagues retrospectively compared the hospital charges of two different surgeons performing the identical procedure in different settings at the same institution (outpatient surgery center vs. main operating room) [27]. One surgeon exclusively performed single-incision ACLR in the outpatient SurgiCenter, and the other surgeon performed the same procedure in the main operating room, giving the patient a choice between outpatient status, 23-h observation status, and, in some cases, a 2-day hospitalization. The SurgiCenter developed a global charge for all services rendered at the time of ACLR, while the main operating room operated in an “a la carte” fashion, with operating room time and all items charged individually. During this time period, the global charge at the SurgiCenter was an all-inclusive $3,855, including a cryotherapy unit, one session of physical therapy, and a drop-lock knee brace. In contrast, patients having outpatient surgery performed in the main OR had an average charge of $8,900, an average difference of >$5,000. More specifically, patients who stayed overnight (23-h observation) or for 2 days postoperatively averaged a hospital charge of $12,040 and $13,503, respectively, or approximately $7,000 and $8,000 more than the outpatient SurgiCenter charge. These findings were corroborated by others, with reported savings from $4,700 to $5,900 per patient when outpatient surgery was performed compared with the cost of performing the same procedure in a hospital operating room with an overnight admission [1].

In 2001, Curran et al. analyzed hospital charges and perioperative complications of all outpatient ACLRs using BTB autograft performed at the Rush SurgiCenter ($n = 284$) between 1994 and 1998 [11]. The average SurgiCenter charge for all patients was $3,443, with a 2.5 % reoperation rate (arthroscopic debridement for symptomatic motion deficits). This study expanded on the authors’ previous findings [27], as significant charge reductions were maintained in the outpatient SurgiCenter with only slight increases reflective of inflationary value, in addition to the low complication rate and high patient subjective satisfaction level. These findings revealed that consistent performance of ACLR on an outpatient basis created considerable cost savings, allowing medical centers to optimize societal resource utilization.

Conclusion

In summary, a variety of factors have contributed to the transition from inpatient to outpatient ACLR. Beginning in the late 1980s and early 1990s at our institution, advances in surgical technique, perioperative pain and nausea management, an increased importance on cost containment, and improved patient satisfaction led to the successful and timely evolution to outpatient ACLR. Today, outpatient ACL surgery is a routine, safe, and cost-effective experience.

14.6 Key Points

- Several factors have played a prominent role in the successful transition from inpatient to outpatient ACL reconstruction, including:
  - Advances in surgical technique (two-incision arthroscopic to single-incision endoscopic)
  - Improved perioperative pain and nausea management
  - Improved understanding of postoperative complications such as arthrofibrosis, hemarthrosis, and DVT/PE, with discontinuation of CPM, intra-articular drains, and tourniquet use, respectively
  - Improved patient satisfaction scores
  - Significant cost savings
- Outpatient anterior cruciate ligament reconstruction is a routine, safe, and cost-effective experience.

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15 Factors Related to Return to Sport After ACL Reconstruction: When Is It Safe?

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15.1 Introduction

Many people undergo anterior cruciate ligament (ACL) reconstruction surgery with the aim of returning to their previous level of sports participation. A stable knee is particularly important for continued participation in cutting or pivoting sports, which inherently challenge knee stability and neuromuscular control.

Athletes at any level, whether it is elite, competitive, or recreational, are typically anxious to know when they will be able to resume sport postoperatively. From the treating clinician's perspective, there are many considerations when determining the timing of the return to sport. Of paramount importance is ensuring patient safety, and this is the central theme of this chapter. The clinician needs to be confident that the knee has attained sufficient healing and recovery to allow the resumption of sports participation with minimal risk of complications. Other issues to be considered include the long-term outcome in terms of both the patient's ability to continue to participate in sport and the health of their knee, as well as the patient's expectations and functional capacity, and current clinical practice.

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There are three key questions, critical to decision-making regarding return to sport, that will be addressed:

1. What is the actual reported rate of return to sport following ACL reconstruction?
2. When do patients typically return to sport following surgery?
3. How can one determine when a patient can safely return to sport?

15.2 What Is the Actual Rate of Return to Sport?

This section addresses the question of how many patients can reasonably be expected to return to sports participation following surgery, *based on results of the published literature*.
While most orthopedic outcome studies describe some return-to-sport outcomes, many use ordinal rating scales such as the IKDC knee evaluation [15] or Tegner sports activity scale [36]. These scales put activities into groups, in an attempt to quantify the demands that various types of activities have on knee function. These activities are not limited to sport, and the scales may have a ceiling effect. Although these and other scales such as the Marx activity scale [20] provide information regarding the types of activities to which patients are able to return following surgery, it is also important to identify the number of patients returning to their pre-injury level of sports participation. Such an approach allows for benchmarking against the original intention of returning the patient to their pre-injury level of knee function.

In an effort to address this and provide some empirical data regarding the numbers of patients returning to sport following surgery, we conducted a meta-analysis of 48 studies published between 1988 and 2009 [2]. The results showed that more than 80 % of patients had attempted some form of sport following their ACL reconstruction surgery [2]. However, return to some form of sport does not necessarily indicate that patients returned to their pre-injury level of sports participation or whether patients were satisfied with their outcome.

The rate of return to the pre-injury level of sport, as opposed to any level or type of sports activity, may provide a more robust evaluation of the return-to-sport outcomes. Our meta-analysis showed that only 63 % of patients were able to return to their pre-injury level. Furthermore, less than half of the patients (45 %) returned to participation in competitive level sport. Clearly, these return-to-sport rates are far lower than the proportion of patients who attempt some form of sport postoperatively and demonstrate the importance of analyzing outcomes according to the original intention of returning the athlete to their pre-injury level of activity.

Since the publication of this meta-analysis, we have published two further papers that have specifically examined the rate of return to the pre-injury level of sport in patients following ACL reconstruction surgery. The first paper examined the return-to-sport rate at 12 months postoperatively in a group who were playing competitive level sport prior to their knee injury [3]. We chose the 12-month follow-up in the light of current clinical practice, whereby patients are typically cleared to return to sport at 6–12 months postoperatively or even earlier. It was shown that while two-thirds of patients had attempted some form of sport by 12 months following their surgery, only one-third had returned to their pre-injury level of competitive sport participation. All patients had been cleared to return to pivoting and contact sports by the surgeon, usually at approximately 9 months postoperatively. Additionally, no relationship could be found between the rate of returning to the pre-injury level of sports participation and knee function as measured by the International Knee Documentation Committee (IKDC) knee evaluation form [15].

The second paper evaluated a group of patients who had participated in regular sport prior to their injury in order to determine the rate of return to sport at 2–7 years postoperatively [1]. At the time of follow-up in this study (mean 39 months), two-thirds of participants were playing some form of sport. Only 45 % were playing at their pre-injury level and 29 % at a competitive level. However, almost all participants (93 %) had attempted some form of sport following surgery, 61 % at their pre-injury level sport at some stage, and 41 % at a competitive level. It is therefore likely that the return-to-sport rate reached a peak in about the second postoperative year and then declined. We also found that return to sport at 12 months after surgery was not related to participation in sport at the medium-term follow-up (39 months).

The previous two studies did not attempt to analyze return-to-sport outcomes according to the types of sports in which participants were involved prior to their injury. It could be argued that patients who played sports involving cutting or pivoting movements prior to their injury but who return to a low knee-demand sport such as cycling following surgery have achieved a lesser outcome, even if they are satisfied with the result. Nonetheless, comparison of an athlete's postoperative ability in sports participation with their functional level prior to injury is likely to give the most robust assessment of the return-to-sport outcomes. Warner et al. [40] attempted to assess sport-specific outcomes following ACL reconstruction surgery via a systematic review of studies that had reported standardized outcomes for a single sport or compared outcomes between multiple sports. The authors concluded that patients are more likely to return to activities such as cycling or jogging than cutting or pivoting sports such as soccer and football. However, they caution that there are limited and heterogeneous data upon which to base conclusions and recommendations.

Other considerations that should be taken into account when assessing return-to-sport outcomes include the age of the patients at the time of surgery, the time from injury to surgery, rehabilitation of the knee both pre- and postoperatively, concomitant injuries, and the surgical technique. It would also be useful to know the sports participation of a matched group of controls that have not sustained an ACL injury as patients may also not return to sport due to nonknee-related factors such as lifestyle, work, or family commitments.

There is a paucity of literature that evaluates whether knee function is a consideration in the reduction or cessation of sport following surgery. We have completed some preliminary investigation of this topic in the patient group followed for 2–7 years postoperatively and found that just over one-half of the participants who did not return to their pre-injury sport reported reasons related to their operated knee [1]. The specific concerns were not documented but may range from functional problems to simply wanting to avoid re-injury. Nonetheless, this does raise the question of what other factors might be related to patients' decisions not to return to sport following surgery.

Some authors have suggested that psychological factors may also contribute to the return-to-sport outcomes. Our group developed the Anterior Cruciate Ligament-Return to Sport after Injury scale to specifically examine psychological factors influencing return-to-sport outcomes and demonstrated a significantly more positive psychological response in people who returned to their pre-injury level of sport when compared to people who had not returned [41]. Other psychological variables that have been shown to be related to returning to sport after ACL reconstruction surgery are interpretation of the severity of preoperative knee symptoms and their impact on current and future function (self-efficacy) [37], the belief that recovery from surgery is mediated by factors the individual can control or is responsible for (internal health locus of control) [25], fear of re-injury [19, 38], and motivation [11]. These studies all suggest that patients exhibiting a more positive postoperative psychological response may be more likely to return to sport. However, this is yet to be comprehensively explored in the literature.

15.3 When Do Patients Typically Return to Sport?

Return to sport following ACL reconstruction surgery has been reported as early as 2 months postoperatively [33], but in most studies, clearance to return to sport typically occurs at around 6 months postoperatively. A consensus among leading clinicians determined the timing of return to moderate sports to range from 4 to 9 months and strenuous sports from 4 to 18 months, based on current clinical practice [12].

Accelerated rehabilitation protocols evolved some 20 years ago, primarily in response to athletes' enthusiasm to progress through their postoperative rehabilitation programs faster than intended by their surgeons [32]. Using a patellar tendon graft, Shelbourne and Nitz [32] pioneered accelerated rehabilitation when they noticed that patients who were noncompliant with their original rehabilitation program (where full weight bearing was not permitted until 6–8 weeks postoperatively) and progressed as they desired returned to full function earlier than the patients who were compliant with the rehabilitation timelines. Importantly, the patients who were noncompliant did not develop instability or other complications as a result of their more rapid progression through postoperative rehabilitation.

Shelbourne and Nitz also demonstrated that their patients who completed an accelerated program regained knee range of motion and strength earlier than patients who completed a nonaccelerated, standard program [32]. This earlier recovery of knee function may assist the athlete to achieve an earlier return to sport. In a subsequent paper, this group reported favorable results in a large cohort that completed accelerated rehabilitation following ACL reconstruction surgery, again using a patellar tendon graft. They reported that their patients returned to competing at full capability at an average of 6.2 months following surgery. There was no increase in re-injury rates when compared to a previous group that had completed a standard rehabilitation protocol. This is important given that one of the main concerns about accelerated rehabilitation is that the healing graft may be stressed too early, resulting in a greater risk of failure.

To our knowledge, there are only two randomized studies comparing the functional outcomes of accelerated and nonaccelerated rehabilitation programs following ACL reconstruction surgery. Ekstrand [9] compared male soccer players who completed a program with the aim of returning to sport at either 6 (early) or 8 (late) months postoperatively. The early return-to-sport group was permitted to commence jogging and isokinetic strengthening exercises at 4–5 months postoperatively, while the late return group commenced jogging and isokinetic strengthening at 5–6 months postoperatively. At 8-month follow-up, the early return-to-sport group was stronger than the late return-to-sport group. However, at 12 months, there were no differences in function or return-to-sport rates between the groups. Beynnon et al. [4] also compared patients completing an accelerated and nonaccelerated rehabilitation program. The accelerated program lasted for 19 weeks, and the nonaccelerated program lasted for 32 weeks. The authors found no difference in knee function or activity level between the groups at 24-month follow-up [4]. Compliance through the duration of the rehabilitation program was relatively low in both groups, although 68 % of the accelerated group patients completed their program, compared to 40 % for the nonaccelerated group.

Overall, these results appear to suggest that shortening rehabilitation programs does not have deleterious effects on patients' knee function and return-to-sport outcomes and may also have the additional benefit of ensuring a greater number of patients actually complete a full postoperative rehabilitation. Completing a full postoperative rehabilitation program may be an important protective factor against the likelihood of further injury upon return to sport. However, it is also important to note that both the Ekstrand [9] ($n=20$) and Beynnon et al. [4] ($n=22$) studies evaluated relatively small numbers of patients. While the results show promise for the efficacy of the accelerated rehabilitation programs, further research employing similar methodological rigor is required to confirm the findings of these studies.

Again it is to be noted that although it appears that standard current clinical practice is for patients to be cleared to return to sport at between 6 and 12 months postoperatively, there is little information reported about when patients actually return to sport.

15.4 How Can One Determine When a Patient Can Safely Return to Sport?

When deciding upon the timing of return to sport with an athlete, there are a number of salient considerations related to maximizing function of the operated knee while allowing return to sport in a safe and realistic time frame. Some athletes are eager to return to sport postoperatively and, as Shelbourne and colleagues have demonstrated [32, 33], are prepared to disregard the advice of the surgeon and return to participation earlier than recommended. However, the surgeon must balance the athlete's desire to return to sport as early as possible, against the biology of graft healing and the implications for further injury.

The questions to consider include the following: When is it safe to stress the graft in terms of graft fixation and healing? When are patients likely to have sufficient strength and neuromuscular control to cope with the physical demands of their sport? How likely is re-injury? Should patients return to high-risk sports, or are they just increasing the risk of osteoarthritis or graft rupture? Armed with the answers to these questions, the health professional is well placed to advise the athlete regarding a timeline for return to sport that meets all parties' desires and expectations.

15.4.1 Graft Fixation and Healing

Whatever method is used for graft fixation, it must be able to withstand the demands of rehabilitation. Developments in surgical technique have facilitated the current rehabilitation protocols that emphasize immediate weight bearing, an unrestricted range of knee motion, early recovery of neuromuscular function, and an early return to sports participation. The ideal fixation may vary according to the type of graft used, surgeon's preference, and surgical technique. However, poor fixation does not appear to be a common cause of graft failure. Readers are directed to Harvey et al. [14] for a review of current fixation methods and suggestions for appropriate use.

Although the biology of ACL graft healing has been extensively studied in animal models, there are less data available from in vivo human studies. Furthermore, the observations regarding timelines for healing and graft function observed in animals do not appear to correlate with the clinical results in humans [31].

Three distinct phases of graft healing have been described, and the biological processes occurring during these phases directly affect the mechanical properties of the knee and are therefore likely to directly influence the time until normal knee function can be restored [31]. The three phases of healing and their approximate timelines in animal models are remodeling (first 4 weeks postoperatively), maturation (weeks 4–12), and ligamentization (from 12 weeks). The substantially reduced mechanical properties of the animal model graft in the first 8–12 weeks appear to contradict the successful clinical outcomes reported following accelerated rehabilitation programs in humans. Additionally, there are conflicting reports regarding whether ligamentization, though frequently referred to, actually occurs in human grafts [7]. Therefore, the properties of the tendon substitute may remain different to that of the native ACL, and it may be that human grafts undergo a process of adaptation rather than full restoration of the pre-injury biological properties of the ACL.

This disparity between the biological processes of graft healing in animal models and the human experience needs further research to accurately describe the timelines for graft healing in humans and to relate the timelines for graft healing to functional capacity.

15.4.2 When Are Patients Likely to Have Sufficient Strength and Neuromuscular Control to Cope with the Physical Demands of Their Sport?

Many clinical guidelines and test batteries exist regarding the criteria that must be met before a patient is cleared to return to sport after surgery. However, while these protocols have been extensively researched and validated and the theory behind them justified, the evidence to support their actual predictive value for a safe return to sport has not been as extensively explored. While many authors recommend patients achieve a certain predetermined functional level before being considered ready to return to sport, it seems that evidence is lacking to demonstrate that patients who meet the chosen criteria actually make a successful and safe return to their sport. Similarly, it is unclear whether patients who fall short of the return-to-sport criteria do in fact successfully return to sport despite their apparent functional limitations.

It is often assumed that adequate knee stability is important before returning the athlete to sport. However, instrumented measures of anterior knee laxity taken while the patient is resting have been shown not to correlate with function [18]. It is also important to consider the relevance of static anterior laxity measures to the rotational as well as the dynamic nature of knee function required for sports participation. An accurate and readily available tool for measurement of either rotational laxity or dynamic function is not presently available.

Other objective measures used to guide return-to-sport decision-making include hop tests and isokinetic muscle strength tests. The IKDC suggests a side-to-side difference of less than 10 % in hop testing qualifies the knee as "normal." Kvist [18] recommended that the side-to-side difference in hamstring and quadriceps isokinetic muscle strength should not exceed 15 % at the time of return to sport. Although such measures are widely reported in clinical follow-up studies, their use as indicators of readiness for return to sports participation may be questioned. Two recent studies have shown conflicting evidence regarding whether IKDC objective outcomes or hop tests differ between athletes who do and do not return to their pre-injury level of sport by 12 months [3, 21].

As the use of objective measures suggest, many authors prefer a goal-oriented approach to rehabilitation progression rather than a time-based progression. An example of this is Shelbourne and Nitz [32], who based their rehabilitation progression on the recovery of strength in the operated limb. Patients completing their accelerated program were permitted to return to light sport as early as 8 weeks postoperatively, provided the strength of the operated limb exceeded 70 % of the nonoperated limb in isokinetic testing, and the patient had completed sport-specific agility training.

Myer et al. [22] published a detailed clinical algorithm for return to sport following ACL reconstruction surgery. The four-stage rehabilitation process emphasized minimizing side-to-side differences in biomechanics of landing, agility, and sport-specific tasks to minimize the chance of re-injury following return to sport. The protocol emphasized the importance of restoring symmetrical neuromuscular control prior to allowing the athlete to commence preparation for returning to full competition. However, while the clinical algorithm provides a comprehensive assessment of neuromuscular function and strong justification for progression through the return-to-sport protocol, there remains little evidence regarding whether athletes who follow the algorithm are more successful in their return to sport than athletes who do not.

15.4.3 Re-injury (Graft Re-rupture and Contralateral ACL Injury)

Wright et al. [42] published a systematic review of six level I or II prospective studies that examined graft rupture and contralateral ACL injury rates in patients at least 5 years following ACL reconstruction surgery using either a patellar tendon or hamstring tendon autograft. The results demonstrated that graft rupture rates ranged from 1.8 to 10.4 %, with a pooled rupture rate of 5.8 %. The contralateral ACL injury rates ranged from 8.2 to 16 %, and the pooled contralateral ACL injury rate was 11.8 %. In other words, patients were twice more likely to suffer an ACL injury to the contralateral knee than a rupture of their ACL graft. However, most studies do not clearly distinguish between graft rupture and instability in the operated knee that may have been present from the early postoperative period. This may in turn influence the factors that are identified as predictors of graft rupture as opposed to failure.

Age is an important risk factor for re-injury. Shelbourne et al. [34] demonstrated that young patients (<18 years) had the highest risk of graft rupture. Patients in this age group have also been shown to be up to seven times more likely to sustain a contralateral ACL injury than patients aged greater than 18 years [17, 34]. The higher risk of subsequent injury in young patients may be related to their greater opportunity to participate in sport but may also reflect incomplete neuromuscular maturation. Careful monitoring of young patients is therefore warranted.

The type of sport to which the athlete returns may also influence graft and contralateral ACL injury rates. A return to pivoting sports has been shown to be associated with an up to tenfold increase in risk of contralateral ACL injury [30, 35].

The mechanism of the initial ACL injury also appears to be related to the subsequent risk of graft rupture, and Salmon et al. [30] have shown a threefold increased risk in patients with a previous history of a contact mechanism of ACL injury.

Surgical factors may also be important. Vertical graft placement has been shown by Hui et al. [17] to significantly increase the risk of re-injury. Improved awareness of the anatomy of the ACL and an attempt to better reproduce it may be anticipated to reduce this risk. The choice of hamstring or patellar tendon autograft does not influence the risk of subsequent graft injury [29, 30].

Shelbourne et al. [34] have also demonstrated a higher risk of contralateral ACL injury in females, although in another study, gender was not been found to be related to the risk of ACL graft rupture [17]. The higher incidence of contralateral ACL rupture in women may be due the ACL being smaller in women [8] as well as differences in their neuromuscular control and knee biomechanics when compared to males. It is well established that females land with an increased abduction moment and ground reaction force which subsequently increases stress on the ACL and thus increases the risk of primary injury by four to six times that of males [16].

Asymmetries in landing patterns at the time of returning to sport have been observed in both male and female patients. Paterno et al. [28] observed that patients landed from a drop vertical jump with a significantly greater peak vertical ground reaction force for the nonreconstructed limb. This asymmetry may predispose both males and females to a secondary ACL injury. However, females may be at even higher risk of secondary ACL injury than males due to preexisting biomechanical differences. Sport-specific neuromuscular rehabilitation may be particularly important in order to minimize the risk of subsequent ACL injury to either limb in athletes who intend to return to landing and pivoting sports.

There are limited data regarding the timing of return to sport and the relationship to re-injury. Shelbourne et al. [34] studied a cohort of 1,415 patients and showed that those who returned to full activity (including sport) before 6 months were no more likely to sustain a subsequent ACL injury than patients who returned later than 6 months. Clearly, there is a need for further investigation of the relationship between the timing of return to sport and the incidence of further ACL injury.

15.4.4 Should Patients Return to High-Risk Sports?

When making return-to-sport decisions, the health of the whole knee must be considered. While it is obviously important to ensure the graft is sufficiently protected by allowing for adequate healing and neuromuscular rehabilitation, just as important is ensuring other structures in the knee have had sufficient recovery time to cope with a return to sport. Using optical coherence tomography, Chu and colleagues have been able to demonstrate subtle changes in articular cartilage structure that were not previously visible using conventional radiographic or magnetic resonance imaging or arthroscopy [5, 6]. Identification of early changes in articular cartilage may help guide the clinician in their advice to the patient, as the extent of the initial injury has been shown to be an important predictor of the development of osteoarthritis [26, 27].

Although it has long been an expectation of ACL reconstruction surgery that it will enable the patient to return to high-injury-risk pivoting sports and simultaneously minimize further injuries to the menisci and articular cartilage, there is also evidence to indicate that the prevalence of osteoarthritis may be similar regardless of whether patients elect to have surgery or not following ACL injury [10, 23, 39]. There is also some suggestion that athletes who return to high-risk pivoting or cutting sports are more likely to develop osteoarthritis than athletes who return to lower level sports [21], although it is not known whether the incidence of osteoarthritis is higher in athletes who return to sport following surgery when compared to athletes who retire from sport following ACL injury.

This raises the philosophical dilemma of whether clinicians should be allowing athletes to return to high-risk sports at all. Myklebust and Bahr [24] have asked whether surgically successful ACL reconstruction actually increased the risk of subsequent development of osteoarthritis as it enabled the athlete to return to high knee-demand pivoting sports which subsequently increased the risk of ACL re-injury or exceeded the support structures of a previously injured knee.

Despite such concerns, many patients, particularly the highly motivated, are likely to return to sport whatever the longer term cost. Perhaps, when advising the patient regarding return-to-sport decisions, the clinician should pose two questions: Is it safe for the ACL graft, and is it safe for the health of the whole knee for the patient to return to sport at this time?

Conclusion

There is no simple recipe when it comes to deciding when a patient can resume their sports participation following surgery. From the evidence presented, it is clear that the decision of when to allow the patient to return to sport depends on many factors. As with the current trend for individualized and goal-oriented programs in postoperative rehabilitation [13], it seems that the return-to-sport decision must be also individualized and goal, rather than time, oriented. The differing demands of knee function for different sports, differences in biomechanics, differences in physiological and psychological profiles, and the athlete's expectations are just some of the factors that must be considered when making the decision.

15.5 Summary Statement

Most patients do return to some form of sport following ACL reconstruction surgery. However, the number returning to their pre-injury level of sports participation is perhaps surprisingly low. Current clinical practice appears to permit a return to sport at between 6 and 12 months post-operatively provided the patient has satisfactory knee stability and function and neuromuscular control. However, there is a lack of evidence to support the use of such criteria. Young age, female gender, and returning to pivoting sports are risk factors for further injury. When making return-to-sport decisions, the clinician should consider not only the ability of the ACL graft to cope with the activity level but whether it is safe for the health of all structures in the knee to return to particular sports at specific times.

15.6 Take Home Messages

- Most athletes (93 %) attempt some form of sport after surgery. However, only approximately 60 % of athletes return to their pre-injury level following ACL reconstruction. *Level of evidence*: *II*
- Return to sport appears to be permitted at 6–12 months postoperatively, although it may be permitted as early as 4 months or delayed until 18 months. *Level of evidence*: *V*
- Although most studies report when patients were cleared to return to sport after surgery, few studies report when patients actually returned to sport.
- There is a disparity between the biological processes of graft healing described in animal and human models. Further research is required to accurately describe the timelines for graft healing in humans and to relate the timelines for healing to functional capacity and a safe return to sport.
- Athletes who return to pivoting sports following surgery may be more likely to develop osteoarthritis than athletes who return to lower level sports. *Level of evidence*: *II*

- There is limited high-quality evidence to guide return-to-sport decision-making following ACL reconstruction surgery. When making these decisions, the clinician should consider whether it is safe for not only the ACL graft but also whether it is safe for the health of the whole knee.

15.7 Appendix: A Role for Motion Analysis in Determining Readiness to Return to Sport Following ACL Reconstruction: A Case Study

A 23-year-old male elite professional Australian Football League (AFL) player suffered a tear of the posterolateral bundle of the ACL in his left knee. Australian football is a fast-moving contact game involving frequent abrupt direction changes, cutting, and jumping and landing. The player had injured his preferred kicking leg.

The player underwent a single-bundle reconstruction, leaving the anteromedial bundle of the native ligament intact. A quadrupled semitendinosus tendon graft was used, with suspensory fixation on the femoral side and metallic interference screw fixation on the tibial side. The articular surfaces and the menisci were intact, and there was no associated collateral ligament injury.

The player commenced a routine rehabilitation program with a view to returning to play at his pre-injury level, in the starting team, at around 6 months. Initial rehabilitation involved restoration of active terminal extension, weight bearing and flexion as tolerated, and no bracing. He progressed satisfactorily and was riding a stationary bicycle at 3 weeks. Subsequent rehabilitation was routine, and he commenced running at 10 weeks, along with balance and landing drills. This rehabilitation program was supervised and progressed by the physical therapy staff of the team.

At 5 months, the player had no effusion, a full range of motion, normal stability of the knee, and good quadriceps and hamstring strength. He was undertaking noncontact training. In order to improve the understanding of his functional status with a view to him returning to play, he underwent laboratory-based three-dimensional motion analysis testing.

An eight-camera Vicon (*Oxford*, *UK*) MX3 motion analysis system and two in-ground force plates were used. The player was assessed during comfortable-speed walking, single-limb landing from a horizontal hop, and running. The data were compared to previously collected data from an active control group, with the exception of the sagittal plane knee moment during running, which was compared to data obtained from the contralateral knee.

During walking, the knee flexion angle was reduced during weight acceptance (Fig. 15.1a), as was the external knee flexion moment which was 55 % of that of the control group data (Fig. 15.2a). Similar reductions in the external knee flexion moment were seen for single-limb landing and running activities (Figs. 15.3a and 15.4a). Seated dynamometry testing of quadriceps function demonstrated good isometric strength (97 % recovery compared to the contralateral limb) and good isokinetic strength at high speed (180°/s)—137 % compared to the contralateral limb. However, there was reduced isokinetic strength at slow speed (60°/s)—77 % compared to the contralateral limb.

With this information in mind, the player undertook further targeted training with emphasis on single-leg press and landing drills directed by team physical therapy staff. He continued to undertake noncontact skills training during this time.

Five weeks later, repeat motion analysis testing was undertaken using the same tasks as previously described.

At the second testing session, the knee flexion angle (Fig. 15.1b) and external flexion moment (Fig. 15.2b) during walking had normalized. The sagittal plane knee flexion moment during landing and running had improved but had not returned to normal (Figs. 15.3b and 15.4b).

On the basis of the improvement, along with examination findings of a clinically normal knee, the footballer was cleared to return to play. However, he suffered a calf strain in the operated limb prior to returning to play, which delayed his return by 3 weeks. The player subsequently made a successful return to senior elite professional

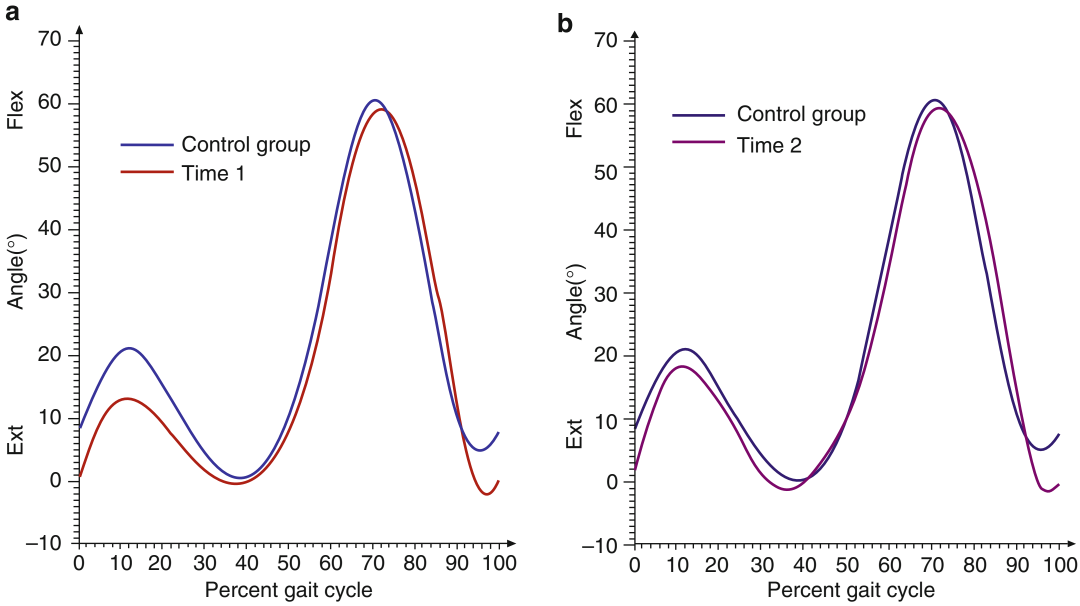

Fig. 15.1 Sagittal plane knee angle during walking. (**a**) First assessment, (**b**) second assessment

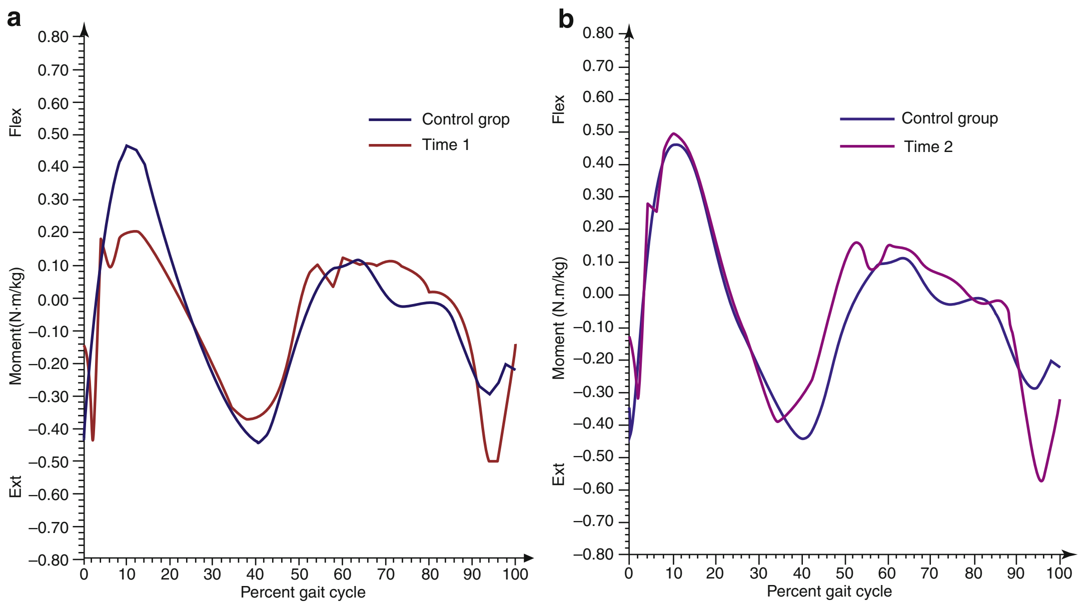

Fig. 15.2 Sagittal plane knee moment during walking. (**a**) First assessment, (**b**) second assessment

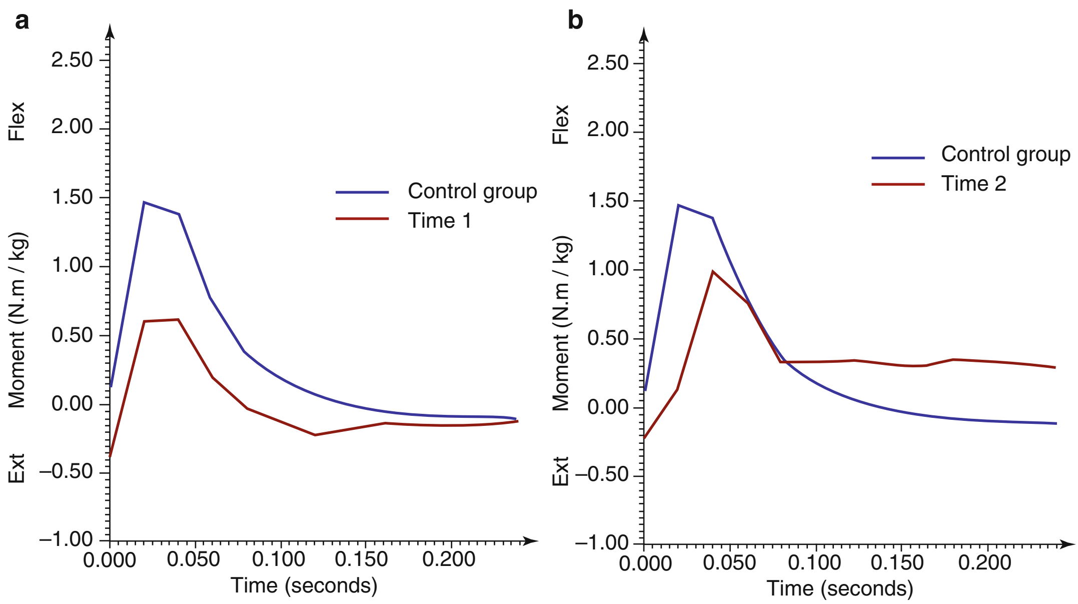

Fig. 15.3 Sagittal plane knee moment during landing from a horizontal hop. (**a**) First assessment, (**b**) second assessment

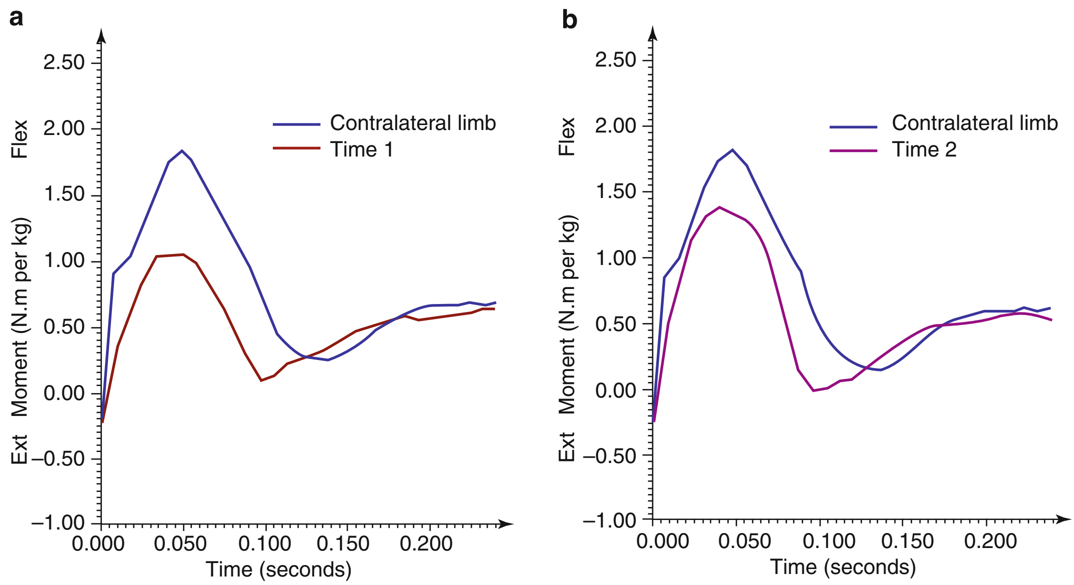

Fig. 15.4 Sagittal plane knee moment during running. (**a**) First assessment, (**b**) second assessment

Australian football at 7 months following surgery. He has not had further problems with the knee over a 5-year period.

Comments About the Case Study
While it is of course unknown whether the same result could have been achieved without motion analysis assessment, in this case the assessment allowed for modification of the rehabilitation program as well as providing an objective assessment of whether the modification resulted in functional changes over a relatively short time.

It is also pertinent to note that testing isometric quadriceps strength alone would not have given a complete picture of the status of the player's recovery of quadriceps function.

These two observations highlight the fact that more detailed testing of neuromuscular function may well be useful to determine whether a player has achieved a level of recovery that allows them to return to sport safely. However, further study is warranted to determine whether such assessments do in fact have predictive value.

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Return to Sports After ACL Reconstruction Surgery: A Risk for Further Joint Injury?

16

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Contents

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16.1 Introduction

Anterior cruciate ligament (ACL) tear constitutes a serious problem in many sports regardless of sex or playing level. Reconstruction of the ACL is therefore a common procedure in this patient group, and although not supported by sound evidence, most knee surgeons typically advocate a layoff from sports of around 6 months following ACL reconstruction [12]. It has been argued that too little attention is paid to the risks of reinjury and other subsequent knee injuries with early development of osteoarthritis (OA) when advising the athlete on whether to return to sports or not after the index injury [15]. The present review therefore describes the return to sports success rate after ACL reconstruction, in particular for team sports, and discusses the potential risk for further joint injury after return to sports from an evidence-based perspective.

16.2 Return to Sports as an Outcome Measure

The return to sports rate is sometimes used as a measure of successful outcome after ACL reconstruction. There are, however, some limitations to consider when using return to sports as an outcome measure. First, what does return to sports mean; is it return to partial training, full training, or to competition? Return to competition might not be an ideal definition since this depends on many nonmedical factors such as length and

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Table 16.1 Sport-specific studies reporting return to sports success rates after anterior cruciate ligament reconstruction surgery in high-level team sports

Study	Study type	Inclusion period	No. of players	Sport	Return rate
Busfield et al. [3]	Case series (evidence level IV)	10 years (1994–2005)[a]	27 males	Basketball	21/27 (78 %)
Fabbriciani et al. [6]	Case series (evidence level IV)	1 year (1997–1998)	18 males	Rugby	18/18 (100 %)
Myklebust et al. [16]	Cohort study (evidence level II)	2 years (1989–1991)	57 females	Team handball	50/57 (88 %)
Shah et al. [22]	Case series (evidence level IV)	5 years (2001–2006)	49 males	American football	31/49 (63 %)
Waldén et al. [27]	Cohort study (evidence level II)	9 years (2001–2009) 6 years (2004–2009)	57 males 14 females	Football	57/57 (100 %) 12/14 (86 %)

[a]1998–1999 was not included

period of season, frequency of matches or other competitions, confidence of the coach, etc. In addition, some athletes are exercising only on a recreational basis without competing at all. Second, even if return to competitive sports is possible after an ACL tear, the athlete might not be able to compete at the same level as prior to injury, a factor that is often not taken into account [2]. Third, given the variability in the functional demands put on the knee joint in different sports, all athletes are not equally dependent on their ACLs to perform well within their sport. For example, a footballer, golfer, cyclist, and sprinter could cope differently with their injuries, and it might be easier to return to bicycling or jogging than to pivoting sports [28]. Fourth, the assessment of time to return can differ between studies, and the ideal cutoff threshold for reporting return to sports is not known. In one recent study on male elite footballers, the majority of those returning to play after ACL tears did so within the first year after surgery [27]. In contrast, only one-third of competitive team sport athletes had returned to competitive sports 12 months after surgery in another recent study [1]. Fifth, ACL-injured athletes rarely have completely symptom-free knees, for example, as seen by low average scores in the knee injury and osteoarthritis outcome score (KOOS) for function in sport and recreation or knee-related quality of life, in spite of being able to participate in their sport [9]. Sixth, one ACL tear is not identical to another ACL tear, and only a minority of ACL tears can be considered as "isolated" [11]. Hence, there are often concomitant ligament, meniscus, or cartilage injuries that may interfere with the ability to return to sports after an ACL tear [3]. Finally, professional athletes who make a lot of money from their sport will have another incentive to return to sports than recreational or amateur athletes. Consequently, the overall financial situation must be put into perspective when comparing return to sport success rates between different sports or between different settings within the same sport.

Nevertheless, a recent systematic review of 48 studies reporting return to sports outcomes after ACL reconstruction showed from pooled meta-analysis that 82 % in a general athletic population were able to participate in sports, while only 63 % could return to preinjury level [2]. In addition to the studies included in that review, a few more studies reporting sport-specific outcomes after ACL reconstruction can be found in the literature (Table 16.1). In these studies, all conducted on collision or contact team sports with a follow-up of at least 1 year after surgery, the return to sports success rates were varying (63–100 %) [3, 6, 16, 22, 27].

16.3 Subsequent ACL Injury

As for many other sports injuries, a history of previous ACL tear is associated with substantial risk of future ipsilateral or contralateral ACL tear [7, 19]. In a study on male Australian Rules

Table 16.2 Patient studies reporting new ipsilateral and contralateral tears after anterior cruciate ligament reconstruction surgery

Study	Study type	Inclusion period	Follow-up (years)	No. of patients	New tears
Hui et al. [11][a]	Case series (evidence level IV)	1993–1994	15	90	Ipsilateral: 7/90 (7.8 %) Contralateral: 22/90 (24.4 %)
Salmon et al. [21][a]	Case series (evidence level IV)	1993–1994	5	612	Ipsilateral: 39/612 (6.4 %) Contralateral: 35/612 (5.7 %)
Shelbourne et al. [23]	Cohort study (evidence level II)	1992–2001	≥5	1,415	Ipsilateral: 61/1,415 (4.3 %) Contralateral: 75/1,415 (5.3 %)
Wright et al. [29]	Cohort study (evidence level II)	2002	2	235	Ipsilateral: 7/235 (3.0 %) Contralateral: 7/235 (3.0 %)

[a]These two studies are reporting on the same patient series, but only "isolated" tears are included in the study by Hui et al. [11]

footballers between 1992 and 1999, 63 players with noncontact ACL tears treated with ACL reconstruction were studied for different intrinsic and extrinsic risk factors [19]. The strongest risk factor for a new ACL tear was previous ACL tear with around 11 times higher risk within the previous year after ACL reconstruction and around 4 times higher risk if the reconstruction occurred prior to the previous 12 months. In another study on 143 female elite footballers in Germany during 2003–2004, a fivefold increased risk of a new ACL tear was found among the 19 players who had a history of previous ACL tear [7]. Importantly, these two studies suggest that the first year after ACL reconstruction is of particular concern regarding the risk of incurring ipsilateral reinjury, whereas contralateral tears are rare within the first year. The influence of aggressive rehabilitation and early return to sports on the risk of reinjuring the ACL is far from completely understood, but there are some new data from a questionnaire follow-up 3–4 years after ACL reconstruction showing that return to competition within 7 months following ACL reconstruction was associated with a significantly higher reinjury risk than return later than 7 months (15.3 % vs. 5.2 %) [13].

The risk of incurring subsequent ACL tear has also been studied in different patient cohorts (not only including athletes) that have undergone ACL reconstruction [11, 21, 23, 29]. Taken together, the annual rate of further ACL injury seems to be around 1 % each in rough terms for both ipsilateral and contralateral tears up to 5 years after index ACL reconstruction (Table 16.2). This trend was verified in a recent systematic review including six other studies than those listed in Table 16.2, where it also was shown that the rate of contralateral ACL tear diverges from the retear rate after around 5 years [30]. Further support of a higher overall rate of contralateral tear than ipsilateral tear was also found in another recent systematic review including eight further studies [24]. In addition, the risk of incurring a subsequent ACL tear seems to be strongly associated with age lower than 18 years at the index tear. One of the studies has reported a sevenfold higher risk of contralateral tear [11], and another study found around 3.5 times higher risk of ipsilateral or contralateral tear [23]. The other important risk factor for incurring a contralateral tear after unilateral ACL tear seems to be return to high-level activity [21, 24], whereas female sex does not seem to be of similar importance as for index ACL injuries [24].

16.4 Secondary Meniscal or Cartilage Damage

Associated meniscal tears and joint cartilage lesions are very common findings at ACL reconstruction surgery, and the occurrence of these concomitant injuries increases with time elapsed from ACL tear to ligament surgery [8]. Similarly, it is well known that ACL reconstruction in general is protective against new meniscal and cartilage injuries compared to nonoperative treatment [4]. However, it is unclear from the literature to what extent return to sports after ACL reconstruction per se leads to subsequent meniscal or cartilage lesions and possibly further knee surgery. In a prospective one-season study on male elite footballers, players with previous ACL injury had a threefold higher rate of new traumatic knee injury compared to players without history of an ACL tear [26]. Most of the traumatic knee injuries recorded were, however, sprains involving the joint capsule or ligaments, and only a few meniscal and cartilage injuries were identified. The main limitation of that study was that the rate of subsequent meniscal tears and cartilage lesions during the remaining player career is unknown since only one season was studied. Still, it is a worrying scenario that return to sports following ACL reconstruction might expose the athlete to subsequent knee injury leading to a vicious circle of repeated traumas and surgeries with accelerated knee joint degeneration in the long term.

16.5 Long-Term Consequences

ACL injury is without doubt associated with development of premature OA in the knee joint of former team sport athletes [16, 25], even if the figures vary because of differences in study design, follow-up period, and radiological classifications used [14, 18]. The development of OA after ACL injury is far from completely understood and is both complex and multifactorial [14]. Associated injuries, such as meniscus lesions, increase the frequency of radiological OA compared to “isolated” ACL injuries [17, 18]. However, the role of the bone marrow edema seen on magnetic resonance imaging (MRI) in almost all typical acute ACL injuries is so far not clear [14]. To date, ACL reconstruction has not been found to be protective against OA [14], and return to high-level sports or other knee-demanding activities after ACL reconstruction might even result in a higher rate of OA development compared to nonoperatively treated ACL injuries given advice on activity modification [17]. Consequently, based on the high rates of subsequent knee injury and OA after ACL injury, it has been questioned whether return to high-level pivoting sports is in the athlete’s best interest if long-term knee health is the primary concern [5, 15].

16.6 Summary Statement

An ACL tear usually causes long layoff from sport, and return to sports is often used as a measure of successful outcome after ACL reconstruction. Recent studies on different team sports have shown between 63 and 100 % return to sports rates. However, return to sports following ACL reconstruction is not uncomplicated and is associated with a high risk of incurring a new ipsilateral or contralateral ACL tear as well as other knee injuries. There is also a considerable risk of developing premature OA after an ACL tear. More attention should therefore be paid to the risks of reinjury or other subsequent knee injuries as well as early development of OA when giving the athlete advice on return to sports after ACL tear.

16.7 Future Research

There is an urgent need for more research evaluating the risk for further joint injury after return to sports following ACL reconstruction. First, it would be of great interest for all the different sports medicine practitioners involved in the treatment of ACL tears to know more when (and if) to safely allow return to different sports. In this respect, it could be valuable to identify athletes who are able to return to sports without suffering any new knee injuries and to study the underlying (success) factors among these athletes. Moreover, it is nowadays common (or even mandatory) to obtain baseline data on anthropometrics, physical examination, psychological questionnaires, radiological imaging, etc., for injury-free athletes as a part of the preseason medical assessment in many high-level sports. These data should ideally be available for researchers in future studies on return to sports after ACL tear to be able to evaluate any persisting deficits compared to baseline values in a larger study sample. Second, the influence of accelerated rehabilitation and early return to sports on the reinjury risk should be studied further since some recent evidence exists that return to competition within 7 months following ACL reconstruction is associated with a higher risk of ipsilateral graft tear. Similarly, more studies are needed to validate the different sport-specific tests used at the end of the rehabilitation to determine readiness to return to sports. A good example of such research is a recent study that followed athletes with reconstruction surgery for an index ACL tear prospectively for 12 months after having tested them biomechanically at the release to return to sports [20]. Hopefully this can end up with some form of consensus guidelines on how to test and medically clear athletes before allowing them to return to sports [15]. Third, as for all injuries, the best "treatment" of ACL tear is without doubt prevention. This area of research should have a high priority in the future, since there is a lack of adequately sized high-quality randomized controlled trials with ACL injury as the primary outcome [10].

16.8 Take-Home Messages

- Recent studies on common team sports have reported return to sports success rates between 63 and 100 % following ACL reconstruction surgery (evidence levels II and IV).
- The risk of incurring new ipsilateral or contralateral ACL tears is increased severalfold after return to sports following ACL tear in team sports compared to noninjured athletes (evidence level II). This risk increase is highest within the first year after surgery for ipsilateral graft retears (evidence level II), whereas it increases with time for contralateral tears (evidence levels II and IV).
- There is a substantial risk of developing premature OA after ACL tear, in particular for tears with associated intra-articular lesions such as meniscal tears (evidence level II).
- More attention should be paid to the risks of reinjury or other subsequent knee injuries as well as early development of OA when advising the athlete on whether to return to sports after ACL tear, in particular for the young athlete with a first-time injury or an athlete suffering a second ACL tear.

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17 Psychological Factors in the ACL Reconstruction Population: Are They Predictive of Patient Outcomes?

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17.1 Introduction

Anterior cruciate ligament (ACL) reconstruction research has focused on technical aspects of surgery and rehabilitation. These factors however may only partially contribute to patient outcome [50]. Less attention has been paid to psychological factors that may influence an athlete's return to sport [8, 50, 73, 106, 107]. Despite successful ACL reconstruction and rehabilitation as determined by pre- and postoperative comparisons of patient-perceived function and symptoms [92] and performance-based tests such as the single and triple hop for distance [38, 44, 75, 87], the percentage of patients that successfully return to preinjury sports participation levels is less impressive. Improving our understanding of a patient's psychological profile prior to ACL reconstruction, rehabilitation, and return to sport may assist the surgical and rehabilitative decision-making process.

17.2 Discrepancy Between Knee Function and Return-to-Sports Rate

A high preinjury activity level combined with fear of not being able to continue the same sports in the future without an increased risk of knee reinjury is the primary reason for ACL reconstruction [16, 20, 42]. Athletes often require a 6–12-month hiatus from sports for full recovery following ACL injury and rehabilitation [47, 63]. Unfortunately, only 65–70 % of patients eventually return to

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preinjury sports activity levels [7, 29, 42]. Patients often report a continued knee reinjury fear up to 4 years post-ACL reconstruction [48, 99]. Athletes who return to their preinjury sports participation level at 12 months post-ACL reconstruction score higher on the ACL-return to sports after injury scale which assesses confidence, emotions, and risk appraisal than athletes that do not [103].

Between 20 and 50 % of patients do not return to the same sports postsurgery despite being "physically" rehabilitated [25, 48, 51], and 10–70 % of those who resume preinjury sports participate at a reduced level or with impaired function [87]. In their review, Kvist et al. [47] found that 56 % of patients returned to their preinjury activity level after ACL reconstruction and rehabilitation. In a meta-analysis of 48 studies representing 5,770 patients, Ardern et al. [2] reported a 63 % rate of return to preinjury sports participation, and only 44 % returned to competitive sports even by 36.7 months postsurgery. At 12 months post-ACL reconstruction, only 33 % of patients attempt competitive sport at their preinjury level and only 67 % return to sports participation [1]. More men returned to competitive sport by 12 months despite the same intentions to return [1], possibly because of greater neuromuscular deficiencies among females [83].

Determination of the percentage of patients that return to full preinjury sports participation level is of greater importance than isolated muscle strength, knee range of motion, or hop test measurements [1, 101]. While 90 % of patients achieve normal or nearly normal knee function based on postsurgery impairment-based measurements and 85 % based on IKDC self-reported function scores, 56 % do not return to competitive sports [2]. No relationship was found between this score and patient return-to-sport rate. Athletically active patients may require longer rehabilitation to ensure a truly successful outcome.

17.3 Restoring a "Fully Functional Human Being"

Patients who elect to undergo ACL reconstruction are often unable to accept the consequences of their injury [34]. Surgery symbolizes not only a full return to preinjury sport level but also return to becoming a completely restored functional human being [34]. Few athletes are prepared psychologically for a sports injury; therefore, they lack necessary coping abilities [39]. When knee injury curtails physical activity and bodily competencies associated with social identity are lost, reconstructive surgery may be perceived as the sole solution despite the fact that the literature has not strongly supported the notion that one has to stop sports post-ACL injury [19]. Many patients believe that a future without ACL reconstruction is a future without sports participation [34].

Patients often feel as though they are not mentally prepared for surgery, and rehabilitation did not match their expectations [34]. To decrease anxiety, the patient should be informed about the surgery as well as the content and significance of the rehabilitation. In addition to frustration, patients may start to question their motivation, creating guilt that negatively influences rehabilitation progress when expectations are not met [34, 62, 86]. Rehabilitation post-ACL reconstruction places high demands on the patient's ability to remain goal oriented over the entire program.

17.4 Self-Efficacy, Confidence, and Goal Setting

Confidence is vital for return to competitive sports [22], and physical and psychological readiness to return do not necessarily coincide (Fig. 17.1) [74]. Athletes with injuries have less confidence than those without injury [40, 49]. Self-efficacy is a judgment of one's potential ability to carry out a task and is associated with rehabilitation protocol adherence, greater effort toward goal achievement, and improved outcomes [3–5, 22–24, 61].

Increased self-efficacy in the ability to perform rehabilitation tasks and stronger beliefs in program efficacy are related to more compliant patient behavior [34, 94]. Collaborative rehabilitation program goal setting can help the patient regain the sense of control needed to strengthen self-efficacy. Greater rehabilitation program guidance is needed as patients redefine their bodily awareness and

Fig. 17.1 The restoration of physical function and psychological readiness do not necessarily coincide

knee reinjury risk coping skills prior to sports return [93]. Female basketball players that viewed a modeling video had increased self-efficacy at 3 weeks post-ACL reconstruction and achieved functional rehabilitation goals earlier [27].

Preoperatively, male patients with high baseline physical activity levels and young (17–29 years), recently injured patients have higher knee self-efficacy scale (K-SES) scores [97]. At 12 months, 15 of 30 patients (50 %) with an ACL-deficient knee and 15 of 33 patients (45.4 %) post-ACL reconstruction had returned or nearly returned to baseline physical activity levels. Significant relationships were observed between K-SES scores and knee injury and osteoarthritis outcome score (KOOS) subscales (pain, other symptoms, daily living function, sports and recreation function, and knee-related quality of life). Early rehabilitation self-efficacy levels differed significantly with gender, age, and physical activity level [97].

When adjusted for age, gender, and preinjury Tegner score, Thomee et al. [96] reported that the K-SES for preoperative knee function predicted which patients returned to preinjury physical activity levels 1 year post-ACL reconstruction. Preoperative self-efficacy regarding perceived future knee function predicted self-rated sports and recreation knee function as suggested by the KOOS. Based on Lysholm score, KOOS sports and recreation scale score, and the related quality-of-life subscale score, the preoperative K-SES score predicted patient knee-related quality of life and outcome success [96]. Preoperative K-SES perceived future knee function score predicted an acceptable patient outcome based on single-leg hop testing. Lastly, the preoperative K-SES knee function score predicted which patients regained acceptable levels of physical activity, symptoms, and muscle function [96].

By 1 year post-ACL injury/reconstruction, patient self-efficacy might be determined by factors such as coping with pain, locus of control, previous injury and/or illness, quality of life, symptoms, and physical function [95]. There is a significant relationship between K-SES score and an internal health locus of control (HLOC), as measured by the multidimensional HLOC scale [95, 102]. Approximately 40 % of self-efficacy, as measured by the K-SES, can be explained by self-reported symptoms and function and the patient's HLOC [95]. Self-efficacy following ACL injury and reconstruction is dependent on how strongly patients perceive an action-outcome relationship.

Over the initial 12 weeks post-ACL reconstruction, psychosocial factors can be improved, baseline levels do not foretell knee pain or function, and interventions to improve self-efficacy or decrease fear of movement or reinjury can improve short-term knee pain and function outcomes [14]. Following knee injury, both the knee activity self-efficacy scale ($r = .651$; $P < .001$) and the 11 item Tampa Scale of Kinesiophobia (TSK-11) ($r = -.599$; $P = .002$) relate to the International Knee Documentation Committee (IKDC) subjective knee form score [41].

Following knee injury or surgery, basketball players who received a modeling intervention of goal setting, education, and self-efficacy statements had greater motivation, improved rehabilitation program adherence, and a better understanding of factors that assisted recovery [27]. By observing a similar patient successfully cope with and perform a task, the observer may be encouraged to adopt similar strategies [27]. If the task is successfully performed, perceived competence and self-efficacy increase and anxiety is reduced [26, 59, 82]. Progressive task complexity and previous physical experiences with a given task help enhance the imagery experience [68].

17.5 Fear of Reinjury, Kinesiophobia, Pain, and Catastrophizing

Fear of reinjury is a common reason for not returning to presurgical sports participation [2, 51, 72, 78]. Patients fear and avoid threatening situations that exceed their coping skills [4]. Patients with musculoskeletal pain who confront their fear of movement-related reinjury are more successful in returning to their previous activity level [46]. High fear of reinjury is related to low knee-related quality of life [48].

Up to 12 weeks post-ACL reconstruction, there is no association between TSK-11 and IKDC subjective knee form scores, possibly because patients are not ready to assess physical readiness for high-demand activities [13]. Fear of movement or knee reinjury also does not relate to perceived knee function by 6 months post-ACL reconstruction [13]. In contrast, pain intensity, as measured with the short form-8 bodily pain rating, was significant, explaining 61 % of the variance in patients ≤ 90 days postsurgery and 44.1 % in patients between 91 and 180 days postsurgery. Pain exerts a strong influence on function early post-ACL reconstruction. Fear of movement or reinjury improves more slowly than pain catastrophizing and self-efficacy.

Elevated TSK-11 scores are associated with lower self-reported function and sports return rates following ACL reconstruction [14]. How patients interpret their pain experience, not just intensity, can influence postinjury fear and catastrophizing [52]. Patients at risk for chronic disability have elevated pain-related fear of movement/reinjury, even during the acute injury phase [30]. Injured athletes often experience negative emotions and reduced self-confidence because of reduced physical ability [39]. Following ACL reconstruction, patients often lack confidence with the injured knee despite objective and subjective restoration of knee stability.

Fear of movement or knee reinjury tends to decrease with greater time postsurgery, becoming inversely related with function specifically as the patient nears sports return [13]. Reducing pain-related fear can be accomplished through education, progressively increased functionally relevant exercise intensity, and self-efficacy-enhancing interventions [52]. Fear of reinjury is the main psychological issue for which education is needed, but it is not consistently addressed [56].

17.6 Mood, Anxiety, and Depression

Athletes have negative emotions immediately and 6 months post-ACL reconstruction, creating a "U"-shaped emotional pattern [49, 62]. The later response coincides with clearance by the knee surgeon for return to sport [62]. Competitive athletes have greater initial emotional disturbances and quicker recovery than recreational athletes. At 24 h post-ACL reconstruction, adolescent patients experience greater pain, catastrophizing, and anxiety than adults, but when catastrophization is controlled for pain scores do not differ.

Professional soccer athletes have higher Beck depression inventory scores 1 day preoperatively and 1 week post-ACL reconstruction compared with amateurs [69]. Compared with adults, adolescents experience greater mood disturbances, greater perceived surgical benefits, and greater use of cognitive and behavioral change processes such as dramatic relief, environmental reevaluation, and self-liberation [100]. Adolescents have higher preoperative mood disturbance levels than adults but also greater psychological readiness for surgery [100].

17.7 Cognitive Therapy, Imagery, and Modeling

The primary self-efficacy source, previous experience, is not available to the athlete that encounters their first severe knee injury and prolonged rehabilitation experience. For them, the best source of self-efficacy information is through vicarious learning (modeling) and verbal persuasion [6].

Imagery and cognitive-behavioral interventions that allow the patient to mentally rehearse rehabilitation tasks, cope with injury-related anxiety and depression, and increase self-efficacy and motivation can decrease fear of movement or reinjury [17, 45, 77, 88, 89]. After five sessions over 4 months, cognitive-behavioral methods such as disputing, systematic desensitization, and time projection reduced knee reinjury fear in an athlete at 3 months post-ACL reconstruction [58].

At 6 months post-ACL reconstruction, guided imagery and relaxation did not improve isokinetic knee extensor torque at 180°/s, but it had a positive effect on laxity based on knee arthrometry measurements [54]. The group that received guided imagery and relaxation techniques had decreased noradrenaline and dopamine levels, suggesting less stress and improved graft healing [32, 43]. An earlier study also reported improved isokinetic knee extensor torque compared to control conditions [17].

A group that observed a vicarious experience modeling video designed to decrease perceived anxiety and pain and improve outcomes had lower preoperative pain expectations, greater self-efficacy to perform rehabilitation tasks, greater confidence with crutch walking, and higher IKDC subjective knee form scores at 6 weeks post-ACL reconstruction compared with a control group [53].

17.8 Health Locus of Control (HLOC)

Having an internal or external HLOC classifies whether patients believe their health is controlled more by their own behaviors or more by fate, luck, or chance [102]. Patients with lower perceived physical function limitations following ACL injury regard their health as being primarily under their control (internal), while patients with greater perceived limitations regard their health as being out of their control (external) [67]. Patients with a high internal HLOC score also have better perceived knee function and sports activity levels 5 years post-ACL reconstruction [66].

An adequate self-efficacy level is needed for HLOC to elicit the desired outcome. Self-efficacy differs from HLOC in that a patient may have an internal HLOC, but because they perceive less than adequate skills (low self-efficacy) to achieve a desired outcome, they may not proceed with the needed action [4]. Individuals that exercise regularly tend to have higher internal HLOC scores than nonexercisers [85]. There is a need for exercise-activity and age-specific HLOC studies [85].

17.9 Self-Determination, Goal Setting, and Positive Self-Talk

Self-determination theory proposes that controlled or autonomous motivations influence patient behaviors. Controlled motivation refers to behaviors that result from external or internal pressure. In contrast, autonomous motivation is reinforced by a desire to obtain perceived benefits. Patients that adopt controlled motivation participate in treatment because of an external force, perceiving that they will get into trouble if they do not, or an internal force such that they will feel guilty if they do not. In contrast, patients with autonomous motivation identify more with rehabilitation goals, perceiving that it is in their best interests to complete treatment. When physiotherapists provide autonomous motivation, patients adhere better to rehabilitation programs, while controlled motivation is negatively correlated with adherence. Following ACL reconstruction, patients that believe the physiotherapist improves their understanding of rehabilitation program options and the rationale are more likely to report autonomous motivation and greater adherence [12]. Goal setting, positive self-talk, and healing imagery are associated with earlier recovery of function in athletes with knee and ankle injuries [37]. When athletes believe they have some control over the rehabilitation process, they are more likely to exert this control, implement psychological skills, and adhere to the program [81].

17.10 Patient Commitment or Willingness

Comparing the IKDC subjective knee form scores of patients that returned to the same sport level following ACL reconstruction with those that did not return does not reveal significant differences

[33]. In contrast, a psychological questionnaire, which measured factors such as level of commitment, willingness, and interest in resuming preinjury activity levels, found that 27 % of patients that did not return to sport scored < 15 (on a 3–18-point scale with a higher score indicating better patient motivation), while 67 % of the patients that returned to sport scored > 15 [33].

17.11 The Exclusive Athlete Role or Identity and the "Endless" Season

High commitment levels usually accompany successful sport and exercise-activity participation. Many individuals ascribe a great deal of psychological significance to sport and exercise involvement, identifying strongly with the athlete role [21]. The seasonal nature of competitive sports influences patient return-to-sport rate at 12 months post-ACL reconstruction [1]. Patients that participated in seasonal sports were more likely to return to full competition than patients that participated in year-round or nonseasonal sports. Definitive target dates, such as the first game of a season, may provide a greater sense of control and ease of recovery planning [1].

Patients make domain-specific judgments of their personal worth and competence. The value or importance attributed to a given self-concept domain determines the extent to which perceived competence in that domain influences self-esteem and motivation. Incompetence in a domain of low importance has little impact on self-esteem; however, incompetence in a domain of high importance can profoundly affect self-worth. In contrast to a patient that places little value on athletic endeavors, the self-esteem and motivation of a patient that highly values sport and/or exercise participation may be strongly influenced by successes or failures in the athletic domain.

Deriving self-identity from the athlete role can have a positive effect on sports performance [28, 105]. Athletic identity guides and organizes cognitive self-related information processing. Patients with strong athletic identities are more likely to interpret an injury in terms of its implications to their athletic function more than a patient that only weakly identifies an athlete role. The extent to which one considers that they are an athlete is influenced by family members, friends, peers, coaches, teachers, and media [35].

Individuals with a strong, exclusive athletic identity are more vulnerable to emotional problems when they experience an injury that curtails sport participation [18, 35, 70, 71]. Athletic injury disrupts the self-identity of the patient that has a strong athletic identity. Sport or exercise may acquire an addictive quality for patients whose self-worth is solely defined by their athlete role [79]. When the patient lacks other self-worth and self-identification sources, there is an increased risk for emotional disturbances [70, 105]. Individuals that strongly commit to the athlete role may be less likely to explore other career, education, and lifestyle options due to their intensive, overriding sports involvement. This may lead to premature identity foreclosure if their athletic career suddenly changes, or is significantly compromised. Individuals with an alternative area to direct energies and commitments are better able to transition out of the athlete role [105]. Maintenance of a strong, but not exclusive, athletic identity may confer lasting psychological benefits to the athlete, particularly if they have also developed other identity roles and their associated coping skills. Further research is needed to explain the relationship between athletic identity and emotional adjustment to injury and compromised or premature sport termination. Although strength and exclusivity of athletic identity can boost return-to-sport intentions, additional coping mechanisms should also be developed. As college students become exposed to other activities and influences, their exclusive identification with the athlete role decreases [9].

17.12 Dialogue or Monologue?

Knee surgeons often rate patient symptoms as less and function as better than the patient, unconsciously underestimating possible complaints and unfavorable answers [76]. Patients tend to report lower Lysholm knee scale scores at 1 year post-ACL reconstruction than an unbiased observer, and excellent, good, fair, or poor category assignments are altered by the data collection method [36]. As self-reported outcomes get worse, the discrepancies between the patient's and the surgeon's ratings increase [36]. To eliminate or greatly reduce bias, independent clinicians should perform evaluations and patients should be allowed to complete written assessments on their own with an understanding of the questions they are responding to.

17.13 "The Perfect Storm"

When ACL injuries occur in teenagers, there is often a confluence of an exclusive perceived athlete role with early sport specialization, continual seasons, high peer pressure, underdeveloped decision-making skills, physical and emotional growth spurts, continuing development of the concept of "self," and high recovery expectations [10, 11, 15, 55, 57, 60, 64, 65, 80, 84, 98, 104]. Parents may also facilitate the exclusive athlete role instead of supporting diversification into other perceived roles such as student, part-time employee, musician, artist, or even as a multisport athlete becoming "cross-trained" in sports with differing psychological as well as physiological demands. This situation creates the "perfect storm" in terms of potential difficulty achieving satisfaction and completely returning to sports at the preinjury competitive level following knee injury and subsequent ACL reconstruction.

17.14 What Is the Desired Outcome and How Can It Be Achieved?

Patients often perceive ACL reconstruction to be their only recovery option and consider their rehabilitation to be longer and more difficult than expected. Many believe that they were not mentally prepared for surgery and prolonged rehabilitation. The desired outcome is to return to sports at their preinjury participation level. Psychological barriers such as anxiety, stress, depression, pain, catastrophizing, kinesiophobia, and fear of reinjury can be minimized through interventions that increase self-efficacy, reinforce commitment, facilitate a more internal HLOC, increase relaxation, and reestablish a realistic knee reinjury risk appraisal.

Fear of reinjury is the predominant emotional factor associated with returning to sport in patients with musculoskeletal injuries [40]. Confidence in performing well and accurately appraising return-to-sport reinjury risk have also been identified as key psychological responses [40]. To achieve this, functional exercises in which the patient perceives behavioral accomplishment relevant to their lifestyle and sport can improve self-efficacy and extinguish fear [4]; however, if baseline strength or range of motion impairments have not been adequately addressed, functional exercises alone may lead to a false sense of confidence.

Cognitive imagery, goal setting, and group activities during rehabilitation can increase self-efficacy and decrease kinesiophobia. Preoperative patient education regarding surgery and rehabilitation program rationale and options can facilitate autonomous motivation, increase adherence, and improve outcomes. Modeling techniques can reduce presurgery anxieties, increase early self-efficacy levels, and improve program adherence [27, 53]. The more varied the circumstances in which fears are mastered, the more likely movement experiences can authenticate self-efficacy and impede disconfirming self-perceptions [4]. Ultimately, experiences based on performance accomplishments produce higher, more generalized, and stronger self-efficacy than vicarious experiences. Although psychological intervention may help anywhere across the ACL reconstruction patient treatment continuum, consideration during the pre-, early postoperative, and return-to-sport planning phases is essential. During the pre- and early postoperative periods, reducing pain and increasing self-efficacy are crucial. As the patient progresses toward returning to sports, steps to decrease fear and develop a rational knee reinjury risk appraisal take on greater importance [1].

Conclusions and Future Directions

Knee surgeons routinely consider presurgical clinical examination factors when determining the need for and timing of ACL reconstruction. Psychological factors should also be considered prior to surgery, during rehabilitation, and during sports return decision making as they can and do influence postsurgical outcomes [8, 50]. Psychological factor screening should be performed in conjunction with criterion-based functional testing. Many questions exist regarding psychological factors, patient function, and how these variables interact following ACL reconstruction and rehabilitation. Self-efficacy, fear of movement, and knee reinjury risk appraisal represent significant psychological influences on the success of ACL reconstruction and rehabilitation [31, 90, 91]. Preinjury activity level may be the largest determinant in the probability of returning to the desired postsurgery activity level.

Patients with high preoperative self-efficacy tend to maintain high levels through rehabilitation. Higher self-efficacy relates to greater perceived knee function, postoperative sports activity levels, and knee-related quality of life [96]. Men, younger patients, and patients with acute knee injuries have higher self-efficacy levels than women, older patients, and individuals with more chronic knee injuries.

Research is needed to better identify how self-efficacy-developing interventions might improve patient psychological deficiencies, thereby improving outcomes and satisfaction. We need to better determine the most effective temporal sequence for intervening with different modeling, cognitive processing, and imagery methods in conjunction with physical function achievements such as developing lower extremity neuromuscular control and dynamic knee stability. This will reduce kinesiophobia and reestablish a more rational knee reinjury risk appraisal. Developing a better understanding of the situational and temporal context to patient's psychological responses following athletic injuries, postsurgery, and at different phases during rehabilitation is needed to improve intervention effectiveness. There is a tremendous need for research in this area to better guide clinical interventions.

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Part II

Clinical Practice: The Problem – The Solution

Acute Anterior Cruciate Ligament Tear Surgery: Repair Versus Reconstruction – When?

18

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Contents

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18.1 Introduction

Injuries to the anterior cruciate ligament (ACL) of the knee are exceedingly common, affecting an estimated 100,000–200,000 patients each year in the United States alone. Patients with an ACL injury typically present in the acute setting with a recent trauma, pain, hemarthrosis, and potential early instability of the knee. A decision regarding treatment of a complete ACL tear is based on the patient age, health, activity level, and functional goals. In older patients or those willing to modify their activities, nonoperative treatment is an option. In younger or active patients unwilling to modify activities, then surgery is recommended to restore stability and function to the knee. Numerous treatments for operative management have been described including primary surgical repair, "healing response" marrow stimulation techniques, and ACL reconstruction with autograft or allograft [4, 15, 36]. Patients with partial-thickness ACL tears or skeletally immature patients represent different clinical entities and thus are addressed individually at the end of the chapter.

18.2 History and Evidence

Initially, attempts at primary repair of the ACL demonstrated failure to heal in both clinical and experimental animal studies [7, 10]. Failure of the repair to heal or continued instability and laxity were noted in 42–94 % of patients [14, 18, 34].

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These results were in stark contrast to other ligaments in the knee, such as the medial collateral ligament (MCL), which had been shown to heal consistently with nonoperative measures [33]. Failure was attributed to the local environment of synovial fluid [6], specific cellular deficiencies [1], and changes in cellular metabolism with the cells being less responsive to cytokine stimulation [19, 24]. The lack of demonstrated healing in primary ACL repair caused this procedure to be largely abandoned in favor of ACL reconstruction either with a cadaveric allograft or autograft. Due to the concomitant development of the arthroscope, arthroscopically assisted reconstruction became widely popular. ACL reconstruction provided excellent functional results with a low complication rate [4]. Although debate continues on the most appropriate graft choice, tunnel position, and number of bundles, arthroscopically assisted reconstruction has subsequently become the accepted "gold standard" for treatment of acute complete ACL injury.

Despite the positive reported clinical and biomechanical results of ACL reconstruction, arguments have arisen against reconstructing the ligament. The first was that using a graft to substitute for a native, healthy ACL would require prolonged periods of immobilization for revascularization. This argument was contradicted early on as Paessler et al. showed healing of ligaments in the setting of a full functional range of motion [30] and as Noyes recommended early motion after arthroscopic and open ACL reconstructions [28]. Other issues included the donor site morbidity from harvesting an autograft and the potential for disease transmission from an allograft with the additional associated cost of cadaveric tissue. Excision of the native ACL also removes the normal neurogenic and proprioceptive functions of the ligament as its nerve fibers are not replaced by the graft. Finally, and most importantly, more recent evidence has demonstrated that even modern, more anatomic single- or double-bundle reconstructions do not always restore the native kinematics of the knee [41]. This lack of normal kinematics has been theorized to play a role in the relatively high incidence of osteoarthritis seen in patients with ACL tears, even after reconstruction [41]. The development of osteoarthritis has also been clearly linked to associated meniscal injury at the time of ACL tear and subsequent meniscectomy [25].

There are few studies directly comparing the different options for treatment of an ACL tear and a paucity of level I evidence. A prospective level I 16-year follow-up by Drogset et al. compared primary ACL repair vs. ACL repair augmented with a synthetic ligament vs. repair augmented with a bone–patellar tendon–bone autograft [13]. In this study of complete ACL tears, the rate of revision was significantly higher (24 % vs. 2 %) in the primary repair group than the group augmented with autograft. In addition, the knees treated with autograft were significantly more stable than those which were not. Eleven percent of the operative patients developed osteoarthritis in the operative knee. Another randomized study showed better function and stability of the knee with repair plus augmentation with the iliotibial band over repair alone or nonoperative management; however, this technique for augmentation (reconstruction) is seldom used today [5]. A systematic review of single-bundle ACL reconstruction in 2008 reviewed 11 studies and 1,024 ACL reconstructions [23]. The overall graft failure rate was 4 %, the complication rate was 6 %, and the development of osteoarthritis was seen in 7 %. Pivot shift testing was negative in 81 %, Lachman testing negative in 59 %, and KT – 1000 difference was <5 mm in 86 % of cases. The authors' conclusion was that single-bundle ACL reconstruction yields a safe, consistent surgical procedure with reliable results.

Although the longest follow-up on primary ACL repair (level IV evidence) demonstrated unsatisfactory results [39], many advances have subsequently been made in understanding the injury and healing process. Studies have demonstrated differences in the cellular response to intra-articular ligament injury as compared to extra-articular injury [42] and have shown the cruciate ligaments to be less responsive to cytokine stimulation [2]. This observation led to the development of marrow stimulation "healing response" techniques to deliver mesenchymal and other progenitor cells and cytokines to aid in healing of intra-articular ligament injuries. An initial study by Rodkey et al. demonstrated a more cellular and more organized extracellular matrix in posterior cruciate ligament (PCL) tears treated with marrow stimulation vs. those in a nonstimulated group [32]. Subsequent clinical studies demonstrated good results with a healing response technique in specific subsets of patients on both ends of the age spectrum (skeletally immature [36] and those aged >40 years old [37]). Further studies in animals and humans demonstrated that there was no provisional scaffold or wound site filling between ends of a ruptured ACL [26, 27]. This research has led to the development of a collagen–platelet composite scaffold to augment ACL suture repair [17]. While this model has shown improved healing and biomechanical properties with increased cellularity in animals, this technique has yet to be studied in humans. However, the recent demonstrations of ACL healing in animals may translate into new areas of study and methods of treatment in humans in the future.

18.3 Complete ACL Tears

For patients with acute ACL tears, surgery is recommended if they are unwilling to modify their activities (Fig. 18.1). For functional goals of cycling, swimming, or walking, patients may do well without ACL surgery. However, if the patient wishes to return to higher-demand cutting-, running-, or jumping-type activities, then surgery should be considered. Although anatomic ACL reconstructions are generally considered the preferred treatment for complete ACL tears in skeletally mature patients, debate continues on whether there is a better option to preserve the native ACL. In our practice, we treat complete ACL tears with either reconstruction of a minimally invasive "healing response" repair.

For younger, high-demand patients (<40 years old), we often prefer an ACL reconstruction using an ipsilateral bone–patellar tendon–bone autograft or allograft. This graft provides good strength and allows for bone-to-bone healing [31]. We perform a two-incision technique for drilling of the femoral tunnel to ensure accurate anatomic placement of the tunnel. Our preferred method of fixation is a 9-mm interference screw at the femoral and tibial interface placed over guidewires. Criteria for performing an ACL reconstruction in the acute period include the following: (1) ability to perform a straight leg raise similar to the uninjured side with no loss of extension, (2) a minimum active range of motion of 0–120°, (3) active quadriceps control, and (4) a minimal skin temperature difference between knees. To create a successful anatomic ACL reconstruction, we adhere to the following principles: (1) anatomic tunnel position, (2) adequate fixation to allow early range of motion, (3) adequate graft strength, and (4) avoidance of impingement. A systematic review has demonstrated that single-bundle ACL reconstruction is a safe and effective procedure with good functional results in patients with an average age of 27 years [23].

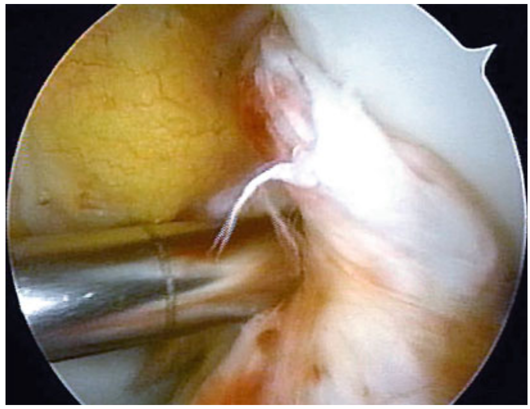

Fig. 18.1 Intraoperative photo of a complete ACL tear

The choice of graft type has long been debated in the literature. While studies suggested that autografts and allografts yielded comparable results [11], initial animal studies showed a slower incorporation of allografts [16], and later data suggested that allograft reconstructions had a higher failure rate [35, 38]. It was also demonstrated that allografts had a much higher failure rate in a highly active population as compared to a lower-activity group and both a high- and low-activity group with autograft [8]. A recent meta-analysis of 534 ACL reconstructions found that autograft was favored over allograft for both graft

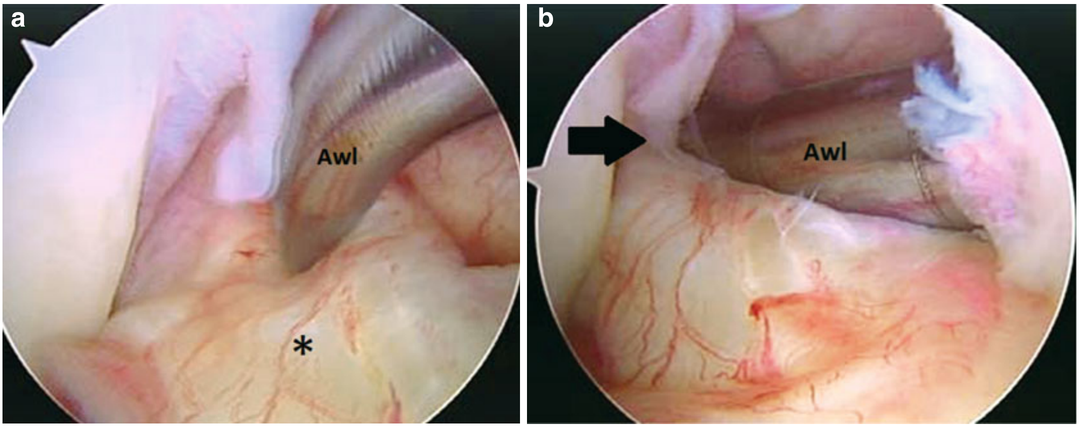

Fig. 18.2 (**a**) Intraoperative photo demonstrating a healing response procedure with punctures being made in the remaining ACL (*asterisk*) with a 45° awl. (**b**) Intraoperative photo of a healing response procedure illustrating the use of a 45° awl placed perpendicular to the femoral attachment of the ACL to make holes in the subchondral bone (*arrow*)

rupture and hop test parameters; however, when irradiated and chemically processed grafts were excluded, there was no significant difference between groups [22]. With the current available data, we believe that both autografts and allografts are viable options for ACL reconstruction. In our practice over the past 5 years, we have used mostly allografts (90 %) and have reserved autografts (10 %) for the very young and extremely active patients and for those patients requesting autograft. We feel that either graft will yield excellent clinical results, and use of allograft negates the donor site morbidity seen with autograft.

For older patients (>40 years old) who want to return to sports and activity, we recommend a minimally invasive healing response. This technique is a less invasive procedure without the potential complications of an autograft harvest or allograft implantation. This procedure is performed by using an arthroscopic microfracture awl with a 45° angle, keeping the tip of the awl perpendicular to the femoral attachment of the ACL. Eight to ten holes are made (3–4 mm deep, 3-mm diameter) in the cortical bone at the femoral origin of the ACL (Fig. 18.2). About 25 punctures are then made in the remaining native ligament at the distal stump and throughout the course of the ligament to aid in invasion of the blood clot. A recent series by Steadman et al. [37] demonstrated a high level of patient satisfaction, good knee function, and a return to recreational activities with a healing response procedure in 48 patients at an average of 7.6 years follow-up. All patients had a complete proximal tear of the ACL and were all over the age of 40 years (Fig. 18.3). For older high-demand patients with a complete midsubstance or distal tear, we proceed with an ACL reconstruction with an allograft.

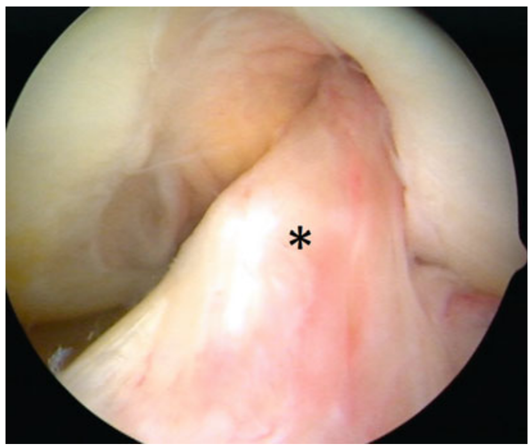

Fig. 18.3 Appearance of the healed ACL (*asterisk*) at a second-look arthroscopy 6 years after a healing response procedure revealing complete healing of the ligament

18.4 Partial-Thickness ACL Tears

Although most patients with an ACL injury sustain a full-thickness tear of both bundles of the ligament, there are subsets of patients who present with partial-thickness tears (Fig. 18.4). A partial-thickness ACL tear may or may not result in functional instability. A tear without functional instability has been defined by DeFranco and Bach as a knee with an asymmetric Lachman test, a negative pivot shift test with the patient under anesthesia, a low-grade KT-1000 measurement (<3 mm), and arthroscopic evidence of an ACL injury [12]. A partial tear that results in functional instability presents similarly to a full-thickness tear and may only be differentiated on magnetic resonance imaging (MRI) or arthroscopy. Although MRI is sensitive and specific for diagnosing ACL injury, partial tears may still be difficult to tell from full-thickness tears (Fig. 18.5). A patient with a partial-thickness tear (or single-bundle rupture on MRI) and a positive pivot shift test is considered to have functional instability. In many instances, patients with either partial- or full-thickness tears will have an asymmetric Lachman examination [12].

Similar to above, our treatment algorithm for patients with partial-thickness tears includes determining the functional goals of the patients and whether or not they are likely to progress to functional instability due to the high demands placed on the knee. In a lower-demand patient with limited functional goals, nonoperative treatment may be appropriate, perhaps preferable. In a patient with high demands or one with a partial tear and functional instability, we typically recommend operative intervention. A study by Noyes et al. estimated that 50 % of patients with a partial-thickness ACL tear would progress to complete ACL insufficiency when the tear affected more than half of the ligament [29]. Another study showed that arthroscopically confirmed acute partial tears progressed to full tears in the chronic setting [9]. It is clear that partial tears may progress to full-thickness tears and quite possibly to subsequent degenerative joint disease. However, at present there are limited studies with insufficient data to ascertain the natural history of partial ACL tears on the development of future osteoarthritis.

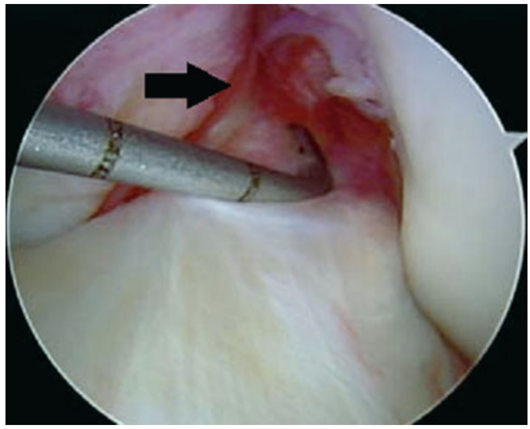

Fig. 18.4 Intraoperative appearance of a proximal partial-thickness ACL tear (*arrow*)

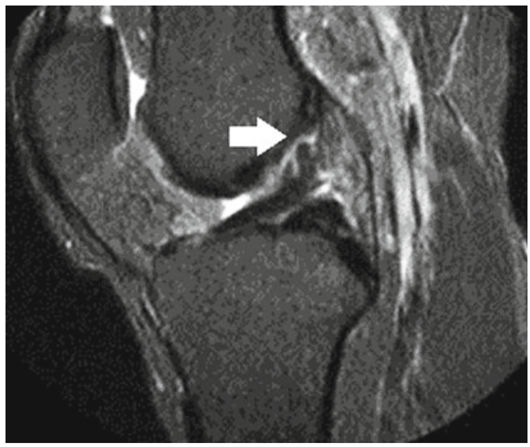

Fig. 18.5 T2-weighted sagittal MRI image demonstrating a proximal partial ACL tear (*arrow*) that is difficult to differentiate from a full-thickness tear on MRI alone

If the clinical diagnosis is questionable, then examination under anesthesia is first performed to assess anterior translation and a pivot shift without the patient guarding. Our preferred operative management of these injuries is a diagnostic arthroscopy to evaluate the ACL and a “healing response” marrow stimulation procedure. If there is an obvious discrete partial tear that is reparable, then we will perform primary suturing of the torn ACL fibers to the intact remainder of the bundle. This technique has recently been shown to restore knee stability and function in a group of 26 athletes [15]. If there is elongation only or intrasubstance tearing, we then proceed with a marrow stimulation response only. In our experience, these techniques have led to good functional outcomes in high-demand patients, allow the proprioceptive abilities of the native ligament to be preserved, and avoid the morbidity of an autograft harvest. In addition, marrow stimulation with or without primary repair does not “burn any bridges” for a future reconstruction should the patient reinjure the ligament or have continued instability.

18.5 Skeletally Immature Patients

Historically, treatment of complete ACL injuries in the skeletally immature population were treated nonoperatively with bracing, functional rehabilitation, and activity modification. This treatment algorithm was developed to avoid transphyseal drilling in an attempt to prevent damage to the growth plate. Once the patient was skeletally mature, they would then undergo an ACL reconstruction if they remained symptomatic. More recently physeal-sparing techniques have been developed including intra-articular and extra-articular reconstructions [21] and transepiphyseal reconstructions [3]. A systematic review of ACL injuries in skeletally immature patients by Vavken and Murray demonstrated universally poor outcomes with nonoperative treatment including a high incidence of secondary meniscus and cartilage injury [40]. Surgical techniques including intra-/extra-articular reconstruction, transepiphyseal drilling, and transphyseal drilling were all found to have superior outcomes to nonoperative treatment. In addition, no growth disturbances were found in the physeal sparing, and only weak evidence exists for growth disturbance for transphyseal drilling if the tunnels are placed in the correct position.

In skeletally immature patients with partial proximal ACL tears, Steadman et al. have shown good restoration of knee stability and function with a minimally invasive “healing response” procedure [36]. Ten of thirteen patients seen in follow-up had an average patient satisfaction of 9.9/10 with improvements in the pivot shift test and KT-1000 testing. Three patients reinjured the involved ACL after healing and went on to have a subsequent reconstruction. No growth disturbances were reported in this series.

Currently, our algorithm is to recommend operative management on all skeletally immature patients presenting with a symptomatic ACL injury to prevent the known secondary injury to the menisci and articular cartilage. In patients with a proximal partial tear, we opt for a minimally invasive marrow stimulation “healing response” to promote healing of the native ACL and avoid any risk of growth disturbance. This technique has been shown to have excellent results without risk of physeal damage or angular deformity. If a patient should retear the healed ACL, we then would proceed with a full ACL reconstruction, with the technique dependent on patient age and Tanner stage as detailed below.

In skeletally immature patients with a complete ACL tear or retear after a “healing response” procedure, we then proceed with ACL reconstruction. The technique is dependent on the level of maturity of the patient. In prepubescent children (Tanner stage 1 and 2), we recommend a physeal-sparing approach secondary to the amount of growth remaining with wide-open physes. This technique is performed as described by Kocher et al. using an iliotibial band graft and a combined extra-articular and intra-articular arthroscopically assisted reconstruction [20]. This technique was initially described as a temporizing measure until skeletal maturity, but follow-up data have demonstrated satisfactory results equivalent to transphyseal techniques; thus, it is a definitive procedure for many patients [20]. For older patients with open physes (Tanner stage 3 and 4), we recommend a “healing response” marrow stimulation procedure vs. possible physeal-sparing iliotibial band reconstruction. For these patients where some growth remains, we will typically use a “healing response” marrow stimulation technique as the procedure of choice. If a patient fails this procedure and still has growth remaining, we would consider a physeal-sparing iliotibial band reconstruction as described above. In our practice, we avoid placing a graft across the physis if there is any significant growth remaining to avoid a growth

Table 18.1 ACL repair vs. reconstruction summary

Maturity	Complete tear	Partial tear
Skeletally immature		
Tanner stage I/II	Physeal-sparing intra-articular and extra-articular reconstruction	Healing response
Tanner stage III/IV	Healing response vs. physeal-sparing intra-articular and extra-articular reconstruction	Healing response
Tanner stage V (physes closed)	ACL reconstruction with bone–patellar tendon–bone autograft	Healing response vs. ACL reconstruction
Skeletally mature		
Age < 40	ACL reconstruction with bone–patellar tendon–bone autograft vs. allograft	Healing response vs. ACL reconstruction
Age > 40	Healing response (for proximal tears) vs. ACL reconstruction with allograft (for midsubstance or distal tears)	Healing response

disturbance or angular deformity. If a patient continues to have symptoms after puberty and the completion of growth, we treat them like an adult. For Tanner stage 5 patients who are postpubescent and the physes are closed, we use a bone–patellar tendon–bone autograft with interference screw fixation similar to the technique described in adults. Since these patients have finished growing, the possibility of a fixation device or bone plug crossing the physis and causing leg length discrepancy or angular deformity is negligible.

18.6 Summary

We believe and have experienced that both reconstruction and repair are viable options for treatment of patients with ACL injuries. Patient age, activity level, functional goals, and skeletal maturity should be carefully considered when making a decision of repair vs. reconstruction. The extent of injury to the ligament (complete vs. partial tear) and location of injury (proximal vs. midsubstance vs. distal) must be determined by physical examination and imaging to make an informed decision. Current evidence supports both techniques in specific patient populations, and our recommendations for when to perform each treatment are summarized in Table 18.1. Operative management of ACL injuries restores knee stability and allows patients to return to a high level of activity. Continuing research will yield more answers in terms of the best procedures and the long-term consequences of each.

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19 Partial Chronic Anterior Cruciate Ligament Tears: What to Do

Joan Carles Monllau, Pablo Eduardo Gelber, Xavier Pelfort, Juan Erquicia, Marc Tey, and Vicente Sanchis-Alfonso

Contents

19.1 Introduction

Do partial tears of the anterior cruciate ligament (ACL) really exist? Its definition has been characterized differently over the last few decades. Wide ranges of incidence have also been reported. It has been remarked that there are subtle and nonconclusive differences in the clinical presentation. It has been said that there is no definitive diagnosis with any imaging modality. It has also been suggested that arthroscopic examination by an experienced surgeon is indispensable for a correct diagnosis. Finally, no conclusive advantage over traditional ACL reconstruction has yet been demonstrated. Therefore, do the ACL partial tears really exist? If they do exist, it raises a number of relevant questions. Should they be operated on? If so, should an augmentation procedure instead of a traditional reconstruction be performed and how should they be done? The main purpose of this chapter is to provide answers to all the aforementioned interrogatives.

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19.2 Anatomy and Biomechanics Considerations

Early descriptions of the two functional bundles of the ACL, the anteromedial (AM) and the posterolateral (PL) bundles, date back to the anatomic study performed by the Weber brothers [55]. Late in the 1970s, a detailed functional analysis of the two bundles [22] and even a third intermediate bundle was described [40]. The aforementioned 40 year-old papers have already sighted the importance of considering the two distinct bundles in reconstruction, substitution, or the replacement of the ACL. However, those studies focused on the importance of the ACL ligament against largely anteriorly directed forces. More recently, biomechanical studies have shown that the ACL ligament and more especially the PL bundle also contribute to the control of rotational stability of the knee joint [59].

It is now widely recognized that the ACL does not behave as a single band of fibers with constant tension. Although each collagen fiber that makes up the ACL seems to function in a slightly different manner from each other, a separation of the ligament into two big fiber bundles is currently accepted as the basis for understanding ACL function [5]. The anteromedial bundle is taut throughout the range of motion of the knee, reaching a maximum tension between 45º and 60º. On the other hand, the PL bundle is primarily tight in extension [23, 49]. It is between 20º and 30º of knee flexion when both bundles carry approximately the same load [38]. The configuration of the two bundles allows them to work together to provide not only the anteroposterior but also the rotational stability of the knee.

19.3 Definition

19.3.1 Controversies

Recently, Colombet et al. [15] have highlighted the difficulty in finding universal agreement as to the best definition of partial ACL tears. Whereas Noyes et al. [41] defined a partial tear as those involving less than 25 % of the ligament. Hong et al. [27] considered partial ACL tear as those which show less than 50 % of the fibers torn.

However, is this estimation of the percentage of fibers torn reliable or accurate enough? A potential cause of controversy is that isolated ACL bundles tears are usually difficult to diagnose even during arthroscopic surgery performed by experienced surgeons. Anatomic, biomechanical, and arthroscopic definitions take the same approach and converge in the most currently used definition. The aim is to distinguish the intact and functional bundle from the injured and nonfunctional ACL bundle.

The American Medical Association for Athletic Injuries [4] has proposed a clinical definition of ACL tears. A partial ACL rupture corresponds to the second degree: moderate sprain caused by direct or indirect trauma to the knee joint. The patient presents with moderate disability, joint tenderness, moderate abnormal motion, swelling, hemorrhaging, moderate loss of function, and a tendency to recurrence.

DeFranco and Bach [19] proposed a multifactorial definition with an asymmetric Lachman test, a negative pivot shift, differential KT-100 laxity equal to or less than 3 mm, and the results of an arthroscopic examination. We believe this is the way to better classify partial ACL tears. However, a clear anatomical definition is needed. This will aid surgeons in properly treating these injuries.

19.3.2 Anatomical Definition

Ihara et al. [28] and Fujimoto et al. [21] have suggested that scar tissue remnants of the ACL may help stabilize the ACL-deficient knee. Although Lawrence et al. [34] had already described the anatomic definition of a partial tear as the direct arthroscopic visualization of a tear of the ligament confined to either the AM or PL bundles in 1996, Crain et al. [18] were the first to describe, in detail, that some specific ACL remnants contribute to a partial stabilization of the knee. In that clinical study, variations in the ACL scar pattern and their relationship with the anterior laxity in 48 patients were arthroscopically examined.

Interestingly enough, they were not aware that they were describing PL and AM partial tears. They described AM tears as ligament scarring to the medial aspect of the lateral femoral condyle in 12 % of the patients. Increased anterior laxity of an average 4.3 mm after resection of these remaining fibers (PL bundle) was observed. The PL bundle ruptures were described as remnants of the ligament that had healed to the roof of the notch in 8 % of their patients. Anterior tibial displacement rose up 3.4 mm after resection of these fibers (AM bundle). This is in agreement with the study performed by Maeda et al. [36]. They intraoperatively evaluated 120 patients at different knee flexion angles with a precise navigation system. They only found increased laxity after a resection of "ACL remnants bridging the lateral wall of intercondylar notch with the tibia" (PL bundle) at 15° of knee flexion. This is biomechanically logical as the PL bundle is a restraint on anterior tibial translation near full extension. Conversely, they did not find any stabilizing role of ACL remnants that bridge the roof of the intercondylar notch and the tibia, which might be interpreted as an AM bundle remnant. However, analyzing their drawings and arthroscopic images, the remnants were attached to a nonanatomic position in these cases. It continues to be difficult to determine when a single-bundle remnant is functional or not. Again, a combination of a clinical, a radiological, and an arthroscopic evaluation by an experienced surgeon are all necessary.

Colombet et al. [15, 16] classified the observed ACL remnants in four different types:

- Totally disappeared ACL, in 50 % of the cases
- Healing to the PCL, in 23 % of the cases
- PL bundle conservation, in 16 % of the cases
- AM bundle conservation, in 11 % of the cases

Although some surgeons doubt that a pure partial rupture can occur, there have been several reports in the literature relative to the matter. Incidences of injury have been reported from as low as 5 % [32] to as high as 25 % [58] of the total ACL tears.

Although the relative incidences of each type may vary, it is the author's opinion that the anatomic definition is the way that ACL remnants should be currently classified.

19.4 Rationale for Partial ACL Tears

The reciprocal tension pattern of the AM and PL bundles suggests that partial tears may affect individual bundles depending on the knee flexion angle at the time of injury [5]. The different roles of the two bundles in providing rotational stability might also explain an isolated rupture of only one bundle. Adachi et al. [1] interviewed 121 patients and concluded that AM bundle ruptures seem to involve a more explosive type of trauma that is predominantly sustained in the anterior direction, whereas a PL bundle tear might involve a less energetic pivoting injury with a rotation component.

It has been recently shown that a reconstruction technique that addresses both bundles of the ACL provides better rotational stability than do techniques that address only one of the two bundles [57]. Therefore, it seems logical that the intact bundle may be preserved and only the torn bundle undergoes reconstruction in patients with a partial rupture of the ACL.

Saving ACL remnants during ACL reconstruction may have some biomechanical, vascular, and proprioceptive advantages for the patient. First, ACL remnants may add biomechanical strength to the reconstruction in the immediate postoperative period, while graft strength primarily depends on the fixation device. In this period, the augmentation may be protected by the intact bundle and may allow accelerated rehabilitation and an earlier return to sport. However, conclusive scientific data to support early return to sport of these patients is still lacking.

A second advantage may be that the residual portion of the ACL may maintain its blood supply (Fig. 19.1), providing a support for the healing process of the graft. Bray et al. [11] showed that surgically induced partial injuries induce significant increase in blood flow and vascular volume in an animal model. It is still to be proven that the time interval for maturity and remodeling is shorter following partial reconstruction.

Saving ACL fibers may also maintain some proprioceptive innervation of the ACL. The human ACL is extensively innervated, and neural elements comprise approximately 1 % of the

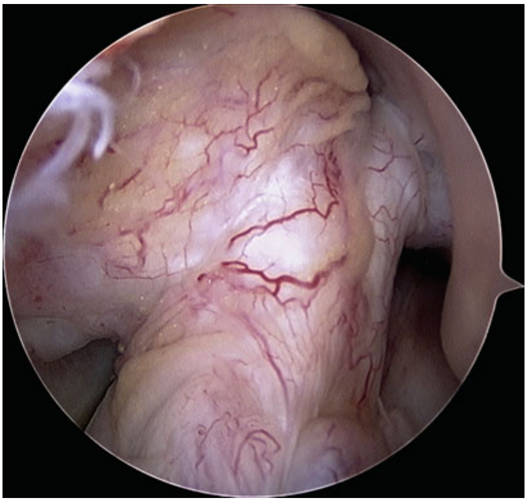

Fig. 19.1 Arthroscopic view of a left knee with an isolated tear of the anteromedial bundle. The remnants of the ACL with its intact vascularity might provide a support for the healing process in the graft

area of the ligament [45]. In theory, keeping ACL remnants maintains increased joint proprioception that may allow a faster return to sport. Proprioception of the knee has been measured in various ways. An ACL-deficient knee has been repeatedly reported as deficient in proprioceptive function [8, 9, 14, 17]. However, the lack of ACL partial rupture specific studies, plus the difficulty in objectively assessing the proprioception status of the patient still make this an unresolved issue.

Finally, intact fibers may also allow optimized accuracy of bone tunnel placement at the insertion sites. The bundle may serve as a guide for orientation and a point of reference for the proper placement of the graft

19.5 Diagnosis

The diagnosis of a partial ACL tear remains a significant challenge. A partial ACL rupture may be suspected from the physical examination. MRI evaluation is another useful tool that sometimes helps in diagnosing a one-bundle tear. However, a tear of a single bundle can only be confirmed arthroscopically.

19.5.1 Clinical Examination

In a recent biomechanical experiment, Akgun et al. [2] resected the fibers of the AL and PL bundles in an alternating order. They observed that after isolated AM bundle transection, the anterior-drawer test and Lachman test were highly positive, whereas pivot-shift test was always negatives. On the other hand, isolated PL bundle-resected knees an anterior-drawer test and Lachman test were usually negative, whereas the pivot-shift maneuver was always positive. Although this pure split of only one of the two bundles is only feasible in an experimental model, it gives a comprehensive idea of the physical examination of isolated bundle tears.

Unfortunately, patients with a symptomatic AM or PL bundle tear habitually complain of nonspecific symptoms like recurrent pain and swelling in clinical practice. Intraoperative biomechanical evaluation of complex motion during the pivot-shift test with a navigation system has recently shown that the AM bundle can also control both rotation and translation during the pivot-shift test at a level similar to the PL bundle [31]. It is true that patients with a symptomatic AM bundle tear commonly describe anterior instability during day-to-day activities and during sports activity, similar to a complete ACL tear. They usually show a highly positive anterior-drawer test at 90º of knee flexion and a KT-1000 side-to-side difference between 2 and 4 mm. Due to the uninjured PL bundle, the Lachman test at 30º of knee flexion is rather small (although with a soft endpoint), and the pivot-shift test is usually negative. However, it is not uncommon to observe some gliding in the pivot-shift test. This may confuse the evaluating clinician as to which of the two bundles is most probably injured. Again, arthroscopic assessment will finally define the rupture pattern. After chronic AM bundle rupture, extension deficit secondary to a Cyclops syndrome may also be observed [29, 54]. This is due to a pedunculated nodule of the AM bundle remnant impinging against the intercondylar notch near full extension.

In contrast, patients with a symptomatic PL bundle tear complain of rotational instability with pivoting rather than complaining of a significant anterior instability. Nonpivoting sports activity might still be performed by the patients without major problems, but pivoting sports (e.g., soccer, basketball) have to be given up because of recurrent problems with rotational instability. The pivot-shift maneuver is usually positive in those patients with limited anterior displacement as seen in anterior-drawer and Lachman tests. This explains the usually encountered small side-to-side differences with the KT-1000 device. In some occasions, locking, which limits flexibility and exercise of knee joint, can occur as a result of isolated tear of the PL bundle on the femoral attachment [13]. This is more commonly observed when the mechanism of injury is a hyperextension of the knee joint and internal rotation of the lower extremity caused by a low-speed impact while the foot is in a fixed state.

In summary, an isolated AM bundle tear displays AP laxity, but (usually) only a gliding shift. Conversely, an isolated PL bundle rupture shows (more commonly) a large pivot shift, but only a 1+ Lachman.

19.5.2 Laximetry

Quantitative assessment of anterior tibial translation has proven to be imprecise, subjective, and poorly reproducible even in complete ACL tears [10, 56]. The most widely used laximeter in the world is the KT-1000 (MEDmetric® Corporation, San Diego, CA, USA). It is an operator-dependent device. It has a degree of precision of approximately 1 mm. It is also highly reproducible with a 3-mm threshold, but only when it is used by an expert rater. Its use may provide up to 50 % of false-negative results that are mainly due to a subject's involuntary or defensive hamstring contraction [30]. It may be theorized that the accuracy for detecting partial ACL tears might be even lower. The recently developed GNRB laximeter GeNouRoB (Laval-France) GeNouRoB (Laval - France) allows for a more reproducible evaluation of anterior laxity. The GNRB has also shown a 0.1-mm precision and a 1.5-mm threshold value for partial tears with 80 % sensitivity and 87 % specificity. Thus, the GNRB might help with a more precise diagnosis and clinical follow-up of partial (and complete) ACL tears [43].

In the clinical situation, rotational instability can be assessed with the pivot-shift test. It seems likely that a positive pivot shift might be considered to be an indicator of a rupture of the PL bundle. This theory is supported by our clinical experience in treating patients who present with recurrent rotational instability after standard single-bundle ACL reconstruction with a vertical graft placed posteriorly on the tibia and high in the notch. In such patients, the pivot shift is positive in a high proportion of patients, the Lachman test is usually negative or slightly positive, and the anterior-drawer test is negative. Similar findings have been observed in patients with isolated rupture of the PL bundle. However, this clinical situation is sometimes found in isolated AM bundle tears or even in complete ruptures of the ACL with some of its remnant healed to the posterior cruciate ligament (PCL). Again, arthroscopic examination is mandatory before diagnosis of isolated bundle tears of the ACL can be made.

In addition, a clinical study validating the pivot-shift test, the Lachman test, and the anterior-drawer test for the detection of isolated bundle tears has never been performed. We are currently using a noninvasive pivot-shift accelerometer, which objectively compares the injured knee with the contralateral knee (KIRA device, Orthokey, Italy). However, the device has not been validated for differentiating partial from complete ACL ruptures yet.

In conclusion, although some advances have been made in recent years, no current assessment tool can diagnose the separate integrity of the individual ACL bundles with a reliable accuracy.

19.5.3 Magnetic Resonance Imaging

Magnetic resonance imaging (MRI) is well known as a sensitive and specific tool for diagnosing a complete ACL rupture. The double-bundle structure of the intact ACL may be seen in a standard view on the sagittal and coronal planes

Fig. 19.2 Coronal view of 1.5-T magnetic resonance imaging. In some standard sequences, the two bundle structure may be distinguished. *AM* anteromedial bundle, *PL* posterolateral bundle

(Fig. 19.2). However, a clear discrimination of the two bundles might often be very difficult. Back in the 1990s, Umans et al. [50] defined the criteria for a partial ACL tear when evaluating the MRI images. They classified a tear of the ACL as partial when, in absence of secondary signs of complete ACL tear, one of the following was observed: (1) abnormal intrasubstance signal intensity with definable intact ligament fibers in continuity between femoral and tibial attachments, (2) a bowing or an undulating contour of otherwise intact ACL fibers, or (3) nonvisualization of the ACL on T1-weighted spin-echo sequences with concomitant discernible intact ACL fibers on either short-tau inversion recovery (STIR) or gradient-recalled echo sequences. They also evaluated the sensitivity and specificity of different experienced radiologists when analyzing standard sagittal and coronal 1.0 or 1.5 T views. Although they observed a high agreement between readers with a kappa greater than 0.75, sensitivity was in the low range of 0.40–0.75. Sensitivity did not show much better performance with a poor range of 0.62–0.81. This was in agreement with the Lawrence et al. study [34]. They compared the results of the original MRI reports with the arthroscopic findings. The only observed agreement in one of the nine cases of partial tears was confirmed arthroscopically. When the images were reviewed after the arthroscopic procedure, they observed some identifiable fibers in the expected position of the ACL on at least one sequence in all cases. Furthermore, they observed that the ligament was wavy or curved in some cases or it even seemed intact in one case.

In line with these findings, Roychowdhury et al. [44] suggested that standard 1–1.5-T axial MRI images could aid in differentiating those partial tears of the ACL leading to a stable or unstable ACL. This was relevant as far as the principal matter in partial ACL ruptures used to be relative to how much of a percentage of the ligament was intact and its relationship to the progression to a complete deficiency [41]. They concluded that when an elongated but smooth ellipse, an attenuated ACL (i.e., narrower mediolateral waist) or when an increased intrasubstance signal intensity are observed on axial MRI images, it is expected to have a stable ACL with either an intact ACL or a partial rupture. Again, they were unable to distinguish between normal ACLs and stable partial tears or complete ACL ruptures from unstable partial tears.

A recent study evaluating the MRIs of 51 patients with an arthroscopically confirmed ACL partial tear was in concordance with previous works [51]. They define a hyperintense signal within the ACL substance, distortion of fibers without obvious discontinuity, attenuation, and/or abnormal orientation of the ACL with respect to Blumensaat's line as magnetic resonance signs of a partial ACL rupture. They reported that if fiber disruption could clearly be detected in the AM or PL bundle of the ACL, an isolated bundle tear could be reported. They reported standard MRI accuracy for the diagnosis of partial tears as low as 25–53 %. They also observed a moderate interobserver agreement. In addition, they observed that one out of five patients with an MRI diagnosis of complete ACL rupture had a partial tear at arthroscopy. Furthermore, some so-called delaminated partial tears cannot be distinguished from those finding accompanying mucoid degeneration of the ACL. Finally, they also concluded that locating a tear in a particular bundle of the injured ACL is seldom possible.

Standard coronal, sagittal, and axial images are the most frequently used MRI images. Although it has been shown that 1.5-T MRI did not improve the accuracy of diagnosing ACL tears comparing to 0.5-T MRI [53], recent studies have proven the superiority of 3-T MR imaging. Currently, most radiologists divide their definition of ACL tears into partial and complete ruptures. However, their definition of partial tear differs widely from the anatomic definition that is recommended here. Van Dyck et al. [52] evaluated the accuracy of a high-resolution MRI in distinguishing between stable and unstable and partial and complete ruptures the ACL. They used the arthroscopic assessment as the gold standard. However, the surgeon defined partial tears as those that show ACL fibers remained in continuity and exhibited resistance to deformation upon physical probing. They did not, again, specifically designate tears in the AM or PL bundles. The study showed that the method had an accuracy of 67 %. This low rate was mainly attributed to the lower efficacy in the characterization of chronic ACL tears.

For isolated bundle ruptures of the ACL, it is helpful to describe the AM and PL bundle using MRI as it may improve the presurgical planning and even rehabilitation protocols might be more specific and cost effective. In this sense, the Freddie Fu group has shown that the characterization of the two distinct bundles [47] and diagnosis of isolated bundle tears [48] can be highly improved by establishing ideal oblique planes in combination with 3-T ultrahigh-field-strength MRI. They established an ideal angle of 32º in paracoronal imaging. These images allow a precise description of the insertion and orientation of the bundles. The oblique sagittal at an ideal angle of 18° was equally necessary for completely describing the anatomy and isolated bundle ruptures. They also did not find any additional benefits of axial images over the oblique coronal and oblique parasagittal views using the 3-T MRI. They also shortened the 3-T scan time to 35 min by choosing a fast spin echo imaging, which is usually longer than lower Tesla MRI.

In summary, a combination of 3-T ultrahigh-field-strength MRI with oblique coronal and parasagittal images are both necessary to improve the imaging diagnosis. On the other hand, standard coronal, sagittal, and axial images in lower Tesla MRIs have limited sensitivity, specificity, and accuracy in the diagnosis of isolated AM or PL bundle ruptures.

19.5.4 Arthroscopic Diagnosis

Even with an extensive preoperative clinical and radiological assessment, the exact injury pattern of an isolated AM or PL bundle tear can only be established arthroscopically. Nevertheless, a previous examination under anesthesia should be carefully performed. The pivot-shift test's sensitivity is largely improved under anesthesia. In fact, the pivot-shift test has only been validated as a useful test in anesthetized patients, because some patients are unwilling to undergo such testing while they are awake [7]. The visual aspect of the remnants is studied to confirm that remaining tibial and femoral fiber attachments are located inside the anatomic ACL footprints. However, even experienced surgeons sometimes find it difficult to diagnose a partial rupture. The quantity and state of the still intact fibers is usually difficult to assess. The best option is to switch the scope to the central portal so that the surgeon can get a direct view of the insertion. An AM bundle tear can be more easily diagnosed. In most cases, the AM bundle is torn from its femoral insertion site or midsubstance with the PL bundle intact or elongated. A thorough arthroscopic probing is necessary to precisely assess the injury pattern, especially on the femoral side. Both bundles have to be examined at various knee flexion angles to consider the different tension patterns of the two bundles. The AM bundle has relatively constant levels of in situ forces during knee flexion and might be best tested arthroscopically between 70º and 90º. In some cases, it is difficult to discern a difference between a PCL healing and a true intact AM

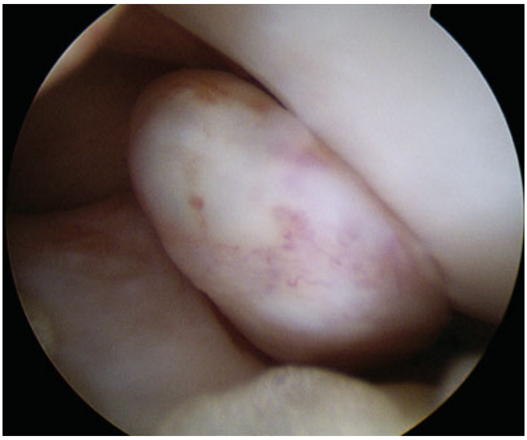

Fig. 19.3 Arthroscopic view of a left knee with an isolated anteromedial bundle tear near full extension. The pedunculated remnant leads to a Cyclops phenomenon

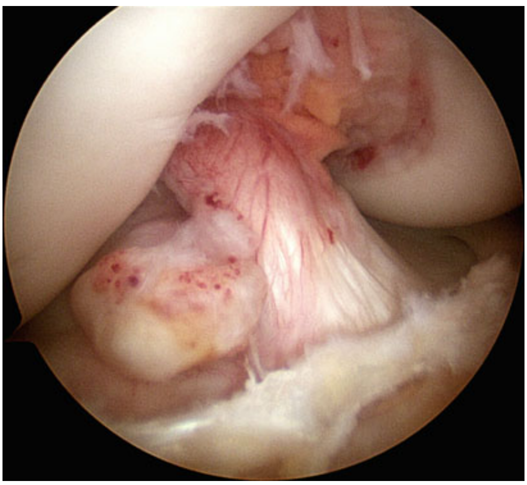

Fig. 19.4 Arthroscopic view of a right knee from a high anterolateral portal with an isolated rupture of the posterolateral bundle of the ACL

bundle. The anterior part of the ACL footprint can better be assessed near extension. This section of the insertion may sometimes look like a clapper placed under the intermeniscus ligament and may lead to Cyclops syndrome [29, 54] (Fig. 19.3).

Conversely, a PL bundle rupture (Fig. 19.4) is sometimes more easily missed when viewing from the anterolateral portal. In such cases, the AM bundle overlies the PL bundle, which can only be seen by retraction of the AM bundle with a probe. The greatest in situ forces of the PL bundle are

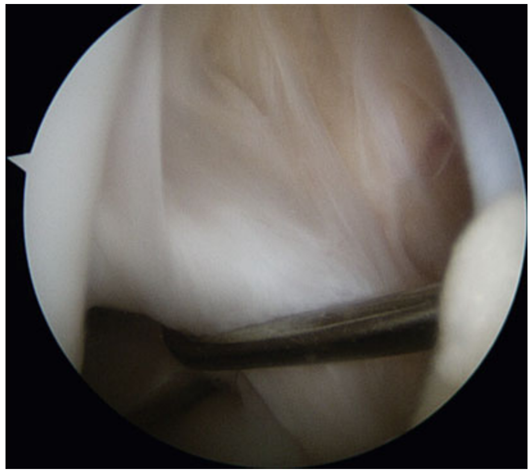

Fig. 19.5 Arthroscopic view of the posterolateral bundle with the knee in the figure-of-four position. Note this normal laxity of the PL bundle. This is not a sign of rupture because the posterolateral bundle is normally lax at 90º of knee flexion

seen between 0º and 30º of knee flexion, but the intercondylar notch cannot be examined arthroscopically close to extension. However, the PL is more easily identified when the knee is placed in the figure-of-four position. The PL bundle tightens up, and the femoral PL footprint is usually rotated and exposed in the anterior aspect of the intercondylar wall (Fig. 19.5). Bleeding and discontinuity are signs of rupture. A lax PL bundle is not a sign of rupture, because it is normally lax at 90º of knee flexion. This is crucial to avoiding overdiagnosis of PL bundle tears. The PL bundle is tight at full extension, and in this knee position, the ligament is difficult to visualize. We systematically perform what we call the *flexion-extension PL bundle test*. Firmly handling the probe under the PL bundle at 90º of knee flexion, the knee is progressively extended (See Video 1). In intact PL bundles, the extra-articular end of the probe will be forced in a downward direction due to the progressive tightening of the bundle. In contrast, when facing a PL bundle rupture, the probe will easily be kept in the starting position because the ruptured ligament will not be tight enough for the probe to tug at it. An advanced level of experience of the normal arthroscopic aspect of the intact bundles and their tensioning patterns might be very helpful.

19.6 Treatment Options

19.6.1 Conservative Versus Operative Treatment

A substantial number of partial tears have been shown to progress to complete tears with increased laxity and a higher rate of meniscal and cartilage injuries [12, 20, 35]. However, not every suspicion of an isolated ACL bundle tear must undergo an augmentation procedure. The sport, the sport's intensity, and patient expectations also have to be considered. Tears of the PL bundle and a positive pivot shift are also factors that might decide on the operative treatment for the surgeon. Noyes et al. [41] also observed that those ACL injuries involving more than 50 % of the ligament were those that generally progress to complete ACL deficiency. A course of a few months of rehabilitation and muscle strengthening might be the preferable option in those patients with few clinical signs and not involved in highly demanding sports.

The final decision to perform an augmentation instead a classical ACL reconstruction is dictated by the ACL remnant anatomically bridging the femur and the tibia with a thickness of more than 50 % of that of the AM or PL bundle and laxity less than 5 mm when tugged at with the probe.

19.6.2 Author's Preferred Surgical Technique

The augmentation of isolated AM or PL bundle tears is performed in a similarly to a traditional single-bundle technique while sparing intact ACL tissue. For an anatomic femoral bone tunnel placement, we support the idea of drilling through the AM portal as placing the graft at the center of the anatomical insertion site with a transtibial technique is not always easily done [3, 6, 16]. It requires drilling the tibial tunnel from a more medial and proximal starting point [6, 24]. However, there is a potential risk of damage to the medial plateau cartilage due to the obliquity of the tunnel [37, 46] and also of partial injury to the medial collateral ligament [6] if we take the aforementioned approach. Moreover, the tibial tunnel obtained might not be long enough to guarantee secure fixation [24]. Some surgeons have advocated independent drilling of the femoral tunnel. Thus, drilling the femoral tunnel through a low accessory AM portal has become the more reliable option for placing the graft anatomically [24, 26].

19.6.2.1 Patient Preparation

The patient is placed in the supine position on the operating room table. A high lateral post is used to stabilize the lower extremity. The injured knee is flexed approximately 90º and maintained with a foot bump. A well-padded tourniquet on the proximal thigh of the operative extremity is strongly recommended. We prefer the lower limb to be free to allow a full flexion angle and free limb motion to evaluate the tension and the quality of the remaining ACL fibers. Thus, a leg holder is not recommended.

19.6.2.2 Arthroscopic Procedure

A routine diagnostic arthroscopy is done through an anterolateral viewing portal. This anterolateral portal is placed higher and lateral to the patella. This position allows for much better assessment of the tibial footprint. Either a high parapatellar medial portal or a transpatellar medial portal is then conveniently established as a viewing portal for the femoral side so that the medial wall of the lateral condyle can be better seen. The fat pad is generously debrided through this portal. This allows for a proper and safe placement of the accessory AM portal. This portal is set as distally as possible with the help of a spinal needle under direct visualization to avoid injuring the anterior horn of the medial meniscus. In addition, the portal is placed as medially as possible without injuring the medial femoral condyle. Associated meniscal or chondral lesions are addressed before the ACL procedure.

Once the isolated bundle rupture of the ACL is diagnosed (see Sect. 19.5.4), the graft is harvested.

19.6.2.3 Graft Preparation

The authors' preferred graft is the ipsilateral semitendinosus tendon (ST) as it is long and strong enough to be triplicated. Additional advantages are little harvest-site morbidity and minor alterations in hamstrings' function in comparison to harvesting the ST as well as the gracilis tendon (GT). We first make a 2-cm longitudinal incision, 2 cm medially to the medial border of the tibial tuberosity (TT). The landmarks for accurately locating them are the lower half of the TT or a line perpendicular to the fibular neck. Next, the pes anserinus bursa and the sartorius fascia are opened transversally on their upper halves. The GT can be easily seen and is isolated with a #1 Vicryl suture. This helps to pull it up and the ST will follow the GT and come up to the surgical incision. The ST is then isolated and pulled strongly with a 90º curved dissector. The insertion of the ST is released, and the tendon is finally harvested with the help of the striper. In the past, the ST tendon was doubled. Due to the small diameter of a double ST tendon that it is sometimes obtained, it was also augmented with the GT in approximately half of the cases. Due to that fact, we are currently triplicating the ST. At least 21 cm of tendon is necessary for the procurement of a usable 7 cm graft. This is mainly so, if the longer AM bundle is the one to be reconstructed. Fixation at the femoral site is obtained with the XoButton device (ConMed Linvatec, Largo, FL, USA), an extracortical fixation implant. The tendon is passed through the XoButton's loop and folded between the first and second-third of its length. The remaining third of the tendon is again folded at the opposite side, and the triplicated tendon is sutured all along its length with a No. 0 high resistance nonabsorbable whipstitch suture (Fig. 19.6). The diameter of the graft is measured in 0.5 mm steps. A diameter of the graft between 6 and 8 mm is usually achieved.

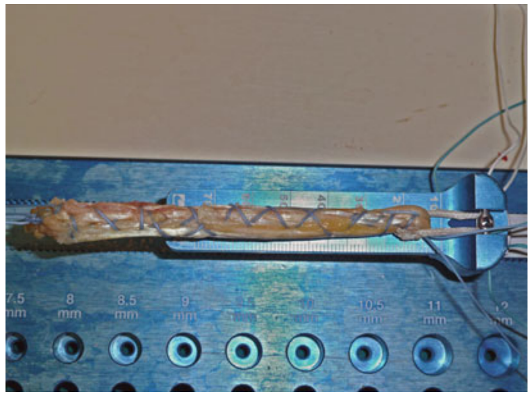

Fig. 19.6 A triple semitendinosus tendon is the author's preferred graft for augmentation procedures

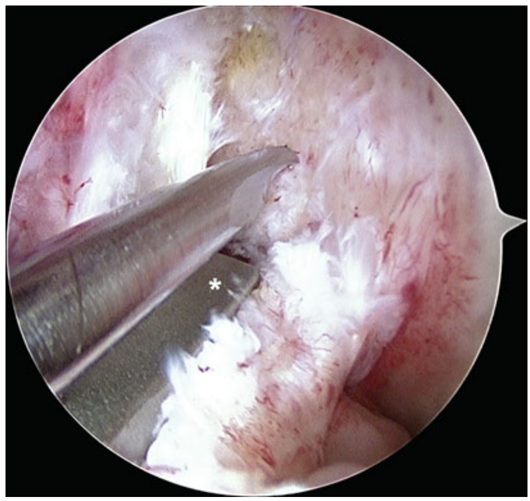

Fig. 19.7 Arthroscopic view of a left knee with an isolated tear of the anteromedial bundle of the ACL. Placement at the center of the femoral AM footprint is located with the help of a femoral offset guide (*). This diminishes the risk of posterior tunnel blowout

19.6.2.4 Anteromedial Bundle Reconstruction

The center of the femoral AM bone tunnel is located with the help of a femoral offset guide (Fig. 19.7). This avoids excessive deep placement of the tunnel and its consequent posterior blowout. Placing the knee at 100–110º of knee flexion might help in the correct placement of the tunnel as the center of the AM insertion is horizontal to that of the PL bundle. Once the center of the tunnel is determined and marked, the knee is further flexed. The next steps are the following: (1) a 2.4-mm K-wire is drilled and subsequently overreamed with a 5-mm cannulated reamer all the way through the lateral femoral condyle width, (2) the tunnel length is measured, and (3) the tunnel is overreamed to the diameter of the triplicated graft about 7–8 mm shorter than the previously measured tunnel length.

For the tibial AM bone tunnel, the tibial drill guide is set at between 55º and 60º, and on the distal tibial cortex, it is placed 2 cm medially to

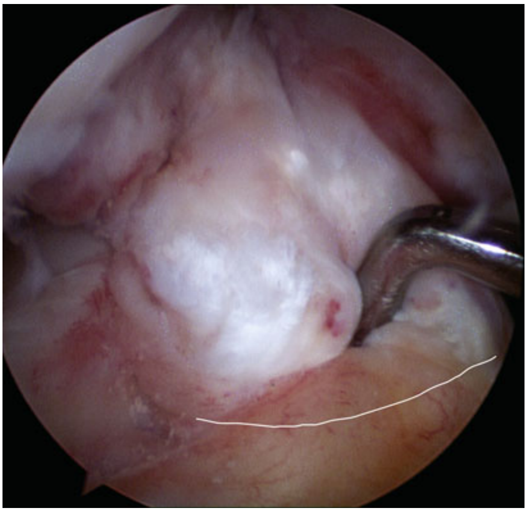

Fig. 19.8 Arthroscopic view of a right knee with the tibial drill guide tip positioned in the anteromedial part of the tibial spine, 4–5 mm posterior to the anterior rim of the ACL stump (*white line*)

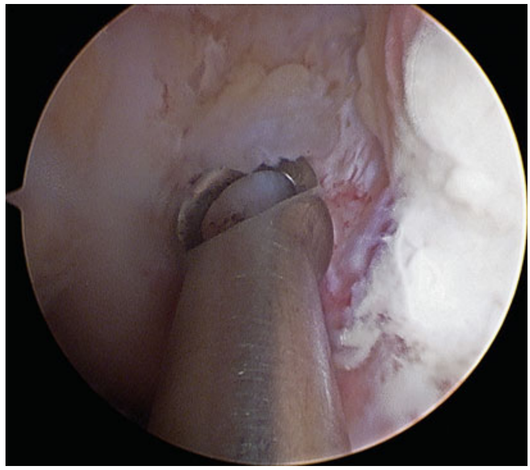

Fig. 19.9 Anatomic placement at the center of the posterolateral bundle femoral footprint can be facilitated with the use of the BullsEye femoral guide. Its open tips allow for easy visualization of the femoral footprint

the TT on the sagittal plane. The intra-articular tip is positioned at the anteromedial part of the tibial spine of the medial tibial plateau and 4–5 mm posterior to the anterior rim of the ACL stump (Fig. 19.8). This distance must be respected so as to avoid intercondylar roof impingement, damage to the transverse intermeniscal ligament, and damage to the articular cortical bone or the articular cartilage. A guide wire is overdrilled with a conventional reamer according to the size of the AM graft without compromising the intact insertion of the PL bundle. The tibial tunnel is drilled 2–3 mm smaller than the diameter of the graft. This may help to minimize the chance of fracturing the exit rim of the tunnel when the drill comes out of the joint line through the soft tibial bone. We finally compress the otherwise soft trabeculae of the tibia with a dilator to aid in compacting the surface of the tunnel. This gives a better tactile sensation when the screw is being introduced in the interface between the bone and the graft.

19.6.2.5 Posterolateral Bundle Reconstruction

Femoral tunnel placement is selected with the scope through the high AM portal or the TP portal. Remnants of the AM or PL bundles are useful landmarks for orientation, and care should be taken to preserve these intact ACL fibers. The center of the PL bundle femoral footprint is located and marked either with the tip of a curved awl or with the help of the BullsEye femoral guide (ConMed Linvatec, Largo, FL, USA) (Fig. 19.9). The latter has an open design, which allows for an easy view of the ACL femoral footprint. In a recent study, the precision and potential advantages of this new guide have recently been confirmed [25]. The knee is then further flexed at a minimum 110º of knee flexion. The next steps for the femoral tunnel are the same as those described above in the AM bundle reconstruction.

For the tibial PL bone tunnel drilling, the ACL drill guide is set at between 55º and 65º. It is placed more medially than the AM bundle tunnel on the distal tibial cortex. Starting the tunnel distally at about 3–4 cm medially to the TT allows for lower angulation of the graft as it goes proximally out of the tunnel. The intra-articular tip of the guide is positioned in the posterolateral part of the tibial ACL insertion an average of 4–5 mm medially to the lateral *eminentia intercondylaris* and 4–5 mm anterior to the posterior root of the lateral meniscus. It is very important to protect

Fig. 19.10 Arthroscopic view of a right knee from the anterolateral portal. The tip of the ACL tibial guide is positioned in the posterolateral part of the tibial ACL insertion. Note how the probe is protecting the intact anteromedial bundle fibers by pulling from the accessory anteromedial portal

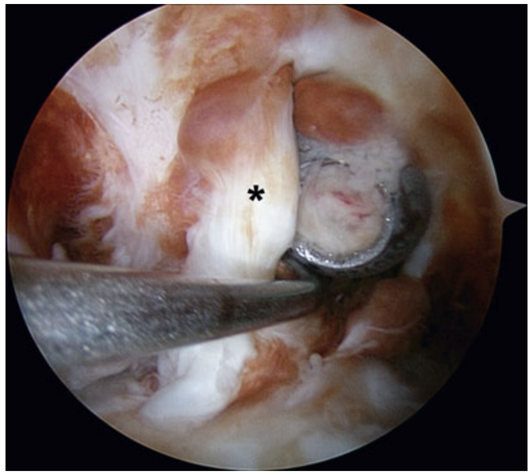

Fig. 19.11 Arthroscopic view of a left knee corresponding to a patient with a previous excessively vertically oriented graft (*). The patient complained of rotatory instability. In such cases, isolated reconstruction of the PL bundle should be considered

the intact AM bundle fibers by pulling them through the AM portal with the probe (Fig. 19.10). A conventional reamer carefully overdrills the guide wire in the same manner as with the tibial tunnel of the AM bundle.

In addition, isolated reconstruction of the PL bundle should be considered in patients with recurrent rotational instability after single-bundle reconstruction and a vertically oriented graft (Fig. 19.11). Unfortunately, the tibial tunnel is placed in the posterior aspect of the ACL footprint to prevent notch impingement in many of these patients. Whenever possible, we attempt to drill a new tibial tunnel from a more medial starting point. Although the old and new-drilled tunnel may partially coalesce near the joint line in some cases, there is usually enough tendon-to-bone tunnel area distally in the new tunnel to allow for healing of the new graft.

19.6.2.6 Graft Fixation

The preferred technique for fixation at the femoral side is an extracortical fixation device, as described above. The length of the femoral bone tunnel at 130º of flexion performed through an AM portal is usually between 30 and 40 mm. Following the recommendations described before, a femoral tunnel shorter than of 30 mm has never been obtained. Thus, we systematically use a 15-mm length loop XoButton. On the tibial side, graft fixation is accomplished with a 30-mm-long bioresorbable interference screw. We usually chose a screw oversized by 2 mm in reference to the drilled tunnel. The screw is fixed at 20–30º of knee flexion in the reconstruction of either of the two bundles. It has been found that under an anterior tibial load, the PL bundle carried a higher load than the AM bundle with the knee near extension and the AM bundle carried a higher load with the knee flexion angle larger than 30° [38]. However, both bundles carry approximately the same load between 20º and 30º of knee flexion. This is the rationale for fixing both of the bundles at the same degree of knee flexion. In fact, it has been suggested that the graft would be straightened by tensing during final fixation and remain straight throughout the entire flexion arc if the AM graft is secured at a high flexion angle [33].

Optionally, an intra-articular drain can be used. Nevertheless, it is the authors' opinion that some residual hemarthrosis might enhance the graft healing process. The lower limb is finally placed in an immobilizer with a simple dressing to make it easy to apply an ice pack.

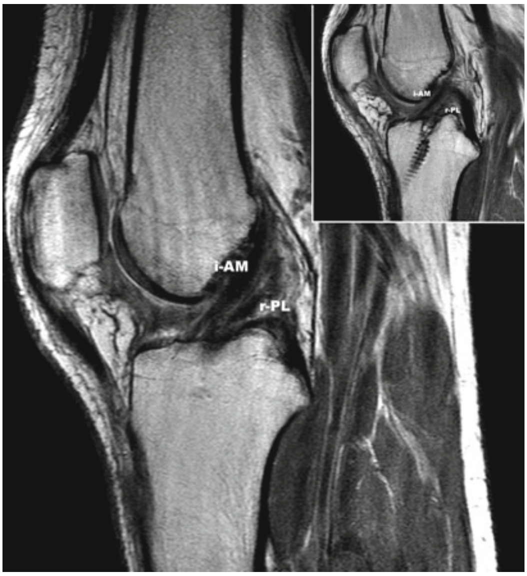

Fig. 19.12 Sagittal views of MRI with a posterolateral bundle reconstructed 6 months before. In these two images, the reconstructed posterolateral bundle as well as the intact anteromedial bundle is clearly seen (*i-AM* intact anteromedial bundle, *r-PL* reconstructed posterolateral bundle)

Fig. 19.13 Three-dimensional computed tomography scan of reconstruction of a right knee with an isolated reconstruction of the posterolateral bundle. Note the anatomic placement of the femoral tunnel at the center of the PL footprint

19.6.2.7 Postoperative Management

We use a rehabilitation program similar to that for a standard ACL reconstruction. However, physiotherapy emphasizes earlier restoration of full extension and quadriceps function. Full weight-bearing and full range of motion is allowed from the beginning. Apart from isometric exercises with the knee in full extension, quadriceps-strengthening exercises are restricted to closed kinetic chain exercises during the first 12 weeks. Sport-specific drills may be started and gradually progressed after 3 months. Full activity and a return to contact sport may begin 6 months after surgery. However, we recommend 8–10 months to the patients before a return to full pivoting sport activity as the supposed faster healing of the graft in the augmentation procedure has not been proven scientifically, yet.

Postoperative magnetic resonance images sometimes clearly show the uninjured bundle and the reconstructed graft (Fig. 19.12). However, a postoperative MRI usually has even more difficulty in differentiating both bundles than preoperatively. Standard radiographic examination is systematically performed to assess tunnel positioning. However, a three-dimensional computed tomography scan reconstruction remains the gold standard in this subject (Fig. 19.13) [25].

19.7 Clinical Outcome

Several studies have been published in the last few years reporting the results of ACL augmentation procedures. Adachi et al. [1] published the first results of an augmentation technique that was first described by Mott et al. [39] in the early 1980s. They showed better results in term of residual laxity in comparison to a classic ACL reconstruction. More recently, Ochi et al. [42] reported excellent joint stability, joint position awareness, and Lysholm scores after a minimum 2-year follow-up after selective AM and PL bundle reconstructions.

We have performed more than 100 ACL augmentation procedures over the last few years. They account for 13 % of the total ACL reconstructions procedures that we have performed in the same period. Twenty-eight of those patients have already been evaluated after a minimum 2-year follow-up (unpublished data). The mean age of these patients at the time of surgery was 31 years. In 18 of the cases, the AM bundle was reconstructed, and a PL bundle reconstruction procedure was performed on the remaining 10. A quadrupled hamstring graft was used in 15 cases, a doubled ST tendon in 7 cases, a doubled GT in 4 cases, a tripled ST and tripled GT in 1 case each one. The average diameter of the graft obtained was 7.2 mm. Functional evaluation was assessed with IKDC, Lysholm, and Tegner scores. Stability was evaluated with the pivot-shift test and the KT-1000 device. Preoperatively, the pivot-shift test was positive in 16 patients (57 %) and Lachman test in all cases. Both tests were always negative during the follow-up evaluation. Anterior tibial displacement with KT-1000 significantly dropped from a mean of 3.5 mm preoperatively to a 0.6 mm postoperatively. Subjective IKDC improved from an averaged 56.6 preoperatively to 93.6 postoperatively. The Lysholm score significantly improved from 65.2 to 96, and the Tegner score only dropped 1.3 points from the previous-injury activity. Three patients developed extension deficits. Two cases were due to Cyclops syndrome and one was secondary to graft impingement. These complications were all resolved arthroscopically either with resection of the Cyclops nodule or with a mild notchplasty in the latter case. In agreement with other short time series, we observed excellent functional results in the short term with a low complication rate.

However, despite numerous papers published in recent years, there are few publications comparing classical ACL reconstruction and ACL augmentation procedures. These long-term randomized controlled trials will be necessary in order to obtain definitive scientific evidence of the advantages of this technique in comparison to traditional ACL reconstruction.

Conclusions

A partial ACL tear should be suspected more often. Although its diagnosis is sometimes a challenge and the natural history is not completely understood, we recommend selective AM or PL bundle reconstruction for active patients with a single-bundle rupture. Jack C. Hughston, one of the pioneers in the field of sports medicine, used to wisely say: "repair what is torn."

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Chronic Anterior Cruciate Ligament Tear: Single-Bundle ACL Reconstruction: Anteromedial Portal Versus Transfemoral Outside-In Versus Transtibial Drilling Technique

20

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20.1 Introduction

A thorough knowledge of the complex anatomy of the anterior cruciate ligament (ACL) and particularly its anatomical attachment sites is crucial to the success of an anatomic ACL reconstruction. The influence of ACL tunnel placement on the kinematics of the knee has been widely demonstrated [31, 37, 41, 45, 48, 50]. Misplacement of the femoral tunnel is one of the most common surgical problems that can lead to less than satisfactory outcomes. The femoral tunnel can be drilled in two different directions. The *double-incision technique* runs from the outside to the inside of the joint. It requires an additional small approach on the lateral aspect of the knee. It used to be more commonly performed, mainly in the 1980s. On the other hand, the *single-incision technique* starts the femoral tunnel from inside of the joint. This inside-out drilling technique may be performed

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either with the drill through the previously established tibial tunnel (transtibial technique) or through an accessory medial portal (anteromedial portal technique) [3, 26]. The superiority of any of these three options is still controversial and somewhat depends on surgeon preference.

The transtibial technique was popularized in the 1990s. It is based on two principles; (1) the isometric behavior of the graft throughout the full range of motion of the knee joint and (2) the avoidance of postoperative complications, especially graft impingement. However, the transtibial technique usually leads to vertically oriented grafts which cannot satisfactorily achieve the required rotatory knee stability. Biomechanical studies have demonstrated that lowering the femoral tunnel toward the footprint of the posterolateral (PL) bundle is more effective at preserving this property [37, 47, 50]. Therefore, ACL single-bundle reconstruction has been evolving over recent years to femoral placement of the graft at an intermediate point between the anteromedial (AM) and posterolateral (PL) bundles. As placing the graft at the center of the anatomical insertion site with a transtibial technique is not always easily done [4, 12], independent drilling of the femoral tunnel through the anteromedial portal has been progressively increasing in use.

The main objective of this chapter is to describe and analyze the advantages and disadvantages of these three different techniques along with the authors' preferred technique.

20.2 Local Anatomy

20.2.1 Femoral Footprint of the ACL

The Weber brothers (1836) first described the roll and glide mechanism of the knee as well as the complex anatomy of the ACL. According to their description, it mainly consists of two different bundles that tense at different knee flexion angles [54]. Palmer, in 1938, was one of the first authors to describe the ACL as consisting of anteromedial (AM) and posterolateral (PL) fiber bundles [48]. The division of the ligament into AM and PL bundles is now widely accepted as the basis for understanding the ACL's complex function [16]. The description of these bundles is based on the relative anatomic positions of the bundle attachments on the tibia [1, 2]. At the femoral insertion site, the AM bundle lies deeper and higher in the notch in relationship to the PL bundle, which is relatively lower and shallower on the lateral wall of the intercondylar notch.

20.2.2 Osseous Landmarks

When there is no remnant of the original ligament, knowledge of bony landmarks is critical. They can be used as a guide to locate the right ACL femoral attachment and so as to anatomically drill the tunnel in case of reconstruction [48]. The femoral ACL attachment site has a broad crescent shape. It is situated at the posterior-superior border of the lateral wall of the intercondylar notch.

McIntosh was probably the first to use the "over-the-top" position in ACL reconstruction [40]. This position refers to an osseous landmark situated at the junction between the roof and the lateral wall at the posterior portal of the intercondylar notch. Some years later, Clancy coined the term "resident's ridge" to name a nearly longitudinal prominent ridge that runs three quarters of the way back on the roof to the lateral border of the notch [30]. It runs anterior to the entire ACL footprint. Its name is related to the confusion generated among inexperienced surgeons when trying to identify the posterior portal of the intercondylar notch. Lately, this ridge has been described as a distinctive change in the slope of the femoral notch roof that occurs just anterior to the femoral attachment of the ACL. Hutchinson and Ash reported that ridge to be present in 90 % of the cadaveric knees dissected in an anatomic study [30]. More recently, its presence has been also confirmed in the early stages of human development, although the authors preferred to name it as lateral intercondylar ridge [18]. According to this last work performed by Freddy Fu's team, the ACL femoral attachment has a unique osseous topography with two osseous ridges. Clancy's "resident's ridge," which seems to be present in all cases, and the *lateral bifurcated ridge*, an osseous crest dividing the AM and PL bundles at its femoral attachment, are present in almost 80 % of the knees [18].

Although some anatomical variations have been described in the ACL femoral insertion site [12], it seems that it has a more uniform morphology than does the tibial site.

In clinical practice, precise intraoperative identification of these osseous landmarks is of utmost importance due to its implications at the moment of locating the exact place to drill the anatomic femoral tunnel.

20.2.3 Femoral Tunnel Drilling

20.2.3.1 Intra-articular and Extra-articular Structures at Risk

Drilling the femoral tunnel may present potential risks for some intra- and extra-articular structures during an ACL arthroscopically assisted reconstruction. This risk will be different if the femoral tunnel is created through the AM portal, through the tibial tunnel, or with an outside-in transfemoral approach. In addition, different anatomical structures can also be damaged depending on the used femoral fixation device (interferential screws, suspensory or transverse fixations).

20.2.3.2 Transtibial Technique

The standard transtibial technique allows for easy and reproducible preparation of the ACL femoral tunnel. The femoral tunnel is drilled through the previously performed tibial tunnel [7]. The two structures most commonly at risk are the posterior cruciate ligament (PCL) and the vastus lateralis muscle. They can be injured with the guide wire or the drill itself. Although the transtibial technique is an easy and safe technique, some studies have recently emphasized that it reduces the surgeon's ability to maneuver while selecting the entry tunnel site of the femoral tunnel. More importantly, it has been demonstrated that the surgeon systematically misses the center of the anatomical femoral attachment of the ACL with this technique [4]. This often results in high femoral tunnel placement and consequently an excessively vertical and nonanatomical graft [34, 36, 43]. Thus, this technique normally fails if an anatomical reconstruction is required.

Drilling a more anatomical femoral tunnel with the transtibial technique requires starting the tibial tunnel from a more medial and proximal starting point [4, 19]. However, there is a potential risk of damage to the medial plateau cartilage due to the obliquity of the tunnel and also of partial injury to the medial collateral ligament if the aforementioned approach is taken [20]. Moreover, the tibial tunnel obtained might not be long enough to guarantee secure fixation [22].

20.2.3.3 Anteromedial Portal

Some surgeons advocate independent drilling of the femoral tunnel. Thus, drilling the femoral tunnel through a low accessory anteromedial portal (AAM) has become another option for placing the graft anatomically without the risk of a transtibial technique with a tibial tunnel more medial and proximal. Lowering the femoral tunnel to the exact anatomical insertion site makes the exit of the femoral tunnel lower and lateral. It presents a risk of iatrogenic lesion to the posterolateral structures of the knee and to short tunnels [6]. The articular cartilage at the posterior border of the lateral femoral condyle, the lateral gastrocnemius tendon, the lateral collateral ligament (LCL), the popliteus tendon (PT), and the peroneal nerve can all be at risk during the procedure [13, 17, 28, 39, 44]. According to some anatomical works, strategies to avoid damage to all these structures include drilling at least at 110º of knee flexion and angling the pins upward [6, 27, 44]. In addition, the risk of injury to the common peroneal nerve is very low with these surgical tips but significantly increases as the knee is placed in lower flexion. The mean distance from the guide pin to the nerve at 70º of flexion was found to be at 22 mm and increased to 44 mm at 120º of flexion [27].

Intra-articularly, the medial femoral condyle cartilage surface and the anterior horn of medial meniscus can also be damaged by the drilling tools. This risk is minimized by establishing the AAM portal as inferiorly (close to the tibia) as possible with the help of a spinal needle and under direct visualization to avoid injuring of the anterior horn of the medial meniscus. In addition, the portal should be placed as medially as possible while taking care not to injure the medial femoral condyle.

With regards to the fixation devices, cross-pin transverse femoral fixation devices, originally designed for a transtibial technique, may also increase the risk of damaging the posterolateral corner structures. According to Gelber et al. [20, 21], there is a high risk of injury to the LCL when the femoral tunnel is drilled from an anteromedial portal at 110º of knee flexion and the tunnel length is 30 mm or less. Likewise, the PT and the lateral gastrocnemius tendon may also be injured. Therefore, the knee should be kept hyperflexed (110º or more flexion), and the femoral tunnel should be drilled as long as possible to avoid any further damage if this approach is to be used [21].

Finally, it has been shown that the degree of femoral tunnel widening after ACL reconstruction using autologous hamstrings is significantly lower with the AAM technique than with the transtibial technique [10]. It has been suggested that a less physiological behavior of the graft following this type of reconstruction might favor micromovements of the graft into the tunnel leading to tunnel widening.

20.2.3.4 Outside-In Technique

This technique seems to be safer for the anatomical structures of the lateral side of the knee [46]. In this case, as the lateral aspect of the knee is open and dissected, the surgeon can obviously choose the entry point of the guide wire on the lateral cortex of the distal femur. Additionally, it avoids the risk to the medial structures in the knee such as the cartilage of the medial femoral condyle and the medial meniscus. Therefore, this technique might be considered the safest for the anatomical structures of the lateral and medial side of the joint. The morbidity associated with the required additional lateral incision has not contributed to greater widespread use of this technique.

20.3 Femoral Tunnel for ACL Reconstruction: Technical Considerations

20.3.1 Femoral Footprint

20.3.1.1 From Isometry to Anatomy

In the early 1980s, Clancy established the ACL reconstruction principles by using the central third of the patellar tendon. The tibial tunnel was drilled using an anatomic outside-in technique. The philosophy of this technique was based on isometry. Thus, no differences in graft's length should be observed over the full range of motion. Although their results were acceptable, probably due to the limited experience in arthroscopic procedures in those days, the technique never became popular. Some years later, a much simpler and reproducible single-incision transtibial technique was popularized. Basically, the surgeon used a specific offset aimer to place the femoral bone tunnel in the "proper" position via the predrilled tibial tunnel (Figs. 20.1 and 20.2). The tip of the guide was placed high in the notch near the *over-the-top* position. It resulted in a tunnel that leaves 2–3 mm of back wall. However, this position most of the time leads to an excessively vertically orientated graft that is far from the anatomical footprint of the ACL (Figs. 20.3 and 20.4) [34]. Again, it is very difficult to center the femoral tunnel in the femoral footprint with this technique [8, 36, 50]. Several studies have demonstrated that these vertically oriented grafts have a limited ability to restore the abnormal kinematics observed in the ACL-deficient knees [1, 4, 8, 19, 23, 25, 29, 33, 37, 42, 49, 51]. In order to avoid the limitations of the transtibial technique, the so-called anteromedial portal drilling technique allows for better and easier positioning of the drill in any desired site of the medial wall of the lateral femoral condyle [11]. Anatomic reconstructions better reproduce the in situ forces of the original ACL and hence offer better clinical and functional outcomes [15, 36, 48]. In addition, the use of an additional medial portal for visualization of the lateral wall of the notch offers a wider view of the footprint.

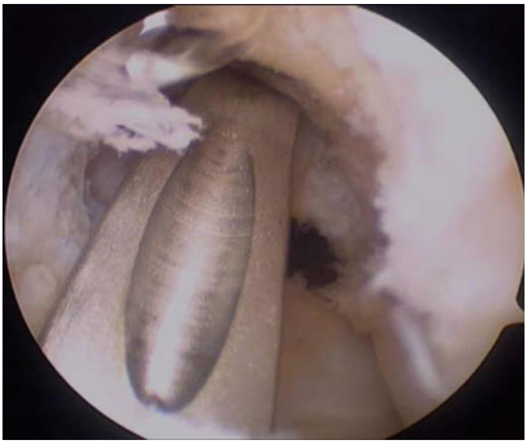

Fig. 20.1 The offset femoral guide position using the transtibial technique. Note the vertical orientation of the aimer in the intercondylar notch

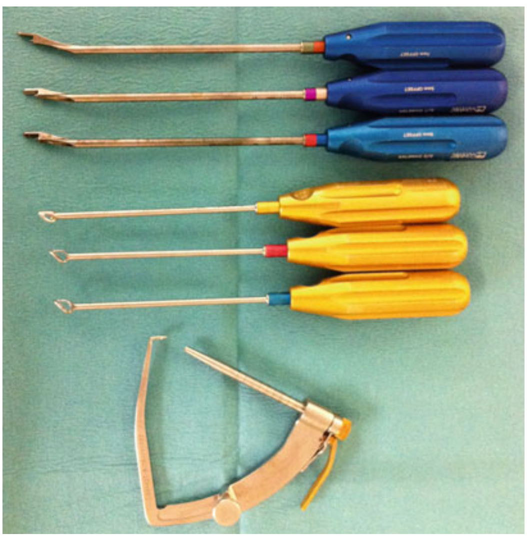

Fig. 20.2 Different anatomical outside-in and offset guides for creating the femoral tunnel

Fig. 20.3 Arthroscopic view of a right knee as seen from the AL portal. ACL reconstruction using a conventional transtibial technique. Note the vertical orientation of the graft

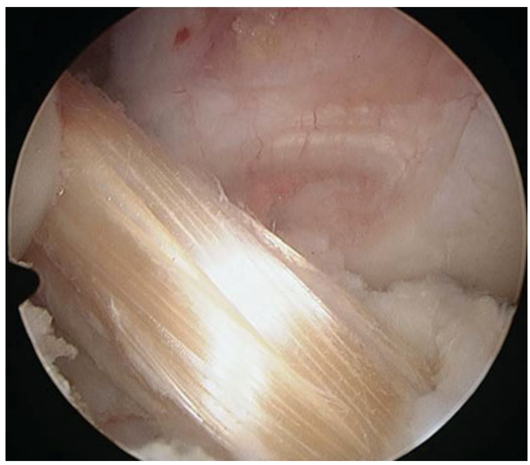

Fig. 20.4 Arthroscopic view of a right knee from the AL portal. ACL reconstruction using the anatomical technique. Note the more oblique (anatomic) orientation of the graft

This also reduces the necessity for *notchplasty*, which is a normal-anatomy-destructive procedure [10, 11, 32, 39].

Several series have already reported on the clinical benefits of the anatomic technique over the transtibial technique in terms of functional and rotational stability [31, 36, 48].

20.3.1.2 Instrumentation: Femoral Guides

Several guides have been developed in the last decades to help in properly positioning the drill guides. In the beginning, drill guides were designed for the outside-in two-incision technique. However, it is usually difficult to locate the correct femoral attachment site with this technique. The main reason is the limited vision that a 30º arthroscope offers when it is introduced through the anterolateral portal. This leads to performing notchplasties almost systematically. In fact, it used to be widely advocated by most authors. However, notchplasty not only leads to a lateralization of the lateral wall of the notch but also to a distortion of the normal anatomy and so to a likely malpositioning of the femoral tunnel [35].

Lately, with the advent of the transtibial technique, new endoscopic drill guides with a specific offset have been introduced. However, using these transtibial guides, the location of the femoral tunnel is restricted by the angulation of the tibial tunnel in the frontal and sagittal planes [4, 15, 52]. Many authors, who now use an anteromedial portal drilling technique, still use this type of femoral guide [13, 17]. However, Gelber et al. [22] has recently demonstrated that offset aimers present a risk of posterior tunnel blowout and a risk of obtaining short tunnels when performing oblique femoral tunnels through the AM portal. Golish et al. [24] has also demonstrated on a cadaveric model that the use of femoral offset guide for drilling the femoral tunnel from an anteromedial portal and with 120º of knee flexion can result in a tunnel length shorter than 20 mm. In parallel, the industry has been developing new specific anteromedial portal tunnel guides so as to better assist anatomic reconstruction (Figs. 20.2 and 20.5). However, in order to properly locate the femoral anatomical footprint of the ACL, the use of the regular outside-in guides under direct vision (i.e., from an anteromedial or transpatellar portal) may still be a good option.

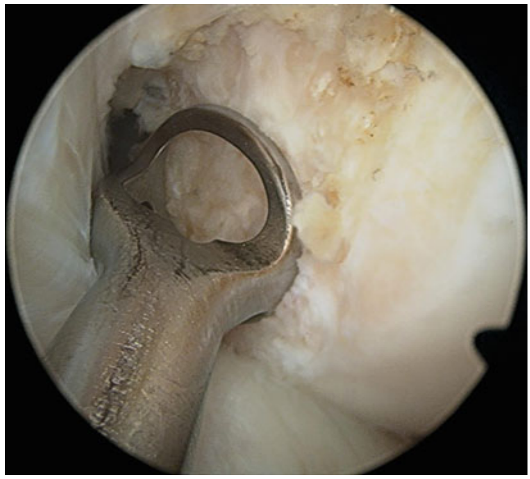

Fig. 20.5 Arthroscopic view of a left knee from a high anteromedial portal. Anatomic femoral guide positioned through the "working" low anteromedial portal

20.3.2 Length, Orientation, and Knee Flexion During Femoral Tunnel Drilling

Anatomic (i.e., lower) femoral tunnels present the risk of short tunnel length [5]. It has been demonstrated that there is a progressive shortening of the tunnel length as the femoral tunnel orientation became more horizontal [24]. These short tunnels may influence not only the graft healing process [55] but also the suitability of some fixation methods.

The degree of knee flexion during femoral tunnel drilling also seems to be a critical point on the tunnel's final length. Several works have assessed how different knee flexion angles affect the final tunnel length when using anteromedial portal drilling [6, 24]. Basdekis et al. concluded, in a cadaveric study, that 110º is the minimum flexion angle to perform the femoral tunnel through the anteromedial portal [6]. Nonetheless, the tunnel length was quite variable from one specimen to another [6, 24]. Some authors have also compared the femoral tunnel length obtained with the anteromedial portal at maximum knee flexion versus the outside-in technique. Although controversial, these authors concluded that the outside-in technique allows for longer tunnels [38]. The lack of uniformity among the published series suggests the existence of several different "anatomic" reconstruction techniques. Non obstante, in a systematic review of anatomic ACL reconstruction studies, van Eck et al. [53] found that one of the most important variables on the tunnel length was the knee flexion angle during femoral tunnel drilling.

Comparison between the transtibial versus the anteromedial technique showed significantly longer femoral tunnel lengths with the transtibial technique (43.3 vs. 34.2 mm, respectively).

Additionally, tunnels shorter of 30 mm in 2 % of the tunnels performed transtibially versus 26 % in the anteromedial portal technique were observed [9]. In our experience, the obtained tunnels have a minimum 30 mm's length when the tunnel is properly placed and the knee is in full flexion.

In summary, in order to guarantee an anatomically positioned femoral tunnel that is long enough, the surgeon should choose between (a) the anteromedial technique with the femoral tunnel drilled at more than 110º of knee flexion and (b) the outside-in or two-incision technique.

20.3.3 Femoral Fixation of the Graft

Several methods are currently available for fixing the ACL graft on the femoral side. The best method is still unclear [14]. From the point of view of the femoral tunnel drilling technique, the different advantages and disadvantages of every method have to be considered. For instance, if the use of an interferential screw through an AM portal is considered, the hyperflexion of the knee during the femoral fixation guarantees the parallelism of the screw placement with respect to the bone tunnel. This is an obvious advantage of the AM portal drilling technique when compared to the transtibial technique. This advantage is also obtained with the two-incision technique.

If a suspensory cortical device is preferred for the femoral fixation of the graft, the length of the femoral bone tunnel is a key factor. Using this type of fixation, part of the femoral tunnel will be only filled by the suture loop of the device. If the femoral tunnel is too short, there is a potential risk of a low contact area between the graft and the cancellous bone that leads to impaired healing of the graft.

20.4 Author's Preferred Method

A single-bundle anatomic ACL reconstruction with an anteromedial portal technique is our preferred method for ACL femoral drilling.

With the patient lying supine, the knee is flexed 90º with the help of a foot support. The use of a pneumatic tourniquet is optional since we prefer the use of an arthroscopic pump to improve vision, particularly when hyperflexion of the knee is needed. A high anterolateral (AL) portal is first established. This high portal allows for better visualization and evaluation of the ACL tibial footprint. Then, a high parapatellar anteromedial (AM) portal is performed. This portal is established mainly for better visualization of the medial wall of the lateral femoral condyle. Once the joint has been completely evaluated and any concomitant injury (e.g., meniscus, cartilage) addressed, a third accessory AM portal is performed. This portal is set horizontally as distally as possible with the help of a spinal needle under direct visualization to avoid injuring the anterior horn of the medial meniscus. In addition, the portal has to be placed as medially as possible without injuring the medial femoral condyle. This allows for a more perpendicular drilling of the femoral tunnel. After a careful inspection of the notch, the ACL injury pattern is also evaluated, and if any healthy remnant of the bundles is considered anatomically and functionally intact, an augmentation reconstruction is considered.

In case of a complete rupture, the notch is cleaned of soft tissue leaving 1–2 mm of the stump of the native ACL. The scope is then switched to the high AM portal to better distinguish the femoral footprint on the lateral wall of the notch. The exact femoral insertion site of the ACL is then estimated using the remnants of the ligament or bony landmarks. Afterward, following a synovectomy of the Hoffa's fat pad, the knee is hyperflexed to at least 110º and kept in position with the help of the foot support. To help in locating the femoral tunnel, a special aimer (Bullseye, ConMed Linvatec Inc. Largo, Fl, USA) is introduced through the low AM portal. The open tip of the aimer is centered on an intermediate point between the AM and PL femoral footprints or in the center of the lateral bifurcated ridge when this had been clearly identified. Then a guide wire is advanced through the guide and exits the joint at the lateral aspect of the lower thigh. The oval end of the aimer allows for easy visualization of the guide pin placement. Then the aimer is withdrawn and the guide wire is overdrilled with a 5-mm cannulated reamer which will allow the suspensory cortical fixation device to pass through the lateral femoral condyle. We systematically used a 15-mm loop XoButton device (ConMed Linvatec, Largo, Fl, USA). Once the length of the tunnel is measured, the tunnel is again overdrilled to the graft diameter but stopping 5–7 mm before the exit in the lateral cortical wall. A dilator is finally introduced for bone compaction.

To better drill the tibial tunnel, the knee is extended back to 90º of knee flexion. The right place for the tibial tunnel is localized with the help of a regular ACL tibial guide. The medial tibial spine and the anterior horn of the lateral meniscus are the two most used landmarks for proper placement of the tibial tunnel. Once the graft is introduced through both tunnels, it is preconditioned with few cycles of movement. The construction is fixed on the tibial side at 20º of knee flexion with a bioabsorbable interference screw (oversized by 2 mm in the case of hamstring grafts).

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21 Anterior Cruciate Ligament Tear: Rationale and Indications for Anatomic ACL Reconstruction

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Contents

21.1 Introduction

Reconstruction of the anterior cruciate ligament (ACL) is one of the most frequently performed operations in orthopaedic sports medicine [17]. Traditionally, treatment for complete ACL tears

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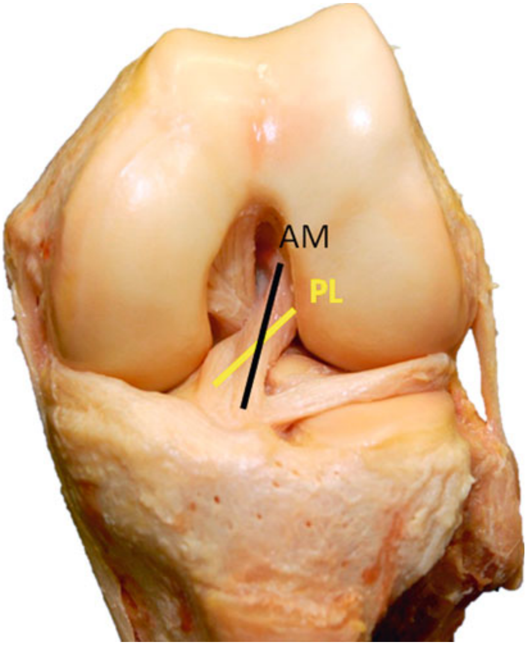

Fig. 21.1 The ACL consists of two distinct functional bundles: AM and PL

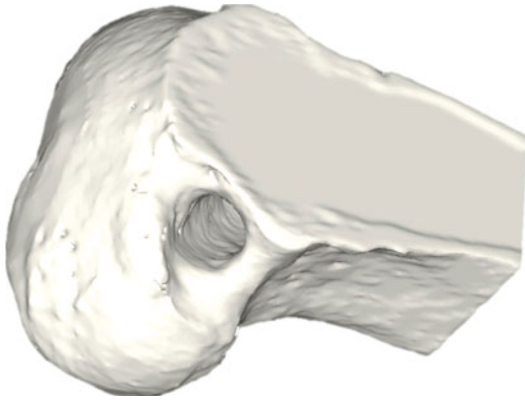

Fig. 21.2 3D CT reconstruction: femoral nonanatomic tunnel placement after traditional SB reconstruction technique with typical "high AM" tunnel placement

has long been a conventional single-bundle (SB) reconstruction [13, 19]. Short-term results for SB reconstructions have been relatively good, with improvement in subjective knee instability and the ability to return to sports [25]. However, in a subset of patients, subjective knee instability persists, and they remain unable to return to prior activity. With SB reconstruction, good to excellent results are only achieved in 60 % of patients and less than 50 % returns to playing sport at their preinjury level [5, 7]. Moreover, long-term results suggest that the rate in which osteoarthritic (OA) changes occur is not reduced by SB reconstruction as compared to nonoperated knees [10, 15, 26]. Multiple studies have shown that the native biomechanical properties of the knee cannot be fully restored by nonanatomic SB reconstruction [8, 40] and that this may be a cause of cartilage thinning [3, 37].

The ACL has been acknowledged to consist of two distinct functional bundles (Fig. 21.1) – the anteromedial (AM) and posterolateral (PL) bundle – since at least 1938 [32]. However, traditionally SB reconstruction techniques focused on recreating the ACL as one ligament and therefore with only one bundle, often resulting in nonanatomic tunnel placement (Fig. 21.2) (a tibial PL to a femoral "high AM" tunnel position). This technique was shown to successfully restore the biomechanical properties of the native AM bundle with the graft adequately resisting anteroposterior translation forces, but failed to restore rotational stability – attributed to the PL bundle – of the injured knee, leading to abnormal biomechanics [40, 41].

Usage of two bundles in ACL reconstruction has led to the use of terms as "double bundle" and "anatomic" when describing these techniques. "Double bundle" (DB) means that the ACL is reconstructed by means of two separate bundles, without specifying the location of tunnel placement. "Anatomic" means that the ACL is in the native anatomic position with the tunnels placed in the native ACL insertion site, regardless of SB or DB technique. Therefore, the terms "double bundle" and "anatomic" are not to be used interchangeably.

Recently, there has been a shift in interest from SB to DB reconstruction. The DB procedure is suggested to more closely resemble the normal anatomy of the ACL by restoring the AM and PL bundles of the native ACL [31]. Moreover, multiple studies have shown clinical superiority of DB reconstruction in restoring anteroposterior and rotational stability compared to the traditional SB procedure [1, 20, 22, 30, 36, 42, 44].

Anatomical reconstruction of the ACL can be defined as the functional restoration of the ACL

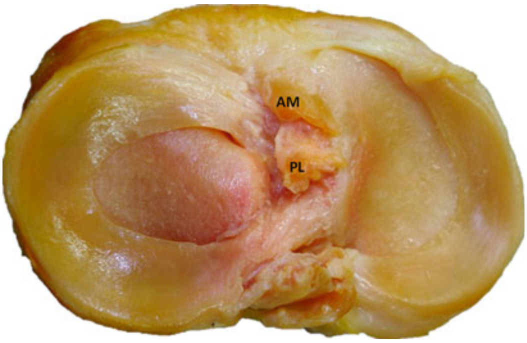

Fig. 21.3 The AM and PL bundles are named according to their relative position on the tibia

to its native dimensions, collagen orientation, and insertion sites [39].

Providing the patient with the greatest potential for a successful outcome is the main goal of anatomic ACL reconstruction. In order to achieve this goal, surgeons should strive toward individualizing each surgery with respect to the patient's anatomy, while observing three fundamental principles: (a) carefully identify the patient's individual anatomy, (b) place the tunnel(s) and graft(s) in the center of the patient's native ACL insertion sites, and (c) restore knee biomechanics by tensioning the graft(s) according to the native ACL properties [38].

21.1.1 Anatomy

Knowledge of anatomy is the basis of orthopaedic surgery. Restoring the native anatomy and physiological function are cornerstones in ACL reconstruction.

The two functional bundles of the ACL – AM and PL – are named according to their relative position on the tibia (Fig. 21.3) [2, 6, 16, 31, 32]. Both bundles are distinguishable – and separated by a vascularized septum – during early fetal development (around 20 weeks) already [11], which leads to the conclusion that both bundles are literally a part of native anatomy.

In order to reconstruct the ACL anatomically, the ability to identify the remnants of the individual bundles and detailed knowledge of the anatomical bony landmarks at the femoral and tibial insertion sites is essential. At the femoral side, the bundles are vertically aligned, with the AM insertion superior to the PL insertion. However, during surgery, when the knee is flexed to 90°, the bundles are more horizontally aligned, with the AM insertion site deeper than the PL insertion site.

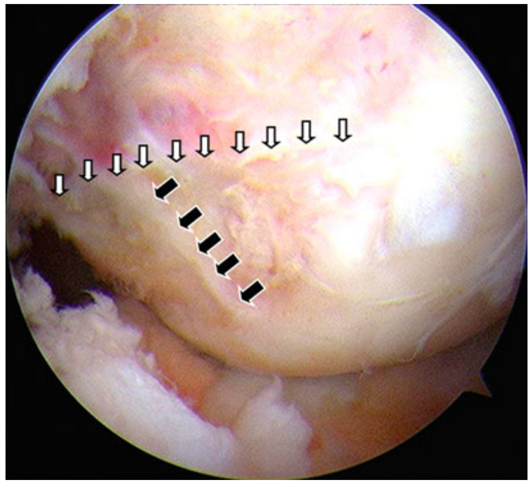

Fig. 21.4 The intercondylar (resident's) ridge (*white arrows*) and the bifurcate ridge (*black arrows*)

The tibial insertion site measures, on average, 11 mm in the coronal plane and 17 mm in the sagittal plane [18, 45]. The tibial AM bundle insertion site is aligned with the anterior horn of the lateral meniscus and has a close relationship with the medial and lateral tibial spine [39].

The femoral insertion site is, on average, smaller than the tibial insertion site, but somewhat larger than the ACL midportion [31]. The AM bundle originates from the proximal portion of the lateral notch wall, while the PL bundle lies more distally, near the anterior articular cartilage surface of the lateral femoral condyle [29, 45].

In chronic cases, the bundle remnants may have completely dissolved. Specifically in these cases, knowledge of bony morphology is crucial. On the femoral side, the most prominent anatomical osseous landmark is the intercondylar ridge (or "resident's" ridge) which is the anterior border of the femoral insertion site. In 80 % of all cases, a second ridge, the bifurcate ridge can also be identified. This ridge separates the origins of the AM and PL bundle and runs perpendicular to the resident's ridge (Fig. 21.4) [12, 34].

21.1.2 Biomechanics

So the native ACL consists of two bundles, AM and PL, which have a distinct anatomical position and configuration. However, distinction between the bundles is not solely made based on anatomy. AM and PL have a synergistic but different function throughout the entire range of motion (ROM) of the knee.

In a fully extended knee, both AM and PL are taut, with PL at its maximum. PL limits rotation of the tibia on the femur and does so up to 60–90° of knee flexion, after which PL loosens [14]. Although AM primarily resists anterior translation of the tibia, at low flexion angles (0–30°), PL also contributes. The AM bundle is under maximum tension when the knee is flexed between 45° and 60° [9].

Obviously, these different tensioning patterns have implications during anatomic ACL reconstruction.

Nonanatomic reconstruction, as performed in the conventional SB technique, does not take these biomechanical differences into account and generally only restores anterior-posterior translation. However, neglecting rotational knee stability may have severe consequences at long-term follow-up [3].

Studies indicate that reconstruction of both bundles better restores knee kinematics, specifically for internal and external rotation [1, 20, 22, 30, 36, 42, 44]. Reconstruction of both bundles is commonly done by actually using two separate grafts or a split graft (DB). However, in individuals with small insertion sites or narrow notches, this may not be technically safe. In these cases, the DB concept can be achieved by a SB reconstruction, provided that the graft is anatomically placed in the center of femoral and tibial ACL insertion sites.

The theory that DB reconstruction is more of a concept rather than an actual surgical procedure is supported by the fact that similar knee kinematics are found for both SB and DB techniques if the graft is placed anatomically [43].

According to the anatomic ACL double-bundle concept, the ACL consists of two functionally different bundles that work synergistically. Hence, the goal of the anatomic ACL reconstruction, which can be accomplished by a SB or a DB technique, is to restore ACL anatomy as closely as possible and, consequently, approximate normal knee biomechanics. This chapter will discuss the indications, contraindications, and surgical technique of anatomic SB and DB ACL reconstruction.

21.2 Clinical Evaluation

The first and most vital part to diagnosing ACL injury is obtaining a detailed history and performing a thorough physical examination. Typically, in the acute phase, patients with a torn ACL present with symptoms such as immediate knee effusion, pain along with initial difficulty in bearing weight, and diminished ROM subsequent to pain and swelling. Patients with a chronic ACL lesion, however, may not have such typical symptoms and only complain of sporadic pain and instability. Concomitant injuries are also common and should be evaluated; however, signs and symptoms may be disguised by the pain and swelling associated with the torn ACL. Symptoms like clicking and locking of the knee associated with joint line tenderness indicate a simultaneous meniscal injury.

Usually, symptoms associated with the acute phase diminish over the first few weeks following injury, and patients regain full ROM. To optimize postoperative rehabilitation and subsequent outcome, it is advised to plan surgery not before swelling has diminished and ROM is regained [27].

Objectifying complaints by means of physical examination should always be done to assess function, ROM, swelling, laxity, and pain but also to rule out multiligamentous injuries and other associated pathologies such as neurovascular involvement. Comparing both legs during physical examination is vital to detect subtle deviations.

Examining the involved knee may be difficult in the acute phase due to pain and swelling; however, a thorough exam is crucial to a complete knee evaluation and should be performed as soon as possible.

The physical knee exam starts with observation of knee alignment with the patient seated,

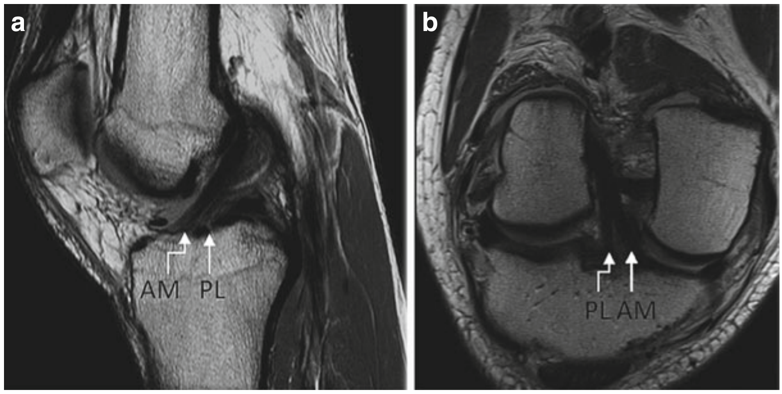

Fig. 21.5 MRI: (**a**) oblique sagittal and (**b**) oblique coronal cuts, showing the AM and PL bundles

standing, and walking, while looking closely for joint effusion, muscular atrophy, and ecchymoses. Next, ROM is measured with a goniometer, and the joint is carefully palpated to assess joint effusion and identify painful or tender areas that may be indicative for concomitant injuries. Specific tests are then performed and should include anterior drawer, Lachman, pivot shift, varus/valgus stress tests, posterior drawer, McMurray, and dial test. Quantification of ACL laxity can be obtained by measuring the degree of anterior tibial translation with a KT-1000 (MEDmetric, San Diego, CA). More than 3 mm side-to-side difference is suggestive for an ACL injury.

21.3 Imaging

Conventional radiographic evaluation of the injured knee is fundamental in the initial assessment for degenerative changes, associated fractures or avulsions, and possible deformities. Therefore, for both primary and secondary cases with suspected ACL tears, conventional imaging is always obtained first. Subsequently, the soft tissue is evaluated with high-quality MR imaging, which is the most effective and accurate noninvasive technique for determining the status of the ACL and identifying rupture pattern and possible concomitant injuries. Additionally, in secondary cases (requiring revision surgery), a three-dimensional (3D) CT scan has proven invaluable to evaluate bony morphology and previous tunnel placement. All three different modalities have a distinct and important contribution to diagnostics and preoperative planning.

Complete radiographic series include weight bearing anteroposterior (AP) view in 45° of flexion, lateral radiographs in 45° of knee flexion, full extension AP radiographs, and Merchant view for patellar evaluation.

MRI can play a definitive role in diagnostics, preoperative planning, and individualizing surgery. To enhance ACL visualization, special MRI sequences such as oblique coronal and oblique sagittal views (Fig. 21.5) are obtained by cutting MRI sections at the same anatomic alignment as the ACL. Additionally, on standard sagittal views, measurements of the tibial insertion site, ACL length, ACL inclination angle and quadriceps and patellar tendon thickness are routinely obtained to help determine reconstruction technique and graft choice (Fig. 21.6).

As stated previously, the decision to perform SB or DB reconstruction should also depend on individual anatomy and associated measurements. For instance, if the tibial insertion site measures more than 18 mm, usage of a DB technique probably yields the best anatomic reconstruction. However, a small tibial insertion site (<14 mm) may not easily permit the drilling of two separate tunnels while maintaining a 2-mm bone bridge between them, in which case a SB reconstruction would be the best alternative [33, 35, 39]. Which technique to use in patients with insertion sites ranging from 14 to 18 mm remains a gray area, and cofactors such as notch size may be paramount.

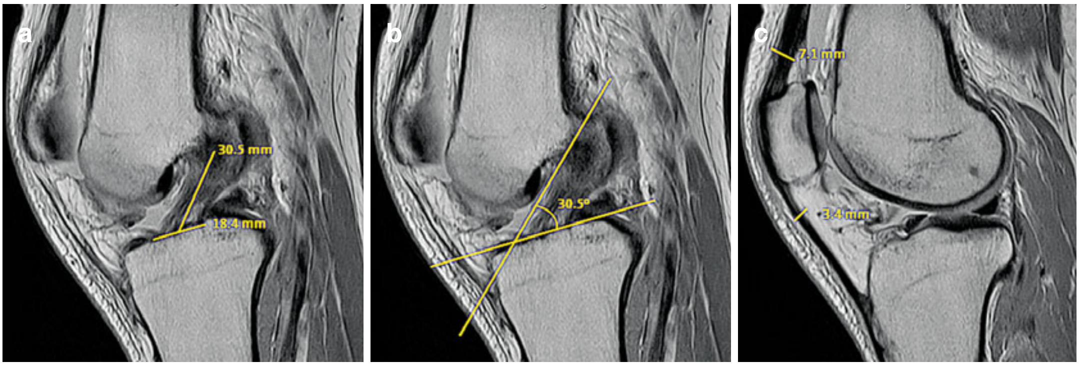

Fig. 21.6 MRI measurements: (**a**) on tibial insertion site and ACL length, (**b**) on ACL inclination angle, and (**c**) on the quadriceps and patellar tendon thickness. The quadriceps tendon usually has a far larger AP diameter than the patellar tendon

At this moment, both SB and DB reconstructions can be performed.

In secondary cases, that may require revision surgery, assessment of previous tunnel placement and bony morphology in relation to the normal ACL insertion sites obviously aides in surgical planning. 3D CT scan reconstructions help determining where the old tunnel was placed and whether and where a new tunnel can be drilled [38].

21.4 Indications and Contraindications

Athletes, children, and active patients who participate in cutting, pivoting, jumping, or quick deceleration sports are commonly best treated with surgical reconstruction of the torn ACL. Additionally, patients with physically demanding professions or with complaints of knee instability or giving way are candidates for ACL reconstruction.

Although children are best treated by ACL reconstruction, open physes are a relative contraindication for a "regular" anatomical reconstruction. Transphyseal drilling in the skeletally immature may cause severe deformities due premature partial physeal closure at the drilling site. Therefore, these cases may be best treated by means of a (nonanatomical) over-the-top procedure or – in adequately skilled and experienced hands – with an anatomical transepiphyseal procedure, usually with a single bundle [28].

In certain patients, nonoperative management may be the most adequate treatment. Particularly so for elderly patients or otherwise patients with a more sedentary lifestyle, and older adults who experience no symptoms after initial knee rehabilitation and have no wish to return to activity.

Contraindications for ACL reconstruction include poor patient compliance with a lengthy rehabilitation program, severe osteoarthrosis, and infectious arthritis.

Initial diagnosis and assessment of individual anatomy and measurements is made on MRI and preoperative planning is done accordingly. However, the definitive decision to do a SB or a DB reconstruction can only be made intraoperatively, since 3D arthroscopic assessment should also be done in order to verify preoperative findings.

21.5 Surgery

21.5.1 Technique

Depending on the preferences of both the anesthesiologist and the patient, surgery is performed under regional or general anesthesia (with or without femoral block). Once anesthesia is induced, a physical examination is repeated; now – without the patient potentially muscle guarding during the different tests – results are more specifically attributable to the ligamentous function of the knee. Examination should include

Fig. 21.7 The patient is positioned supine on the operating table with the affected knee secured in a leg holder and the contralateral limb in the high lithotomy position

ROM, Lachman, pivot-shift test, anterior and posterior drawer, valgus and varus stress, and external and internal rotation at 30° and 90° of knee flexion, and again, comparison should be made with the unaffected limb.

After examination under anesthesia is completed, the patient is positioned (Fig. 21.7) supine on the operating table with the affected knee bent over the end of the table and the upper thigh – fit with a pneumatic tourniquet – secured in a leg holder. The tourniquet is inflated to 250–350 mmHg depending on patient's size and mean arterial pressure. In this setting – after securing the upper thigh – the knee should allow at least 120° of flexion, full extension, and varus/valgus stress. The contralateral limb is positioned in the high lithotomy position away from the surgical field, with special attention to avoid positioning complications such as tourniquet effect or neurologic palsy.

In order to optimize visualization during surgery, a three-portal technique is used (Fig. 21.8) [4]. The high anterolateral portal (ALP) is established first to accommodate diagnostic arthroscopy. The incision for this portal is placed just laterally to the lateral border of the patellar tendon, with the most distal point placed at the line of the inferior pole of the patella. Correct placement of this portal allows a broad view of the tibial insertion site and avoids Hoffa's fat pad. Diagnostic three-compartment arthroscopy is performed to assess ACL rupture pattern and evaluate chondral surfaces, meniscal condition and potential concomitant injuries. Next, under

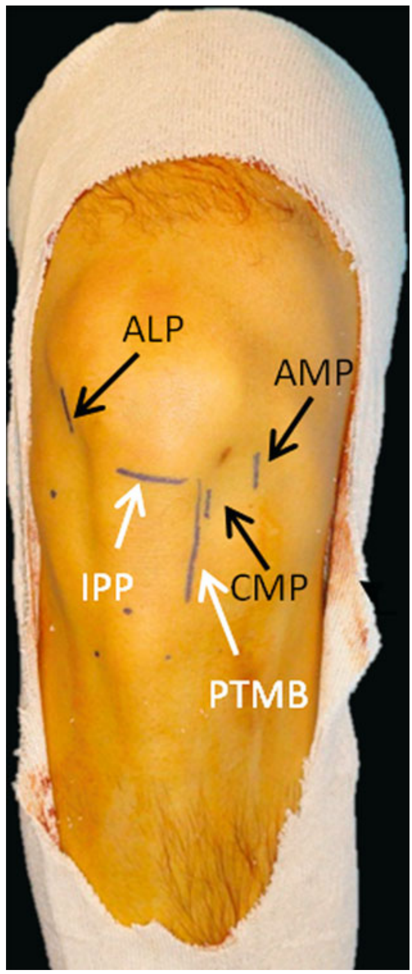

Fig. 21.8 In order to optimize visualization during surgery, a three-portal technique is used: the anterolateral portal (*ALP*), the central anteromedial portal (*CMP*), and the accessory anteromedial portal (*AMP*). *IPP* inferior pole of the patella, *PTMB* patellar tendon medial border

spinal needle guidance, placement of the central anteromedial portal (CMP) and accessory anteromedial portal (AMP) is accomplished. For the CMP, the needle is placed through – or just medially of – the lower third of the patellar tendon and should freely access the central portion of the intercondylar notch. The AMP is created approximately 2 cm medially to the medial border of the patellar tendon and just above the anterior horn of the medial meniscus, providing free access to the femoral ACL insertion site. A spinal needle should be used to aid in the portal placement. There should be at least 2 mm between the spinal needle and the femoral medial condyle to ensure safe drilling of the femoral tunnels. Attention should be paid to not damaging the meniscus, while establishing this portal with a scalpel. Then, with all portals in place, a clear view of the medial and lateral wall of the intercondylar notch is acquired, obviating the necessity of notchplasty. The CMP provides a straightforward view of the intercondylar notch and femoral ACL insertion site, and through ALP, the medial wall of the notch as well as the tibial insertion site is visualized. The AMP is commonly used as a working portal, allowing instruments, and provides a distinct advantage during femoral tunnel drilling.

After diagnostic arthroscopy, the ACL and its rupture pattern are more closely evaluated. Through the ALP and CMP, both the insertion sites are identified, and the ACL remnants carefully dissected to identify the AM and PL bundle insertion sites. Then – through ALP – attention is paid to the tibial insertion site, thoroughly measuring the total length, midwidth, and individual bundle-widths with an arthroscopic bendable ruler (Smith & Nephew Endoscopy, Andover, Massachusetts) [44] (Fig. 21.9) after which a cautery device is used to mark the center of the AM and PL insertion sites on the tibia (Fig. 21.10). Subsequently, with the same ruler, measurements of the notch are taken (Fig. 21.11), documenting width at the base, in the middle and at the apex, as well as the height on the medial and lateral side.

With the scope through the CMP, the lateral wall of the intercondylar notch is visualized. The remnants of the ACL are then carefully dissected with a cautery device, and the AM and PL insertion sites visualized and marked (Fig. 21.10). Once the remaining soft tissue is removed, the intercondylar ridge and bifurcate ridge should be identified (if present) as the bony margins of the femoral insertion site. With the knee flexed in 90°, the intercondylar ridge divides the lateral wall of the notch in approximately an upper two-third and a lower one-third – the latter being the femoral ACL insertion site (Fig. 21.12) – and the bifurcate ridge runs perpendicular to it, dividing the lower third in the AM and PL insertion sites (Fig. 21.4). Once again, measurements are taken; the total length of the insertion site and both the AM and PL insertion site widths are documented. Objectifying individual anatomy and subsequently individualizing surgery can only be done by taking measurements. Also will these measurements provide definitive guidance in the decision regarding usage of a SB or a DB technique. Although choosing the graft type is a complex process and beyond the scope of this chapter, measurements will also help determining graft choice and size – either a soft tissue autograft (preferable), allograft, or hybrid graft containing autograft and allograft is used.

After all measurements are taken and documented and key decisions regarding the surgical procedure are made, the femoral insertion site is visualized and a Steadman awl is used for creating the initial hole for the guide wire to follow into the center of the PL insertion or the center of the ACL footprint, for a DB or SB reconstruction, respectively (Fig. 21.13). Then, with the knee in full flexion (120° or more), the first part of the femoral tunnel is drilled with a powered acorn reamer to a depth of 25–30 mm. The initial drill size used on power is typically 1 mm less than the desired size of the tunnels. Maximum knee flexion is important to prevent from iatrogenic damage to the posterior wall of the lateral condyle, lateral collateral ligament, the posterolateral corner, and the peroneal nerve on exit and also to obtain maximum tunnel length. After that, a powered 4.5-mm (Endobutton) drill (Smith & Nephew, Endoscopy, Andover, Massachusetts) is used to penetrate the far cortex, and the femoral tunnel

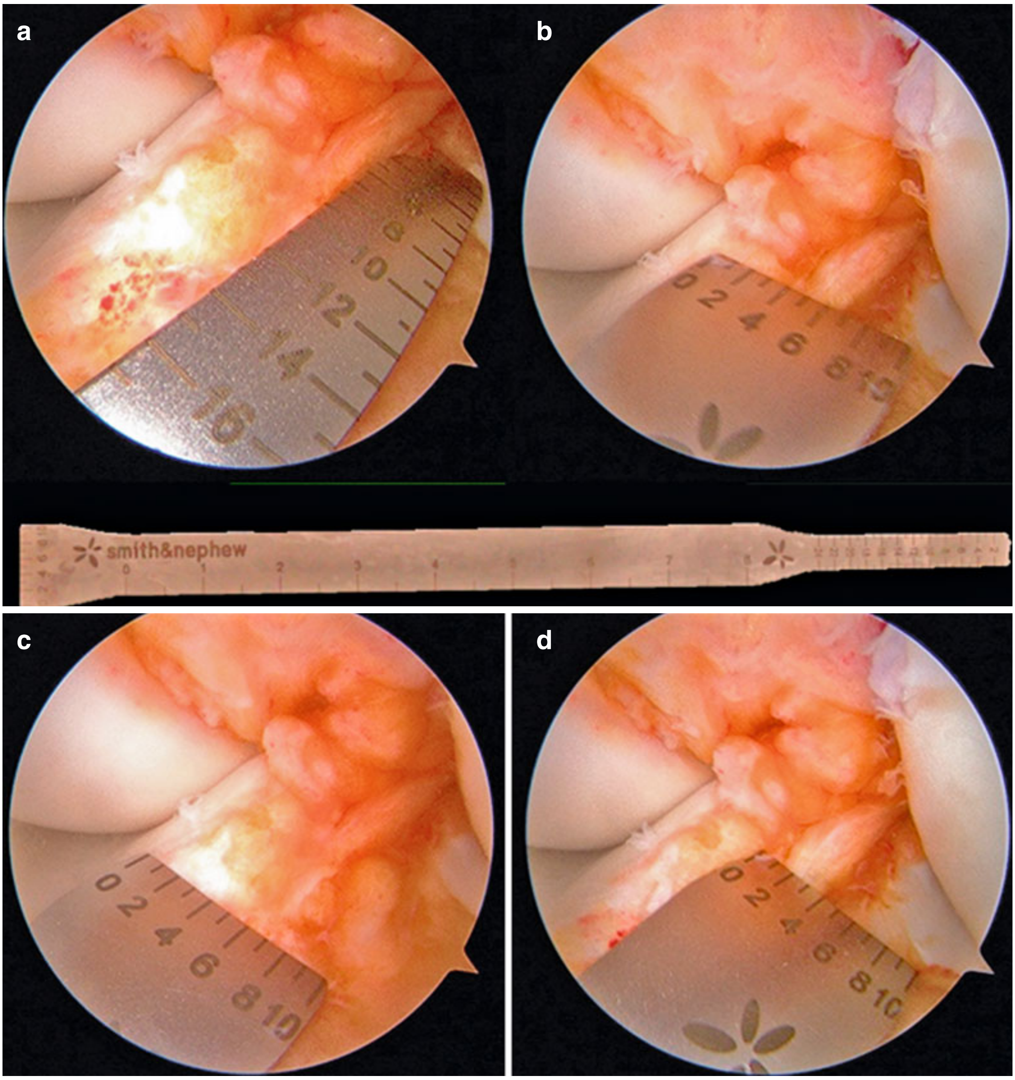

Fig. 21.9 Measuring the total length (**a**), midwidth (**b**) and individual bundle-widths, AM (**c**) and PL (**d**), with an arthroscopic ruler

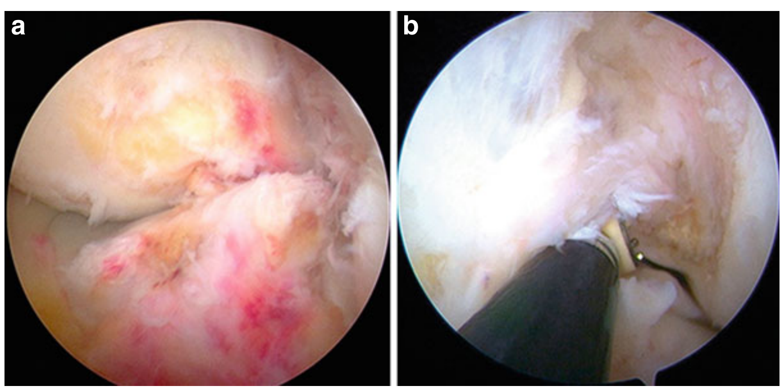

Fig. 21.10 With a cautery device, the AM and PL insertion sites on both the tibia and the femur are marked. First on the tibial side (**a**) after which the remnants on the femoral side are carefully dissected and the AM and PL insertion sites are visualized and marked (**b**)

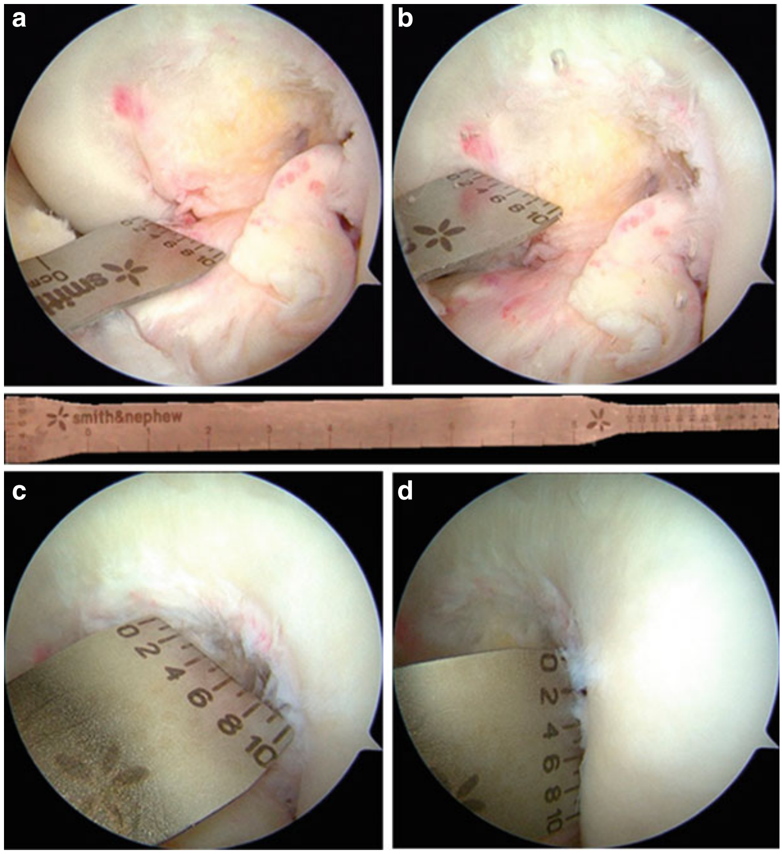

Fig. 21.11 With a ruler, the notch is measured at the base (**a**), midwidth (**b**), apex (**c**), and the height of the medial and lateral (**d**) wall

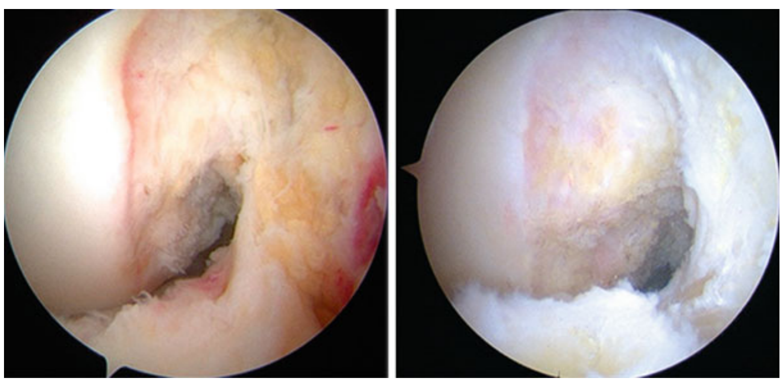

Fig. 21.12 The intercondylar ridge divides the lateral wall in an upper two-third and a lower one-third approximately. The lower one-third usually comprises the ACL insertion site

length is measured with a depth gauge. Adequate tunnel diameter is then established with a manual drill and finalized with a hand dilator.

For the femoral side, almost all steps are identical for the PL tunnel as for the SB tunnel drilling. The main exception is, of course, the tunnel location – in the middle of the insertion site. The other is that an oval shaped dilator is used for femoral SB tunnel dilation, according to the femoral insertion site shape when a soft tissue graft is used.

Next, the tibial tunnels are constructed. Because these tunnels are constructed outside-in, a longitudinal 3-cm incision is made over the anteromedial side of the proximal tibia, centered between the anterior tibial crest and the medial

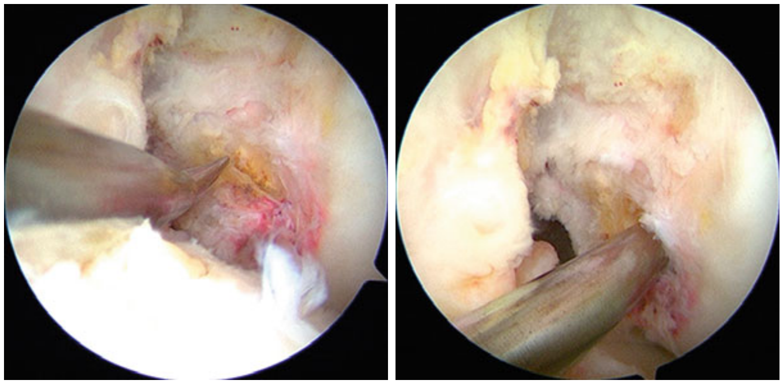

Fig. 21.13 With a Steadman awl, the initial hole for the guide wire to follow into the center of the ACL footprint is created, for a SB reconstruction

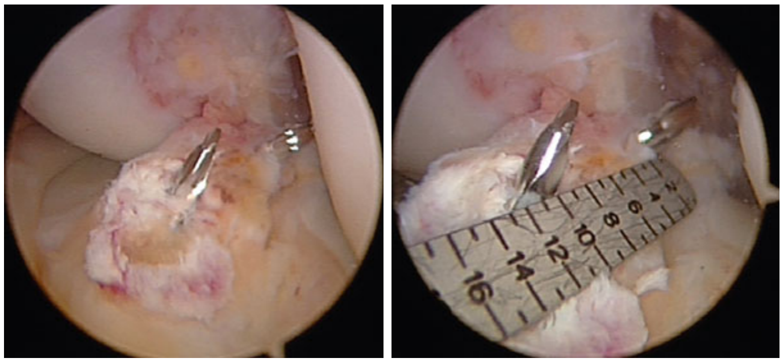

Fig. 21.14 With both the tips intra-articularly in the center of the PL and AM respectively, the distance between the wires is measured to confirm the drilling safety

tibial crest at the level of the anterior tibial tubercule. Then, a tip-to-tip aiming guide – set to 45° – is placed through the CMP or AMP in the center of the marked PL insertion site. Scopic visualization is accomplished through ALP, carefully monitoring the posterior lateral meniscus root not being damaged during drilling. Then, assisted by the aiming guide, a 3.2-mm guide wire is advanced into the joint and left in place with its tip just surfacing in the center of the PL insertion site. After which, the same procedure is repeated for the AM bundle, only now with the aiming guide set at 55°. With both the guide wires intra-articularly (Fig. 21.14) in the center of the PL and AM respectively, the distance between the wires is measured to confirm the drilling safety, ensuring that there will not be possible confluence of both the tunnels. The guide wires should be at least 1 cm from one another in the proximal tibial anteromedial cortex to allow safe drilling without tunnels' confluence. Then, using a cannulated compaction drill, the PL tunnel is drilled. Again, the drill size is 1 mm less than the desired tunnel size. To prevent from potential chondral damage on the femoral side, a curette can be placed over the guide wire tip intra-articularly. Once the tunnel is constructed, further dilatation is carried out by hand. The same procedure is then repeated for the AM tunnel.

SB reconstruction is conducted in a similar fashion. However, only one tunnel is constructed, with the aiming guide set at 55° and aimed right in the center of the footprint between the AM and PL insertion sites (Fig. 21.15).

After tibial tunnel drilling, in DB reconstruction, the femoral AM tunnel still has to be constructed. So the scope is placed through the CMP, and the AM insertion site is visualized. The AM tunnel can be constructed using three different approaches: through the tibial PL tunnel, through the tibial AM tunnel, or through the AMP. Of course, the result – regardless of the approach – should be anatomical placement of the tunnel; to this end, the tibial PL tunnel approach is successful over 60 % of the time, whereas the tibial AM tunnel approach is successful only approximately

Fig. 21.15 One tunnel is constructed, with the aiming guide set at 55° and aimed right in the center of the footprint between the AM and PL insertion sites

10 % of the time [24]. Drilling the femoral AM tunnel through the tibial tunnels has the advantage of more divergent placement of the PL and AM tunnel. Frequently, the PL tunnel has a smaller diameter than the (future) AM tunnel, and transtibial AM drilling (through the tibial PL tunnel) should be done using a half-moon drill bit (Fig. 21.16). If anatomic placement of the AM tunnel is not possible or even when questionable, the AMP approach is always a good option and should be used. Again, the same steps performed to drill the femoral PL tunnel should be conducted for the femoral AM tunnel.

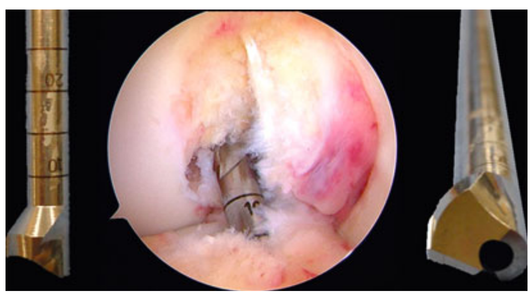

Fig. 21.16 Transtibial (PL to AM) drilling with a half-moon drill bit

With all tunnels in place, the graft(s) may be passed. The PL bundle graft is first advanced through the tibial tunnel and then further advanced through the femoral PL tunnel where it is secured with a suspensory fixation device. Next, the same is done for the AM bundle. Under arthroscopic visualization, both grafts are tensioned and checked for possible impingement throughout full ROM. Of course, finding impingement is very unlikely because the grafts are anatomically

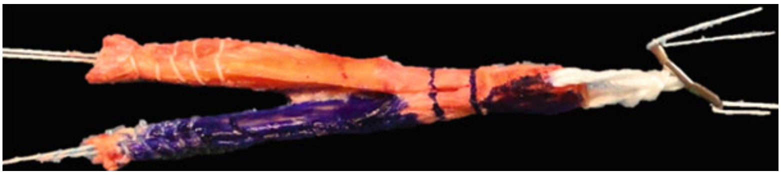

Fig. 21.17 The final (quadriceps tendon) graft: split in the longitudinal direction for a DB procedure, both arms at least 6 cm in length and a patellar bone block (≥10×20 mm)

placed. The knee is then cycled several times, tensioning both bundles and eventually fixated with an interference screw or post-screw and washer, depending on the surgeon's preferences. The PL bundle is fixated in full extension and AM under 45° of flexion. For the SB procedure, graft passage and fixation is identical, but under 15° of flexion. For the three-tunnel technique, the graft is passed through AMP and then to the femoral tunnel. Correct positioning of the bone plug should be verified to assure femoral restoration of PL and AM bundle insertion sites. Subsequent tensioning pattern and fixation is the same as for the DB four-tunnel technique.

Although DB reconstruction is most commonly performed using four tunnels (2 femoral × 2 tibial), a three-tunnel technique (1 femoral × 2 tibial) may sometimes be a useful alternative. This is specifically so when working with a quadriceps graft with a patellar bone block (which can also be used for a SB procedure). Femoral tunnel placement is then done according to the SB procedure, whereas the tibial tunnels are constructed according to the DB technique. The final graft, which is split in the longitudinal direction for a DB procedure, should be at least 6 cm in length in both arms and include a patellar bone block that measures 10×20 mm (Fig. 21.17). While performing surgery, the graft may be prepared on a back table, tailoring it to the specific individual measurements derived from MRI and intraoperatively.

21.5.2 Fibrin Clot

Although an anatomically reconstructed ACL may have little comorbidity and provide a good sense of stability in an early phase already, graft maturation takes time and remains the main argument not to return to (cutting) sport too soon.

In an attempt to enhance the biological healing and maturation process, a fibrin clot is usually added to the graft. During surgery, 50–60 ml of blood is collected from the patient and then slowly stirred in a beaker until a clot has formed (after approximately 5 min). In soft tissue grafts, parts of the fibrin clot are sutured into the proximal and distal ends to enhance healing inside the tunnel too (Fig. 21.18). Eventually, the fibrin clot is placed between the both reconstructed bundles intra-articularly, just before fixating the AM bundle on the tibial side. The AM bundle is – while loose – pulled aside with a looped suture, allowing a cannula to come in through AMP and insert the clot between the both bundles (Fig. 21.19). With the clot in place, AM is then tensioned and fixated.

21.6 Postoperative

21.6.1 Recovery

Immediately after surgery, the knee is immobilized with a brace, and patients are discharged with adequate pain medication and a cooling device the same day. During the first week(s), emphasis is on minimizing pain and swelling and restoring full ROM, particularly extension. The brace should remain locked in extension during the first week, and patients are encouraged to frequently use cold and elevation of the leg. Regaining ROM and muscle function contribute to minimizing swelling and are, of course, important in the general rehabilitation process. The day after surgery patients begin to perform ankle pumps, quadriceps sets, straight leg raises (SLR), gastrocnemius and hamstring stretches, and heel slides. The patient ambulates with axillary crutches using a weight bearing as tolerated gait

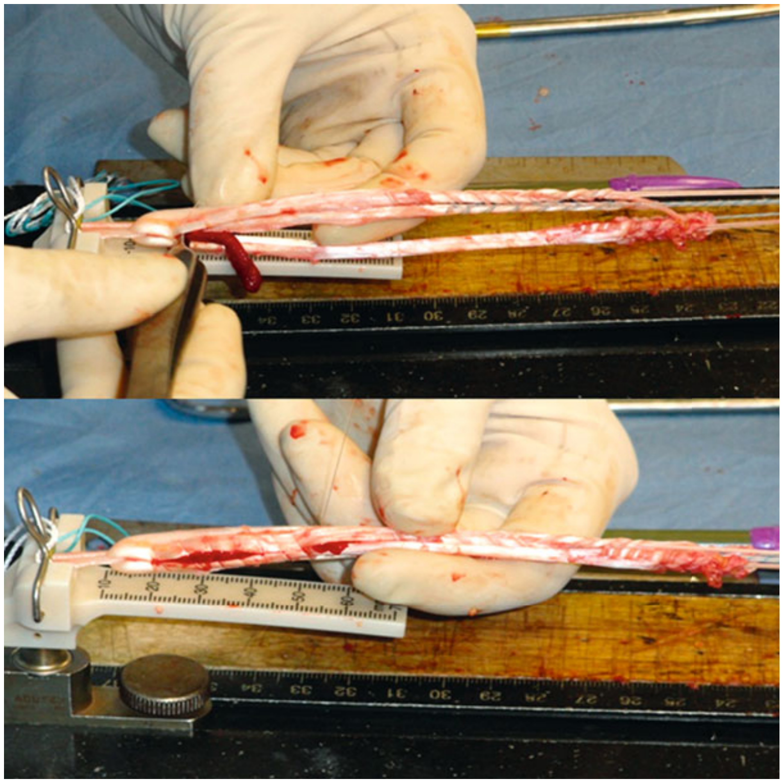

Fig. 21.18 Parts of the fibrin clot are sutured into the proximal and distal ends to enhance healing inside the tunnel too between the both bundles

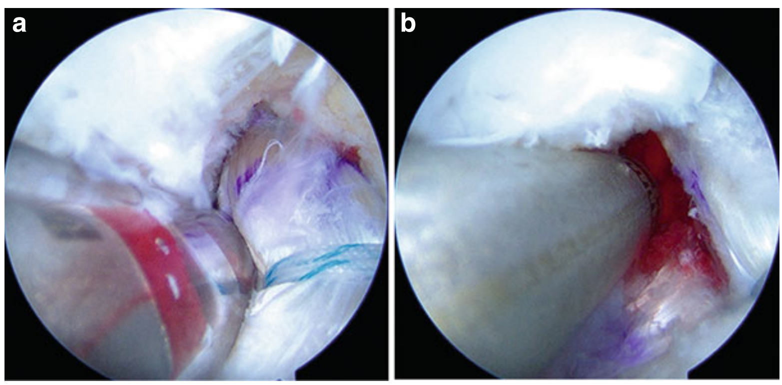

Fig. 21.19 The AM bundle is – while loose – pulled aside with a looped suture (**a**), allowing a cannula to come in through AMP and insert the clot (**b**)

with the brace locked in full extension. Unless the patient has a concomitant meniscus repair, the brace can be unlocked for ambulation at the end of the first postoperative week.

21.6.2 Rehabilitation

During the first few weeks, emphasis is on restoring – and remaining – full ROM and quadriceps muscle strength. The patient is carefully monitored and guided by both the physical therapist and the orthopaedic surgeon. Particularly so because anatomic ACL reconstruction exposes the graft to increased loading, when compared to non-anatomical reconstruction [21]. Caution and protection of the graft during the (early) healing period are of the essence.

Strengthening exercises are slowly introduced and gradually increased. Generally, crutches and brace are weaned after 6 weeks, depending on the progress made. Once quadriceps muscle strength resumes, straight line walking can be initiated at 6 weeks with progression to jogging in a straight line and a stationary bike around 3 months. Pivoting and cutting exercises are not initiated until at least 6 months and return sport is generally no sooner than 9 months postoperative (with or without a functional brace depending on discretion of the surgeon and patient).

As mentioned previously, with anatomical reconstruction, patients may have a short(er) recovery and rehabilitation period and feel confident to return to sport in an early phase already. However, this may be deceiving because the graft remains weak and is subject to higher forces too [23]. Healing and maturation are generally thought of to take a long time, but it is not exactly known how long. Moreover, there is no proven objective instrument available to assess the healing stage the graft is in. Potentially, a MRI can help evaluate the stage of healing the graft is in, but to date, this is not decisive.

21.7 Complications

Both DB and SB reconstructions have the same potential general complications including hemarthrosis, effusions, neurovascular injury, arthrofibrosis, wound infection, tibial or femoral fractures, tunnel widening, and DVT.

What's more is that DB reconstruction is a technically more challenging procedure than a SB reconstruction. The concept of anatomical reconstruction should be first solidified in the SB technique before attempting the DB approach.

21.8 Summary

Understanding of native anatomy and biomechanics is the basis of orthopaedic surgery and anatomical ACL reconstruction. Also, recognition of individual variability is vital to provide the best outcome for each individual patient. To this end, it is important to objectify anatomy by taking measurements pre-, intra-, and postoperatively and adjust the surgical procedure accordingly.

Anatomical ACL reconstruction strives to restore the patient's individual, native anatomy of the ACL as closely as possible. As such, the two functionally different but synergistically working bundles – AM and PL – should both be reconstructed similar to the native situation, placing the tunnels in the actual insertion sites and using insertion site diameter to determine actual graft size. Both SB and DB reconstructions can be performed in an anatomical fashion depending on the size of the native ACL.

Rehabilitation should go slow – despite possible marked progression patients may make – and clinicians should refrain from overzealous compliance with the patient to return to activity soon.

21.9 Take Home Messages

- Traditional nonanatomic SB reconstruction does not adequately restore native biomechanical properties of the knee [8, 40] and may cause cartilage thinning [3, 37].
  – Level of evidence: V
- DB reconstruction is clinically superior to traditional SB reconstruction [1, 20, 22, 30, 36, 42, 44].
  – Level of evidence: I
- Anatomic and "double bundle" are two different terms, not to be used interchangeably.
  – Level of evidence: V
- Anatomical reconstruction of the ACL can be defined as the functional restoration of the ACL to its native dimensions, collagen orientation, and insertion sites [39].
  – Level of evidence: V
- Do not let surgery change anatomy. Let anatomy change surgery. Each individual's (anatomy) is different. Therefore, each anatomic ACL reconstruction should be different.
  – Level of evidence: V
- Both SB and DB reconstructions can be performed in an anatomical fashion. The SB technique provides better results in patients with a total tibial insertion site size of <14 mm [33, 35, 39].

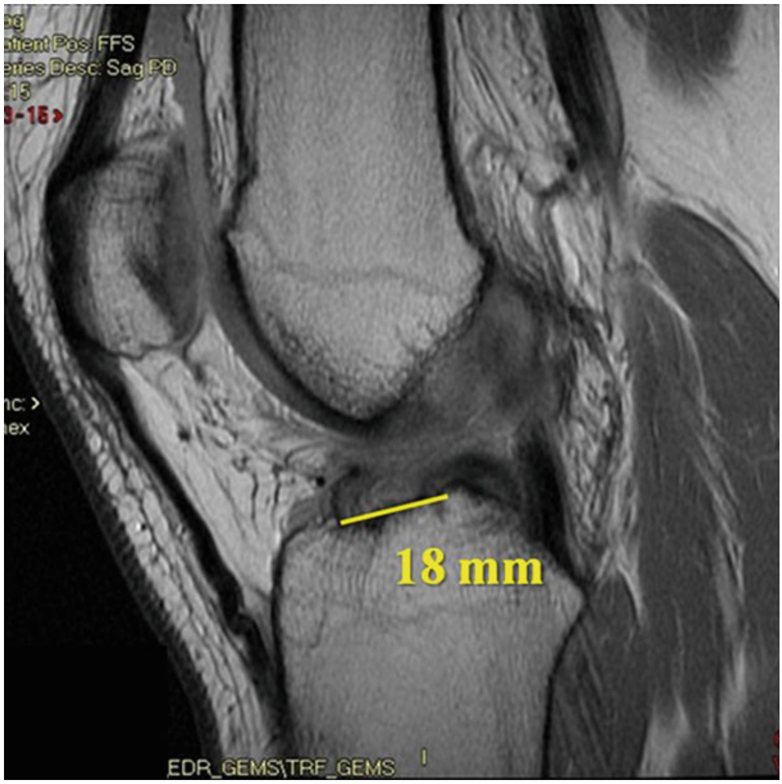

Fig. 21.20 Case 1. The length of tibial insertion site is 18 mm on sagittal MRI

- Level of evidence: V
- See what you are doing. Good vision is vital during surgery and accomplished by using a three-portal technique [4].
- Level of evidence: V
- Let objective findings, such as measurements, guide during deciding on SB or DB reconstruction [39].
  - Level of evidence: V
- Do not hasten rehabilitation. Graft healing and maturation take time [21].
  - Level of evidence: V

21.10 Appendix: ACL Reconstruction: An Individualized Surgery

Case 1

A 22-year-old male, who is 6′ 4″ tall and weighs 345 lb, sustained an injury to the left knee while he was going up for a rebound when playing basketball 1 month ago. He heard a “pop” at the time of injury and had complaints of persistent pain and giving way ever since. Physical examination revealed a grade 1 Lachman test with soft end points and negative pivot-shift test. Measurements with a KT-1000 arthrometer (MEDmetric, San Diego, CA) revealed a side-to-side difference of 2 mm with a 30 lb anterior force and the knee in 30° of flexion. Subsequent MRI showed a ruptured ACL and bone bruising of the lateral femoral condyle. Measurement of the ACL tibial insertion site on sagittal MRI was 18 mm in length (Fig. 21.20).

Two months after injury, we performed ACL reconstruction surgery. During evaluation under anesthesia, the injured knee showed a grade 2 Lachman test with a soft end point, a grade 1 anterior drawer test and a grade 2 pivot-shift test. Arthroscopic evaluation showed a complete AM and PL bundle tear with proximal attachment and no meniscus tear or chondral lesions. Intraoperative arthroscopic measurements with a ruler revealed a tibial insertion site length of 17 mm and midwidth of 10 mm. The femoral insertion site was 16 mm in length and measured 8 mm at midwidth. The intercondylar notch was 11 mm wide at the

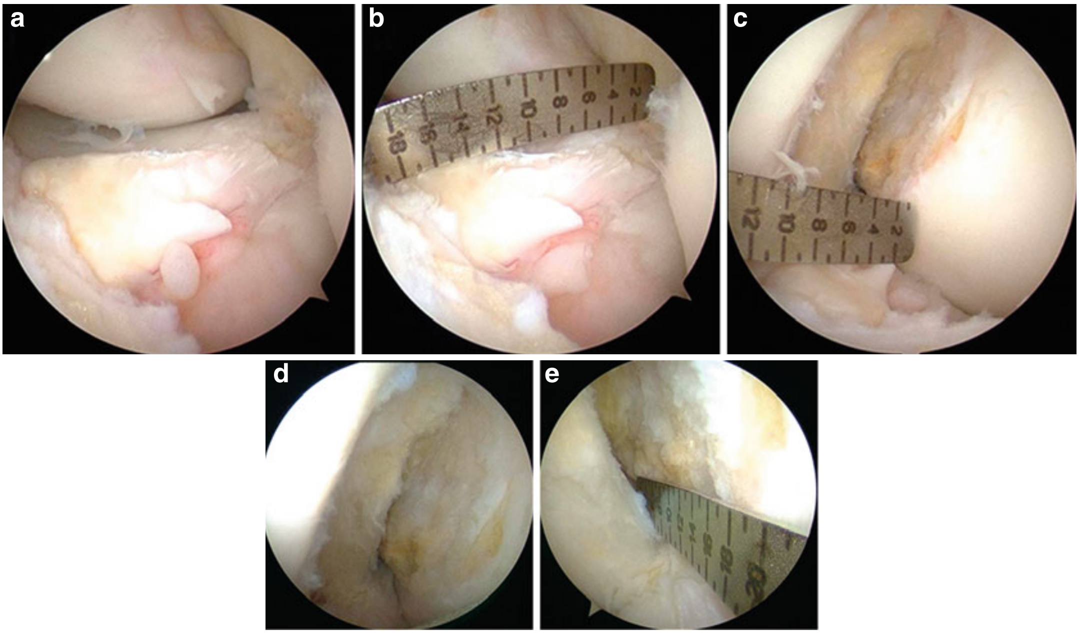

Fig. 21.21 Case 1. Intra-articular measurements of the ACL insertion site and intercondylar notch. Shown are the tibial insertion site (**a**, **b**), the intercondylar notch (**c**), and the femoral insertion site (**d**, **e**)

base, 10 mm wide at midwidth, 6 mm wide at the apex, and 22 mm high (Fig. 21.21).

Case 2

The second case is a 14 year-old female who sustained a twisting injury of her left knee while playing football in gym class. She is 5′ 6″ tall and weighs 110 lb. The office exam demonstrated an anterior unstable left knee with a grade 2 Lachman test with soft end points, a grade 2 pivot-shift test, and 3 mm of side-to-side difference on KT-1000 arthrometer measurements. The MRI revealed a complete intrasubstance tear without meniscal or chondral pathology. The ACL tibial insertion site on sagittal MRI was 17 mm in length (Fig. 21.22). The physes were nearly closed, as evaluated on MRI and X-rays.

Five weeks after injury, we performed ACL reconstruction surgery. Physical examination findings were consistent under anesthesia as compared to preoperative evaluation at office visit. Arthroscopic evaluation showed a complete AM and PL bundle tear with proximal attachment without chondral, cartilage, or meniscal lesions. Intraoperative arthroscopic measurements revealed

Fig. 21.22 Case 2. The length of tibial insertion site is 17 mm on sagittal MRI

18 mm tibial insertion site length and 10 mm midwidth. The femoral insertion site was 13 mm in length and 9 mm at midwidth. The intercondylar notch was 17 mm wide at the base, 14 mm wide in

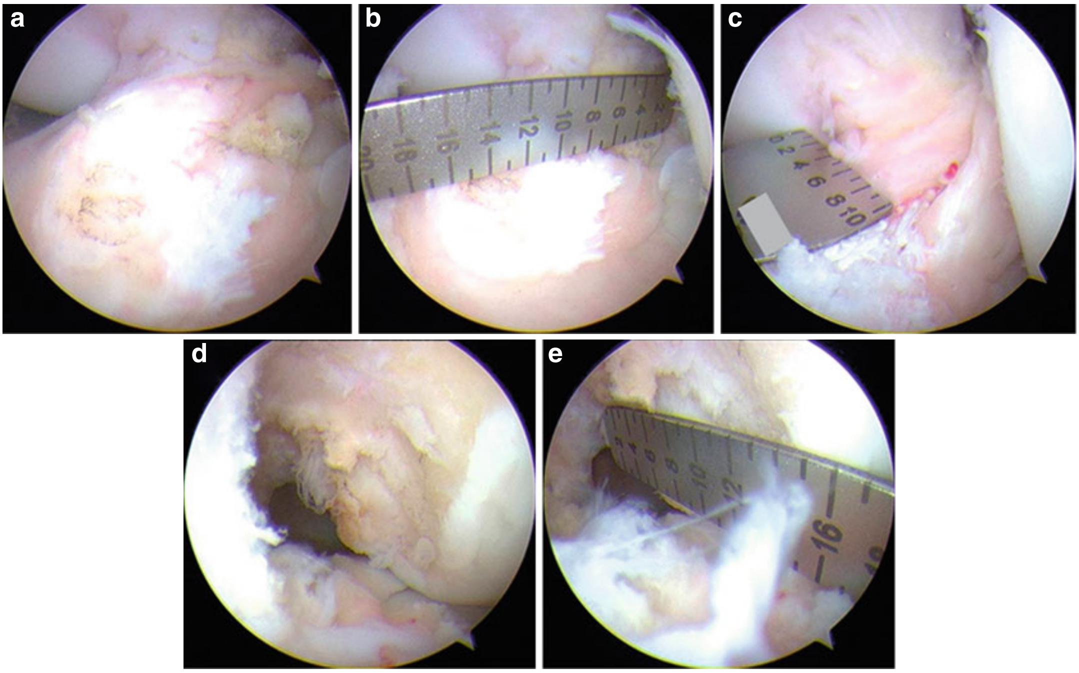

Fig. 21.23 Case 2. Intra-articular measurements of the ACL insertion site and intercondylar notch. Shown are the tibial insertion site (**a**, **b**), the intercondylar notch (**c**), and the femoral insertion site (**d**, **e**)

the middle, 10 mm wide at the apex, and 21 mm high (Fig. 21.23).

Comments About Cases 1 and 2

The anatomical ACL reconstruction concept is based on the morphological characters of each patient and individualizing each surgical procedure accordingly. If the length of tibial insertion site is less than 14 mm arthroscopically, we consider SB reconstruction. Other relative indications for SB reconstruction are open physes, severe bone bruising, a narrow notch, severe arthritic changes, or multiple ligamentous injuries. If the length of tibial insertion site is more than 18 mm, we consider DB reconstruction to fill the native ACL insertion site with graft sufficiently. For patients with a tibial insertion site between 14 and 18 mm, either SB or DB reconstruction can be performed. In these cases, the eventual decision may be guided by cofactors such as femoral insertion morphology, notch size, or complicating injuries.

In Case 1, the tibial insertion site length was 17 mm, and either SB or DB technique can be employed. However, the width of the intercondylar notch was only 11 mm at the base, making a DB procedure technically complicated with the added risk of damaging cartilage on the medial femoral condyle or potentially penetrating the posterior wall of the lateral femoral condyle. Additionally, it is difficult to create both femoral tunnels anatomically. Specifically, the AM insertion site may be hard to reach with a drill. Drilling transtibially may not reach the native insertion site, while drilling through the AMP, the medial condyle may damage. Therefore, we chose for an anatomic SB reconstruction with a transportal technique (Fig. 21.24a).

For the second case, however, the tibial insertion length was 18 mm – which seemed rather large for her height – and she had a 17 mm wide clearance at the base of the intercondylar notch. For these reasons, she was eligible for an anatomic DB reconstruction (Fig. 21.24b). Because of her small stature, her hamstring tendons did

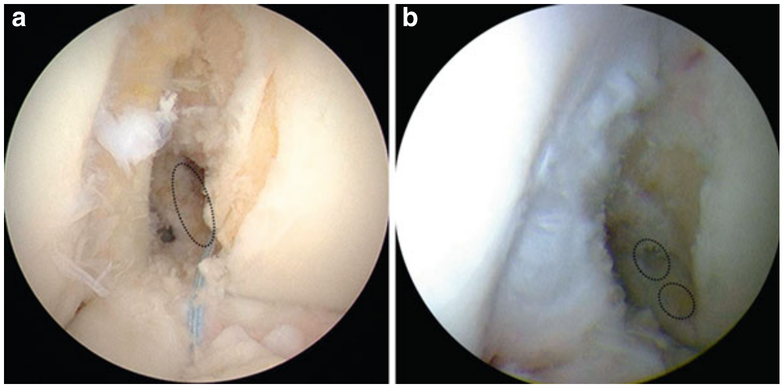

Fig. 21.24 Femoral tunnel positioning in Case 1 (**a**) and Case 2 (**b**) respectively

not provide enough graft to construct two bundles. Therefore, we used an (peroneus longus tendon) allograft for PL bundle and the harvested hamstring autograft for the AM bundle. In this case, the sizable insertion site and notch allowed for a DB reconstruction. Moreover, a SB procedure would have not reconstructed the same percentage of native ACL insertion site (also due to the small graft).

These cases clearly illustrate that body habitus is not always correlated to actual knee anatomy and that objective measurements may greatly vary between individuals.

Conclusion

Anatomic ACL reconstruction is the functional restoration of the ACL to its native dimensions, collagen orientation, and insertion sites, and one of the goals of surgery is to restore the native insertion as completely as possible. In order to achieve this goal, surgeons should strive toward individualizing each surgery with respect to the patient's anatomy. Preceding cases hopefully provide some insight in the considerations a surgeon should make before deciding on the actual procedure. All patients are different and so are their treatment options. For patients with tibial insertion sites between 14 and 18 mm, it can be particularly difficult to decide on the best treatment. Systematically reviewing the possibilities and boundaries in these cases should provide some guidance in the decision-making process.

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Clinical Relevance of Meniscus in the Treatment of the ACL-Deficient Knee: The Real Value of Meniscal Transplantation

22

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22.1 Introduction

There is a general consensus relative to the critical role the meniscus plays in maintaining normal knee function. Load transmission, shock absorption, joint lubrication, and joint congruity are among the main functions that have been well documented [4, 17]. The meniscus, apart from transferring forces across the joint, prevents tibial displacement on the femur particularly when the anterior cruciate ligament (ACL) is torn [17]. The long-term effects of meniscectomy, including articular pain, cartilage deterioration, and final loss of knee function ending in knee osteoarthritis, are also well known [7, 16, 30, 32].

The main function of the ACL is to control both anteroposterior as well as rotary knee stability. Although an ACL tear is one of the most common orthopaedic injuries, isolated injuries to it are uncommon. Most frequently, acute lesions include a combination of the ACL and menisci in both athletes and the general population [4, 19, 43]. Furthermore, chronically unstable knees can do secondary damage to the menisci (if not injured in the acute setting) due to abnormal biomechanics. These knees may later develop osteoarthritis [19, 20, 28, 29].

Allograft meniscal transplantation (AMT) was introduced in the mid-1980s to alleviate joint line

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pain and maintain knee function [24]. Recent long-term follow-ups confirm that this improvement can be maintained over time [39, 41, 43]. However, no current study exists that compares the long-term results of AMT with a meniscectomized control group in which no treatment has been attempted [11].

In order to obtain a functionally stable knee, ACL reconstruction has been extensively practiced since the beginning of the last century [12, 23]. The technique of ACL reconstruction has constantly evolved and been refined over the years, and the results have been rated as excellent or good in most of the published series. However, some aspects of the technique remain controversial, as are surgical technique, tunnel placement, and optimal graft choice [21, 28, 36]. Currently, accurate restoration of knee kinematics seems imperative after ACL reconstruction in order to protect the knee against the possibility of later developing osteoarthritis [40].

Due to the importance of both the meniscus and ACL in the knee joint and the documented deleterious effects that their loss may induce, the idea of a combined reconstruction has recently emerged. This chapter will develop the rationale that the authors currently use with this condition as scarce literature is available on this particular issue.

22.2 Current Trends in Meniscal Substitution

A meniscal tear can be treated with resection, repair, or substitution. Meniscal resection produces long-term deleterious effects for the joint that have been well recognized since the early works of King and Fairbank [7, 13, 16]. Meniscal tissue is largely avascular and thus has an inherently poor ability to heal [25]. Therefore, meniscal repair techniques need not only stabilize the torn tissue but to also enhance the local biological environment in order to promote healing in most instances [25]. The long-term outcome after meniscal repair shows a significant ratio of failures as well as an increased success rate when the repair is performed in combination with an ACL reconstruction [37, 43]. Furthermore, damaged menisci cannot be repaired, and meniscectomy is still inevitable in some cases. Some of these patients will later develop joint line pain, the so-called postmeniscectomy syndrome.

In an attempt to address this syndrome and particularly in young patients, AMT was developed in Germany [24] and was then extended worldwide. Many studies have evaluated the outcomes for AMT at short-, mid-, and long-term follow-up. They consistently agree that this operation provides good to excellent results in terms of pain, knee function, and patient satisfaction [8–10, 33, 34, 39, 41, 43]. In recent systematic reviews of available literature on the matter at hand, the authors found that improvements in both objective and subjective outcome measures are found in relatively young patients without significant chondropathy who underwent concomitant procedures for cartilage defects, limb malalignment, and/or knee instability [6, 11, 22]. Therefore, AMT is currently indicated in nonobese (BMI < 30), nonarthritic young patients with a complete symptomatic meniscal defect. Malalignment, instability, and/or focal chondral injuries may also be accepted as indications if they are addressed prior to or at the time of transplantation [9, 22]. With regard to the technique, the results of some in vitro biomechanical investigations have shown that meniscal transplants that were only fixed with sutures have resulted in load distribution patterns that are similar to meniscectomized knees [1, 2]. However, the use of bone blocs or a meniscus alone only fixed with sutures has proven to be equally safe and reliable over time with no significant clinical differences between them [6, 11, 22, 27]. A precise implantation technique that closely reproduces the original anatomy of the lost meniscus seems to be the only mandatory rule [5, 27].

Lastly, some relevant issues concerning AMT such as the potential chondroprotective effect, the type of implant preservation technique, the implantation procedure, and when to transplant are still to be resolved [6, 11, 22, 27].

Very recently, the limited availability of meniscal allografts along with potential infectious disease transmission has motivated some authors to explore the possibilities of scaffold-guided meniscal tissue regeneration. The device is placed in the space where an irreparably damaged meniscus has been removed and is firmly anchored to the surrounding tissue. Following implantation, the matrix of the implant is invaded by cells and undergoes a process of remodeling that ends up as new meniscus-like tissue. Two types of meniscal scaffolds are already available. The Collagen Meniscus Implant or CMI® (ReGen Biologics, NJ, USA) was developed from bovine collagen in the 1980s [31]. The most recent is Actifit® (Orteq, UK), a polyurethane-based scaffold. Both are intended for partial defects of the meniscal tissue when the horns and rim over the entire meniscus are still intact [42].

One randomized clinical trial and two long-term follow-up studies have proven the CMI to be a reliable tool for pain relieve in previously meniscectomized knees while promoting some degree of new meniscus-like tissue regeneration [26, 45]. According to early reports, Actifit® seems to produce similar short-term results [42].

22.3 Current Trends in ACL Reconstruction

The ACL-deficient knee leads to both anterior and rotatory instability. Over the last 20 years, ACL reconstruction has mainly been performed with a single-bundle, all-endoscopic, single-incision technique due to its reproducibility [23]. One major concern with regard to this technique is the coronal positioning of the femoral tunnel as it is sometimes difficult to drive the femoral step guide to the "over-the-top" position. This results in a vertical graft that is able to restrain AP motion but is less able to restore rotational stability as demonstrated by Loh et al. [18]. Recently, a more horizontal orientation of the graft on the coronal plane has been advocated by many authors in order to obtain a better functional reconstruction. To that end, either an accessory inferomedial drilling portal or an outside-in drilling technique can be used. This type of reconstruction, the so-called anatomic reconstruction that is thus denominated due to the obliquity of the resultant graft, more closely reproduces the original ACL's anatomy and has been noted to limit graft stretching, notch impingement, and overconstriction of the knee [23].

Some authors go one step forward and feel that to fully reproduce the in situ forces of each ACL bundle, a more anatomic double-bundle ACL reconstruction technique is required [40]. In a recent randomized controlled trial, anatomic double-bundle ACL reconstruction showed to be significantly superior to conventional (transtibial) single-bundle ACL reconstruction and better than anatomic single-bundle reconstruction. Although anatomic single-bundle reconstruction was superior to conventional single-bundle reconstruction, these differences were small and may not be clinically relevant [15, 21]. The consequences of the abnormal motion generated in those suboptimally reconstructed knees can be the long-term joint degeneration associated with ACL reconstruction [19, 20, 36, 38].

Assuming that double-bundle ACL reconstruction could provide better outcome for patients in terms of closer restoration of normal knee biomechanics and improving the rotatory laxity of the knee, Longo et al. recently conducted a systematic review to test this hypothesis. From the current evidence available, they concluded that a simple single-bundle ACL reconstruction is a suitable technique, and it should not be abandoned until stronger scientific evidence in favor of double-bundle ACL reconstruction will be produced [21].

Nevertheless, it seems that regardless the final technical option chosen, only an "anatomic" reconstruction is able to reproduce the complex anatomy and function of the ACL, and so the former simple transtibial technique may be responsible for most of the graft failures recorded in previous literature. Therefore, it is no longer acceptable to state that ACL reconstruction cannot reduce the evolution to osteoarthritis of the involved knee unless an anatomic reconstruction has been performed. However, how can these differences influence the final outcome of the ACL reconstructed joint in the long run is still to be answered.

22.4 ACL Reconstruction Plus AMT: Available Data

Meniscal injury has been proved to be an important pathogenic factor in degenerative joint disease as well as increasing instability in ACL-deficient knee. In a recent review, Trojani et al. [38] retrospectively analyzed the causes for failure of ACL reconstruction and the influence of meniscectomies after revision in a multicentric study. They found a 70 % meniscectomy rate in revision ACL reconstruction. When comparing patients with a total meniscectomy ($n=56$) and patients with preserved menisci ($n=65$), a better functional result and knee stability was encountered in the nonmeniscectomized group [38]. Pernin et al. evaluated the long-term outcome (25 years) of ACL reconstruction plus extra-articular augmentation. They found the onset of osteoarthritis to be correlated with medial meniscal status and femoral chondral defects at time of surgery concluding that total medial meniscectomy and articular cartilage damage were risk factors for osteoarthritis. To sum up, it seems that regardless of knee stability obtained after ACL reconstruction, meniscectomy accelerates degenerative joint changes [30].

From the biomechanical point of view, Levy et al. demonstrated in a cadaveric model that excision of the medial meniscus and section of the ACL allowed significantly greater increases in anterior displacement of the knee than those already increased by the isolated section of the ACL [17]. More recently, Spang et al. demonstrated that medial meniscectomy increased ACL strain and produced a significant augment in tibial displacement relative to the femur in the ACL-deficient knee. Conversely, medial AMT was able to restore strain values and displacement values to normal in this cadaveric model [35].

In addition, Musahl et al. demonstrated that the lateral meniscus is a more important restraint to anterior tibial translation during combined valgus and rotatory loads applied during pivoting motion, in a laboratory study [28]. The level of compressive loads supported by a meniscectomized lateral compartment might at least be partially compensated for a lateral meniscal allograft as demonstrated by Huang et al. [14].

In recent literature, among the possible indications for AMT, ACL-deficient patients who have had a prior medial meniscectomy were already included. The idea of a combined reconstruction is based on the benefits from the increased stability afforded by the transplanted medial meniscus [9, 22].

However, only a few series have described the outcome of combined AMT and ACL reconstruction [10, 33, 34, 43]. Graf et al. studied eight patients who underwent medial AMT and ACL reconstruction at an average follow-up time of 9.7 years. All of them had symptomatic knees due to a previous total or near-total medial meniscectomy. With regard to the standard IKDC form scores, one had a nearly normal score, four had abnormal scores, and three severely abnormal scores. At the latest follow-up, the IKDC symptoms evaluation produced two normal scores, five nearly normal scores, and one abnormal score. The IKDC function test showed five normal scores, one nearly normal score, and two abnormal scores. Six of the eight patients were extremely pleased with the function of the knee and were active in recreational sports. All eight patients would recommend the procedure to a friend and would undergo the procedure again given similar circumstances [10].

Rueff et al. followed up at a minimum of 5 years the outcomes of a series of patients after medial meniscus transplantation and primary allograft ACL reconstruction. These series (group 1) were compared with those of age-, sex-, and activity level-matched patients who underwent meniscal repair or partial meniscectomy and allograft primary ACL reconstruction (group 2). Although group 1 had greater preoperative knee pain levels, their pain levels at 5 years postoperatively were comparable to those in group 2. With the exception of swelling, comparable improvements were observed between groups for all other variables [33].

Sekija et al. also studied, at an average of 2.8 years follow-up, the objective and subjective clinical outcomes of a series of 28 patients that underwent combined ACL reconstruction and AMT in an uncontrolled retrospective review. IKDC overall subjective assessment showed 86 % of the series to have normal or nearly normal scores, while SF-36 physical and mental component summary scores were at higher levels than those of the patients' age- and sex-matched populations. Objectively, nearly 90 % had normal or nearly normal Lachman and pivot-shift test scores, and KT-1000 arthrometric testing demonstrated an average increased anterior translation of 1.5 mm compared with the contralateral knee [34].

Von Lewinski et al. recently determined the objective and subjective long-term outcomes of the first free meniscal allograft transplantations after 20 years follow-up. A series of five patients with complete absence or nonrepairable lesion of the medial meniscus underwent concomitant medial meniscal transplantation with a deep frozen meniscal allograft, ACL reconstruction, and femoral advancement of a temporary detachment of the MCL. The clinical outcome of the patients was evaluated using clinical assessment, Lysholm score, KOOS, IKDC score, radiographs, and magnetic resonance imaging. The Lysholm score ranged between 21 and 97 points. The total KOOS ranged between 28.4 and 91.1 %. According to the IKDC score, two patients were rated as nearly normal (B), two as abnormal (C), and one as severely abnormal (D). The radiological evaluation according to the Kellgren-Lawrence classification showed an increase of the degenerative changes between one and four grades. This is the longest available follow-up in a series of patients having combined ACL and AMT. Despite the relative clear results, it is difficult to draw any conclusion due to the fact that some aspects of meniscus transplantation that have not been considered turned out to be important overtime. Several factors might influence the poor results observed: the series is too short, the allografts used were lyophilized, all patients revealed a cartilage damage at the time of surgery, the possible deleterious effects of the MCL advancement were not foresee, and finally the way the ACL was reconstructed, probably far from what today is considered standard [43].

Therefore, according to the available data, this concomitant ACL reconstruction and AMT seems to constantly produce good results. However, the comparison is mainly done with retrospective series of ACL reconstruction plus meniscectomy, and so no definite conclusions can be drawn. Again, there is a need of prospective randomized controlled series comparing both surgical interventions.

22.5 Author's Perspective

Since meniscectomy in an ACL-deficient knee may lead to a significant increase in laxity, combined reconstruction of both structures is plenty of sense. Concomitant ACL reconstruction and meniscus repair have been reported to create a more favorable biological environment for meniscus healing, and so the same philosophy is applied in this case. Although there are no definite guidelines to use this combined surgery, there is increasing evidence on the beneficial effects of this combined approach to the affected knees.

In the author's experience, ACL and AMT combined reconstruction is regularly performed in appropriate candidates since the late 1990s. Selection criteria are as follows: symptomatic meniscal defect (either medial or lateral) and ACL torn in a young (meaning patient in a nonprosthetic age) and well aligned patient, with a BMI less than 30 and limited cartilage damage.

Currently, AMT is accepted as a regular technique for those knees with complete absence of meniscal tissue. However, when dealing with partial symptomatic meniscal defects, the most appropriate choice would be a meniscal implant. Meniscal substitution with a collagen meniscal implants (CMI®) either as an isolated procedure or combined with an ACL reconstruction has proven to provide significant pain relief and functional improvement at midterm follow-up [26, 45]. When these implants are compared with simply meniscectomy in patients with chronic problems due to a previous single or multiple meniscal surgeries, the clinical results clearly favor meniscal implantation [31].

22.5.1 Surgical Strategy

The unstable knee can be addressed at the same time as the meniscus transplant as both surgical techniques do not interfere with each other and the rehabilitation protocols are about the same. Nevertheless, there can be some circumstances that prevent the ACL tibial tunnel from being placed at the most appropriate site, particularly when using a bone bridge technique. Such being the case, a staged procedure would be recommendable, and the ACL reconstruction must be done within a 3-month period which is time enough for the bone to heal, as persistent knee instability might be detrimental to the graft [27]. A detailed description of all aspects of the surgical technique of both ACL and AMT reconstruction can be found in several books. However, some particular aspects of the author's surgical strategy for this combined reconstruction are outlined below. Both the AMT and the ACL reconstructions are performed using a total arthroscopic technique due to its reduced surgical morbidity, more precise recognition of the anatomical landmarks, and better cosmetics.

22.5.1.1 Medial Meniscal Transplantation

For medial meniscus transplantation, a two-tunnel technique using bone blocks at both horns of the meniscus is our preference. The surgery is carried out with the patient lying supine in a regular orthopaedic table with a pneumatic tourniquet applied high in the thigh and a lateral pivot to apply valgus stress when needed. After a systematically arthroscopic evaluation of the joint, through conventional anterolateral and anteromedial portals, the meniscal rim or wall of the deficient compartment is freshened up either with a shaver or high-frequency trephination to improve peripheral healing response [25]. A third low anteromedial accessory portal adjacent to the patellar tendon and in line with the anatomical attachment site of the medial meniscus posterior horn is then performed. Using this portal, the meniscal insertion sites are localized with the aid of a regular low-profile ACL tibial guide. A 6–7-mm bone tunnel is drilled starting in the anterior cortex of the tibia for both anterior and posterior horns fixation. In some knees, it might be difficult to get to the posterior horn of the medial meniscus, and a limited notchplasty under the anatomical footprint of the PCL may help to get room in such circumstances (Fig. 22.1). In tight knees, a limited release of the superficial part of the MCL is performed with an 18-gauge spinal needle making several punctures all across the ligament while applying valgus stress. The allograft was previously prepared with n0 high resistance mattress suture placed at each end with a third suture at the union of the posterior and middle thirds (Fig. 22.2).

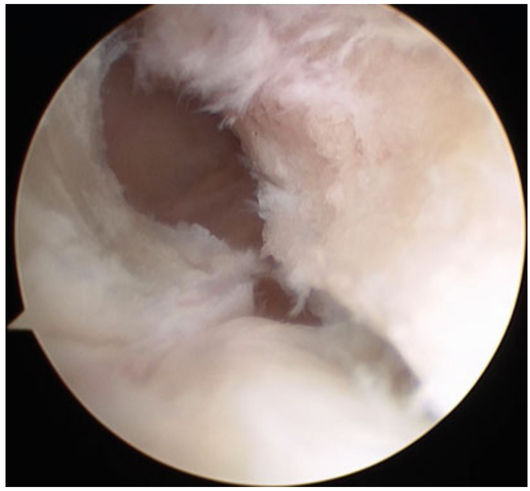

Fig. 22.1 Arthroscopic view of a right knee showing a limited notchplasty of the medial femoral condyle. This maneuver allows the surgeon to see well the insertion site of the medial meniscus posterior horn

Fig. 22.2 Medial meniscus allograft with bone blocks prepared with n0 high resistance mattress suture placed at each horn, ready to be inserted in the joint

Once the meniscal bed and the allograft have been conveniently prepared, the graft is pulled from the previously passed sutures to its anatomic position

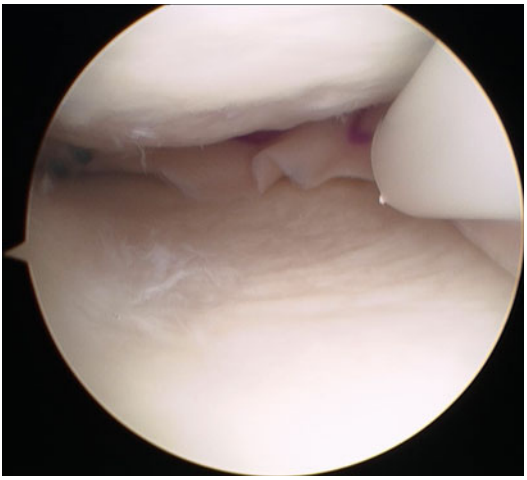

Fig. 22.3 Arthroscopic view of a right knee showing a medial meniscus allograft already in place. Fixation of the posterior half of the graft is performed using an all-inside suturing technique

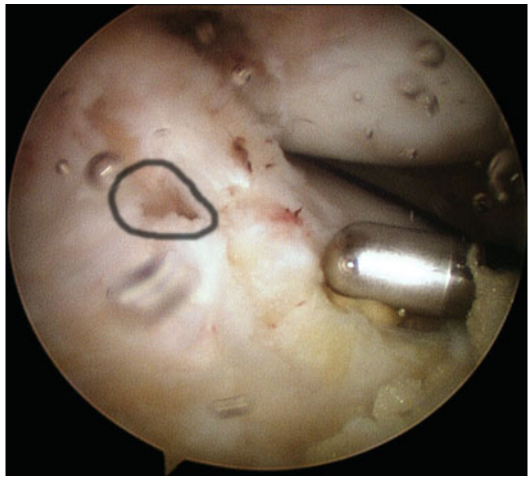

Fig. 22.5 Arthroscopic view of a right knee. Notice the distance between the allograft anterior horn insertion site (tip of the radiofrequency device) and the ideal tibial tunnel for ACL reconstruction (*gray line* framed area)

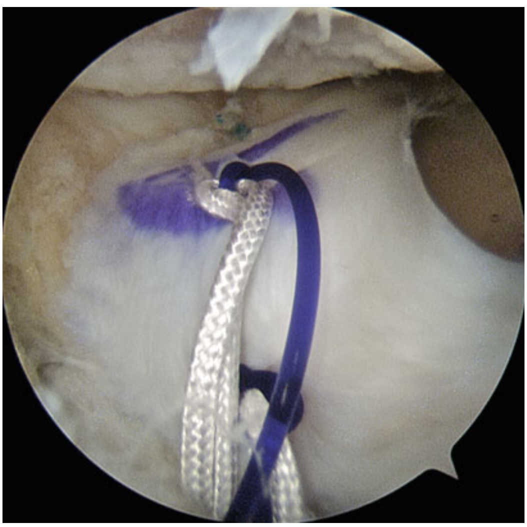

Fig. 22.4 Arthroscopic view of a left knee. Notice the outside-in suture used in the anterior third of the graft

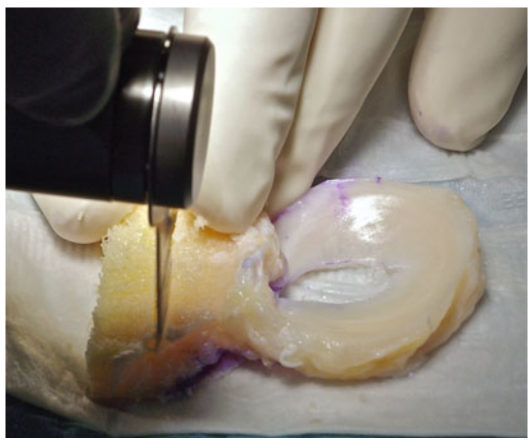

Fig. 22.6 Detail of a lateral meniscus allograft preparation for a bone bridge in slot technique

through an enlarged arthroscopic portal. The further fixation of the allograft is performed using a combination of all-inside (posterior and middle thirds) and outside-in (anterior third) suturing technique (Figs. 22.3 and 22.4) [27].

Due to the anatomical position of the tunnels, no interference with the ACL tunnel is regularly encountered while combining these aforementioned techniques (Fig. 22.5).

22.5.1.2 Lateral Meniscal Transplantation

For the lateral meniscus, a bone bridge technique that better preserves the native distance between horns and eliminates the risk of their incorrect placement is the author's preference (Fig. 22.6). This technique requires an especial set of instruments (Meniscal Transplant Set, Stryker Orthopaedics, Mahwah, NJ 07430, USA). The patient also lies supine with a high tourniquet in the involved thigh with both legs

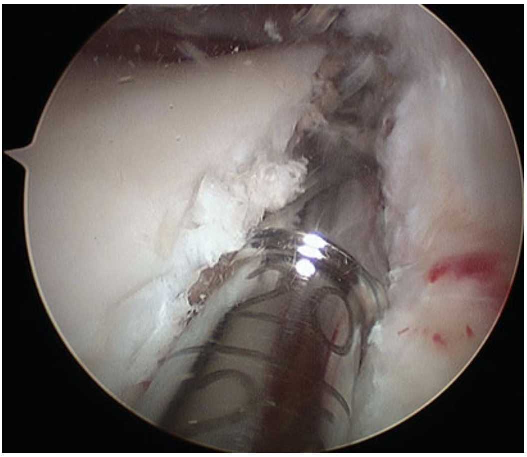

Fig. 22.7 Arthroscopic view of a 7-mm drill, initiating the trough

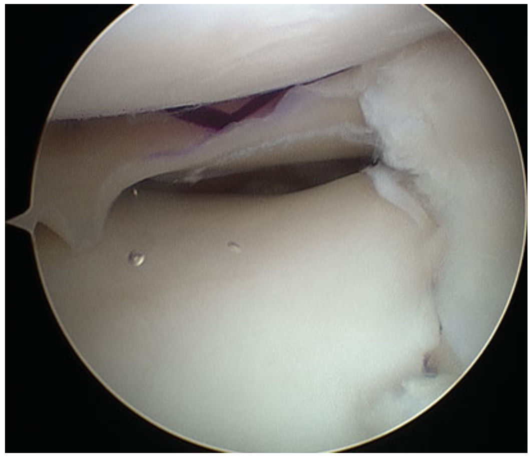

Fig. 22.8 The meniscus graft is visualized in the lateral compartment. Proper placement and fixation of the bone bar and meniscus is verified

free to facilitate the figure-of-four position. The procedure requires the creation of a slot in the tibial plateau, at the level of the lateral tibial spine, where the bone of the allograft bridging the meniscus horns is to be accommodated. In this technique, a guide pin connecting the anterior and posterior horns is introduced through a low anterolateral portal (created at the same level of the lateral meniscus just in line with the desired position of the planned trough). The inserted pin is followed by a drill and finally shaped with a 7- or 8-mm-width box cutter to create the trough (Fig. 22.7). Finally, a rasp is used to smooth out the edges of the slot. The same width and length matched size must be obtained with the graft. The graft is placed in its bed simply by sliding through the enlarged (some 2.5 cm) low anterolateral portal (Fig. 22.8). The bone bar can be ultimately fixed with an interference screw or left alone, as the authors do, assuming that the bar is kept in place by the joint congruence (Fig. 22.9) [27].

22.5.1.3 Especial Considerations

In skeletally immature patients, the technique of AMT varies a little bit from the one used in the medial side. The graft is prepared without any bone at its ends. Thinner bone tunnels (5–6 mm) are used in order not to injury the still open physeal plates. The rest of the procedure is about the same.

If a scaffold is to be used, the surgical technique is much easier as no tunnels are needed. The surgeon simply prepares and measures the meniscus bed, cuts the implant to the desired measure, and introduces and fixes it in place using a regular meniscal suture technique.

No drain is used after surgery since a postoperative blood effusion might create an appropriate biological environment for the healing process to start.

The rehabilitation process is quite similar to what is recommended after ACL plus meniscal suture.

22.5.1.4 ACL Reconstruction

In case of a combined ACL reconstruction, the two-tunnel technique for AMT, either with or without bone blocks, is preferred. When a bone bridge and slot technique is to be used, the authors do prefer to stage the procedure doing first the AMT and delaying the ACL reconstruction some 3 months.

With the knee in 110º of flexion kept in place with the help of a foot support and the scope in the high AM portal to better identify the ACL's femoral footprint on the lateral wall of the notch, a tunnel centered in the bifurcate ridge is drilled

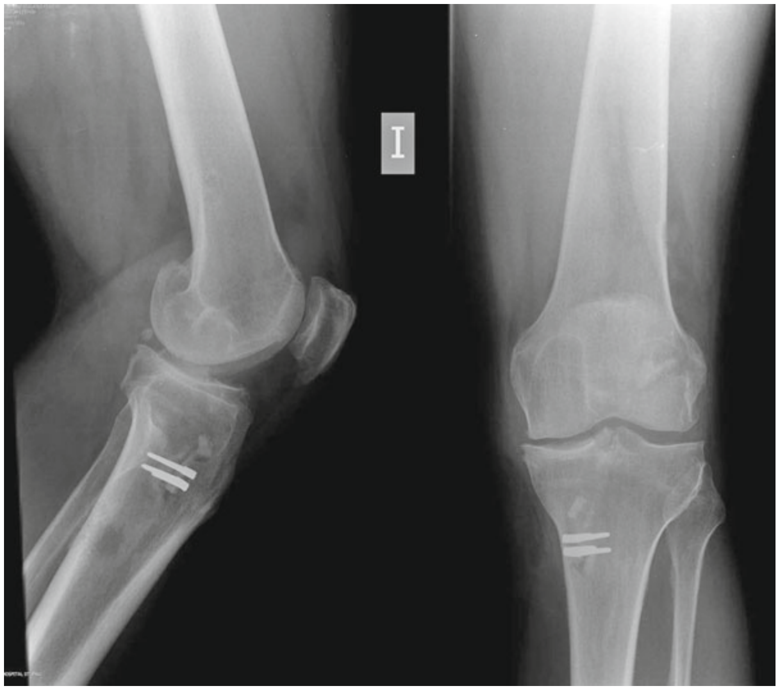

Fig. 22.9 Three months AP and lateral postoperative X-ray of a patient after combined medial meniscus transplantation and a bone-patellar tendon-bone ACL anatomic reconstruction performed at the same time. Fixation of the ACL graft was done with absorbable interference screws at both sides, and additional staples were used in the tibia as the graft was too long. Note the nonfixed bone bar perfectly healed in the tibial bed

using an especial aimer (Bullseye, ConMed Linvatec Inc., Largo, FL, USA). The remnants of the native ligament may also help in localizing the exact femoral insertion site. Then, the tibial tunnel is drilled with the knee at 90º of flexion at the most appropriate part of the anatomical footprint. The medial tibial spine and the anterior horn of the lateral meniscus are the two most used landmarks for proper placement of this tunnel. Attention must be paid to avoid any convergence of the previous tunnels drilled for the AMT. When combining ACL plus AMT, all tunnels needed are drilled first and then the AMT is performed. Once the meniscal graft is introduced and fixed through both tunnels, it is preconditioned with few cycles of movement. As a last step, the ACL graft is introduced and fixed.

As mentioned before, in the case of lateral meniscus transplant, there may be some interference that prevents the ACL tibial tunnel from being placed at the most appropriate site particularly when using a bone bar technique. Such being the case, a staged procedure is recommended. However, ACL reconstruction should be completed once the bone bar is radiologically healed because knee instability might be detrimental to the graft.

22.5.1.5 Combined or Additional Procedures

Chondral injuries are commonly encountered in this kind of patients, and its treatment is an important step in the whole procedure [29, 44]. The surgical option depends on the size, depth, and localization of the lesion as well as the surgeon's experience. However, it is likely that those treatment modalities that include bone marrow stimulation (microfracture technique) are more appropriate as they may create an adequate biological environment for the cartilage, the transplant, and the ACL to heal.

Finally, malalignment is thought to cause abnormal loading on the meniscal allograft that might produce early graft failure [3, 22, 27]. Therefore, an osteotomy has to be done previously as a staged procedure or at the time of the combined procedure when considering surgery under these circumstances.

Conclusions

Meniscal allograft transplantation was introduced in the 1980s to deal with symptomatic meniscal defects in young patients. It has provided good clinical midterm results when used on patients who have undergone meniscectomy. ACL reconstruction has been refined over the last century rendering good or excellent results in most published series. The limited available information regarding the combination of both procedures gives promising results. In the author's experience, the simultaneous restoration of both meniscal and ACL functions encourages combined ACL reconstruction with AMT for using on appropriate candidates.

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Clinical Relevance of Chondral Lesions in the Treatment of the ACL-Deficient Knee: Microfracture Technique

23

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Contents

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23.1 Introduction

An intimate relationship exists between anterior cruciate ligament (ACL) injuries and chondral injuries, especially in athletes [2, 10, 13, 25]. In the setting of ACL injuries, cartilage injury is often discussed as either focal chondral lesions or chronic chondral degeneration that occurs over time following the injury. In reality, this dichotomy is certainly more intertwined. When the ACL actually ruptures, chondral injury to some extent nearly always occurs. While this relationship may seem intuitive given the consistent "kissing" contusion seen on MRI in the lateral compartment following acute injury, this fact is supported strongly by a recent study in which 100 % of "isolated" ACL tears (42 knees in 40 patients) had MRI evidence of chondral injury when the imaging study was performed within 8 weeks of the knee injury [16].

While some degree of chondral injury apparently occurs with every ACL tear, high-grade focal chondral lesions visible at arthroscopy represent only a portion of these injuries. These high-grade focal lesions can be immediate at the time of injury or occur remotely from the initial injury as a result of continued instability in the knee if ACL treatment is delayed. Albeit with a wide variability, the literature documents the incidence of both the acute high-grade focal defect and the development of a subsequent focal defect following delayed therapeutic intervention.

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23.2 Background

In a systematic review of combined ACL injuries and acute high-grade chondral defects, the incidence of high-grade cartilage injury in acute ACL tears is reported to be between 16 and 46 %. These data were compiled from five studies published between 1985 and 2008 that documented chondral injuries in knees that were evaluated within 3 months of the injury [3]. In another study, Tandogan et al. reported that 19.1 % (146/764) of patients with ACL tears were found to have at least one chondral lesion. While chondral lesions were noted in all three compartments of the knee, 60 % were found in the medial compartment with the majority of those being in the middle weight-bearing portion of the condyle. Using the ICRS Cartilage Standard Evaluation Form, 23 % were grade 1, 44 % were grade 2, 22 % were grade 3, and 11 % were grade 4 lesions. The mean area of these lesions was 219 ± 175 mm^2. A significant relationship was found between the mean ages of those with grades 3 and 4 lesions versus those with no lesion or grades 1 and 2. In addition, the time from initial injury to arthroscopy correlated with an increased number of grade 3 or 4 lesions. The odds of having a grade 3 or 4 lesion were 2.7 times higher if time from injury was 2–5 years versus 1 year [27].

While simultaneous ACL and chondral injuries definitely occur, the rate of chondral defects in an ACL-deficient knee increases significantly as the time from ACL injury increases. This fact is documented in the publication by Tandogan et al. as well as other studies [12, 14, 20, 27, 29], and this finding is similar in both athlete and non-athlete cohorts [10]. A delay as little as 1 year from the time of injury to ACL treatment yields a statistically higher rate of chondral injury [14]. Yuksel et al. assigned patients with ACL injuries into three groups according to time from injury to treatment—the acute group (0–6 weeks), the subchronic group (6 weeks to 12 months), and the chronic group (greater than 12 months) [29]. Chondral lesions were noted at a rate of 8.9, 25.9, and 69.9 %, respectively, in each group, and these rates were found to be statistically significant in their difference. These rates translated into a relative risk of 3.6 for the subchronic group and a relative risk of 23.8 for the chronic group [29].

With the recognition that these focal defects occur at a not-insignificant level, the question emerges as to the clinical relevance of these defects in the setting of the ACL-injured knee. This very question was addressed in a study by Shelbourne et al. [19]. They evaluated two cohorts of ACL-reconstructed patients: one group of patients had Outerbridge grade 3 or 4 chondral defects that were left untreated, and a second group had no chondral defects. The authors noted that the defect group had statistically significant lower subjective scores than the no defect group; however, the subjective scores were high enough to indicate few symptoms. In addition, the scores obtained from the defect group were equal to a previously surveyed non-injured athlete group. Despite this difference, no differences were detected between objective measurements and activity levels, and the authors conclude that little difference existed between the two groups at greater than 6 years from the time of surgery [19].

The idea that chondral defects render little effect on the outcomes of ACL reconstruction was further supported by Widuchowski et al. [28]. This group identified 51 patients with Outerbridge grade 3 or 4 chondral defects from 586 ACL reconstructions. Similar to the above study, these chondral defects were left untreated. At both 10 and 15 years of follow-up, no differences in Lysholm, Tegner, and IKDC scores were found when a comparison was made to a control group of ACL injuries without chondral defects [28].

In contrast, a recently published study based on data from the Norwegian National Knee Ligament Registry reported that patients with focal full-thickness cartilage lesions and ACL reconstruction do not fare as well as patients with ACL reconstruction without full-thickness chondral defects [18]. The outcomes measure used in this study was the Knee Injury and Osteoarthritis Outcome Score (KOOS) over a 2- to 5-year follow-up period [18]. Certainly, the results of the other studies are based on longer-term follow-up; therefore, the question remains as to whether the result of this shorter-term study will change over time. Further study is needed to answer this question. In addition, prospective studies are needed to determine definitively if chondral defects influence outcomes of ACL reconstruction.

With the discrepancy noted above, no specific algorithm exists to guide the surgeon in the treatment of high-grade focal chondral defects in the setting of the ACL-injured knee. In the absence of an ACL injury, focal chondral defects can cause pain, effusion, and mechanical symptoms that would likewise prevent effective return to high-level activity. With the typical ACL-injured patient being an active patient involved in high-impact sporting activities, it is difficult for most surgeons to simply ignore a high-grade chondral lesion at the time of surgical intervention to treat the ACL injury.

While effective stability can be achieved reliably with ACL reconstruction, the optimal management of chondral defects in the setting of ACL injuries is not known; hence, the ability to halt chondral degeneration in the knee remains elusive. A number of techniques exist for the management of focal cartilage defects including debridement with lavage, marrow stimulation techniques, osteochondral autografts or allografts, autologous chondrocyte implantation, and periosteal transplantation [1, 7, 8]. Unfortunately, the literature is sparse in studies which specifically address management of focal chondral defects in ACL-deficient knees. Despite this lack, it seems appropriate to the authors to manage high-grade focal chondral defects simultaneously with ACL surgical treatment. An unstable knee leads to higher risk of chondral damage, and chondral damage in a reconstructed knee may lead to persistent symptoms that prevent full recovery [10, 14, 27, 29].

As it is well documented in the literature, cartilage has a poor intrinsic ability to heal. The impact on the cartilage at the time of injury typically kills the chondrocytes in the affected area, or the cartilage fully delaminates leaving an empty defect. The tidemark usually remains intact with a focal cartilage injury which prevents blood from getting to the area of injury, and the synovial fluid does not carry nor bring adequate progenitor or mesenchymal stem cells to the area that would allow for healing of the chondral defect [11].

23.3 Research and Clinical Experience

For the past 30 years, the senior author (JRS) has treated focal full-thickness cartilage defects with microfracture. Microfracture is a minimally invasive, low-cost, straightforward technique developed for the treatment of high-grade cartilage lesions. The technique evolved from previous procedures that accessed the marrow elements in the bone either through abrasion arthroplasty or drilling. Though these earlier techniques accessed the marrow elements, destruction of the subchondral plate and thermal necrosis limited their effectiveness. Microfracture was developed to circumvent these undesirable effects. However, the microfracture "technique" is more than a surgical intervention as it encompasses both a surgical procedure and a customized rehabilitation process [9, 26].

In addition to clinical studies, much of our basic science understanding of microfracture comes from the equine model. A number of studies using horses have been completed that have helped to refine the technique to maximize its clinical effectiveness in patients [4–6].

In the initial study using horses, chondral defects were made arthroscopically. Lesions were then treated with microfracture or left untreated. At 4 months and at 12 months, the defect sites and repair tissue were evaluated. The microfractured lesions were noted to have significantly more repair tissue as well as more type II collagen. It was also noted during evaluation of the specimens that areas where calcified cartilage remained were devoid or at least deficient in repair tissue [4]. This finding led to a subsequent study in which microfracture was performed in the equine model with the calcified cartilage layer removed or retained. The findings from this study demonstrated that removal of the calcified cartilage layer with retention of the underlying subchondral plate yielded more repair tissue and of better quality than leaving the calcified cartilage layer in place [6].

A third key study in the equine model was conducted to better understand the early healing stages of the microfracture procedure in order to refine and validate the rehabilitation process rationale to promote optimal healing. This study demonstrated that type II collagen expression increased through the first 8 weeks following the procedure. In addition, the quality of the tissue at 8 weeks was found to be superior to the tissue at 2 weeks. As a result of this equine study, the protected weight-bearing period following microfracture in clinical patients was set at 8 weeks [5].

When evaluating an ACL-injured patient, particularly in the acute setting, it is difficult by history or physical examination to determine that a high-grade chondral lesion exists concurrently. The surgeon should have a high degree of suspicion for injury in addition to the ACL tear and should work to rule out chondral lesions, meniscus injuries, and other ligament injuries. The role of MRI is especially helpful to determine the presence of a concomitant chondral lesion. If outside the acute phase, pain with persistent or recurrent effusion may suggest the presence of a chondral defect in the ACL-deficient knee.

The goal of microfracture is to provide an environment for reparative tissue to form at the site of a focal high-grade chondral lesion. Microfracture accomplishes this goal in three interconnected ways. First, the marrow elements are accessed and allowed to fill in the defect with a blood and marrow clot, or a "super clot." These marrow elements rich in progenitor cells are reached in a low-energy manner with the use of surgical awls ("pics") such that thermal necrosis is not an issue as is possible with drilling. Second, the separate microfracture holes allow the subchondral plate contour to be maintained, thereby providing a solid foundation for anchoring of the reparative tissue. Third, the roughened surface resulting from the multiple microfracture holes provides a surface to which the clot can readily and solidly adhere.

23.4 Microfracture Surgical Technique

As detailed in multiple publications, the steps for performing microfracture are as follows [21–24]. The microfracture portion of the procedure is done toward the end of the arthroscopic portion of the procedure. The specific timing of this step

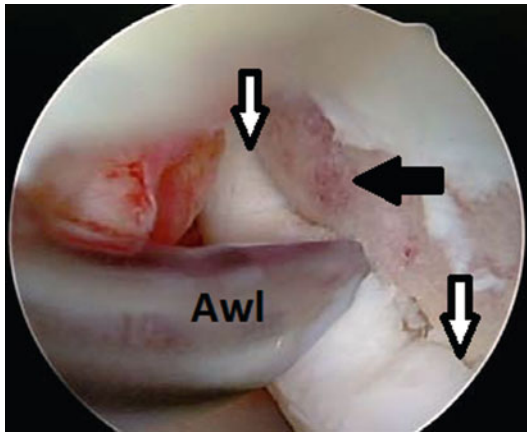

Fig. 23.1 An arthroscopic photograph illustrating microfracture of a femoral condyle lesion. Note the well-shouldered surrounding cartilage (*black and white arrows*) and the removal of the calcified cartilage (*solid black arrow*). The arthroscopic awl is held perpendicular to the bone, and microfractures are made starting at the periphery

may vary depending on the specific surgical technique used for ACL treatment. Nonetheless, the intent is to provide the best possible environment for the "super clot" to form and adhere to the defect site. Though not proven, the additional blood in the joint following ACL reconstruction may enhance filling of the defect.

Upon identifying the defect site, unstable cartilage is removed using a combination of a curved curette and a full radius resector. The goal is to remove as little cartilage as possible that allows for the removal of all unstable pieces and results in a stable and well-shouldered rim of healthy, viable cartilage to contain the clot. The curette is then used to completely remove the calcified cartilage layer while leaving the underlying subchondral plate intact. Arthroscopic awls are then introduced to perforate the subchondral bone. These awls or pics have been designed with 30°, 45°, and 90° angled tips. The 30° and 45° pics are typically used for the femoral condyles and tibial plateaus, whereas the 90° pic is used for the patella. Ideally, a perpendicular angle to the bone is achieved for penetration into the bone (Fig. 23.1).

The microfractures are initially made around the periphery of the lesion. Holes are then peppered throughout the center of the lesion. The holes should be as close together as possible yet of

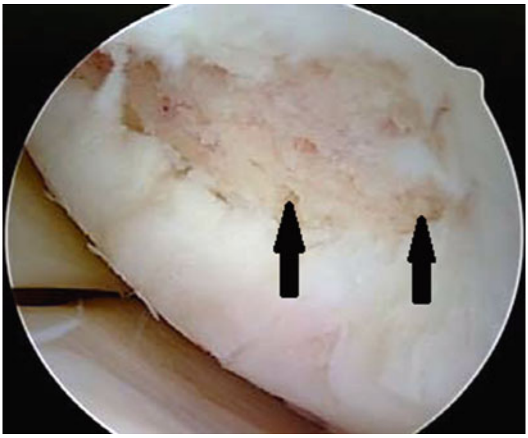

Fig. 23.2 Multiple microfractures have been made around the periphery as well as throughout the central portion of the lesion (*arrows* point to examples). The perforations are spaced enough to maintain the contour of the subchondral bone. Also, the surface is left rough to promote marrow clot adherence

sufficient distance from each other to prevent hole convergence (Fig. 23.2). Ideally, there should be about 10–12 pic holes per cm^2. This spacing will allow for the maintenance of the contour of the subchondral plate. The awl is advanced approximately 2–4 mm in order to access the marrow elements. Often a fat droplet will emerge from the hole indicating that the appropriate depth has been reached. The roughened surface made by the pics allows for the adherence of the marrow clot and therefore should remain as is rather than smoothing the surface. The arthroscopic fluid pump is turned off at the conclusion of the procedure to visualize bleeding from the microfracture perforations (Fig. 23.3).

While the procedure is the same, the patella is often more challenging to microfracture given the angles. The 90° awl is typically used, and the recommendation is to advance the tip into the subchondral bone by hand rather than by mallet to allow for penetration rather than translation or skiving of the instrument. Alternatively, an accessory portal may be required in order to get the appropriate angle with the use of any one of the pics.

The decision to perform microfracture concurrently with the ACL procedure or whether to stage the procedures separately depends on the location of the chondral lesion and other associated pathology. If the lesion is on the femoral condyle or tibial plateau, microfracture and the ACL procedure can typically be carried out at the same surgery. In contrast, the procedures are more often staged if the lesion is on the trochlea or patella. With this scenario, the microfracture would be performed first, and then the ACL procedure would be done 6–12 weeks later. The reason for staging the procedures stems from competing objectives in the rehabilitation protocols. While it may seem convenient to perform the procedures concurrently, it is critically important to consider the rehabilitation process so that the benefit from each procedure is fully maximized.

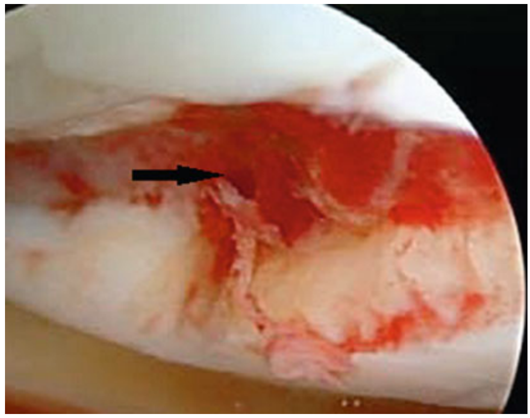

Fig. 23.3 The arthroscopic fluid pressure has been reduced, and bleeding is observed from the microfracture perforations (*arrow* points to example)

23.5 Rehabilitation

The rehabilitation following the procedure is as critical as the actual procedure itself. The customized rehabilitation process has been developed and evolved from the basic science and clinical studies we have done. The intent is to protect the "super clot," as the progenitor and mesenchymal cells in the clot produce the reparative matrix in the defect. Providing the ideal environment allows these cells to produce the functional repair cartilage matrix.

The initial 8 weeks is the critical period to protect the maturing clot. This time frame is scientifically based on the equine study that evaluated stages of healing by week [5]. In addition to protecting the clot, it is important to restore range of motion, regain quadriceps function, and eliminate the joint effusion. Directly after surgery, patients are placed into a continuous passive motion (CPM) machine. The range is initially set at 30–70° for femorotibial lesions and progresses as tolerated. Ideally, the patient will be in the CPM machine 8 h/day for 8 weeks. In a study from 1994, it was shown clearly that patients who used a CPM machine following microfracture demonstrated superior healing compared to patients who did not use the CPM [17]. We restrict weight bearing to crutch-assisted light touchdown for the first 8 weeks, and patellar mobilizations are initiated immediately unless microfracture has been done in the patellofemoral joint. We have found that this simple exercise prevents patellar tendon adhesions. If a patellofemoral microfracture has been done, then patellar mobilizations are delayed for 8 weeks. Isometric quadriceps exercises are initiated, and cryotherapy is used for 7 days [9].

The postoperative rehabilitation is customized to each patient and depends on chondral lesion location and concomitant pathology. For example, a patient with a femorotibial lesion begins using a stationary bike with no or light resistance between 2 and 6 weeks after microfracture depending on lesion size. Aquatic running with the operative leg not touching the bottom of the pool can be started at about 4 weeks.

After the initial 8 weeks, the patient progresses from partial to full weight bearing and active range of motion. When full motion has been achieved, the therapy program transitions to an endurance phase. We rely on cardiovascular equipment such as stationary bikes and treadmills, deep water running, and lap kicking in the pool with increasing intensity during this phase. The patient also begins closed-chain, double-leg exercises with flexion to 30° with graduation to shallow-range single-leg exercises and an elliptical trainer at 4 months after surgery.

At 4–6 months, power-based strengthening begins. This phase can include sports-specific strengthening strategies. A staged running program is started at 25 % speed with 25 % increase in speed weekly. The patient can also initiate single-plane agility exercises with progression to multiplane drills once the running progression is completed.

Not before 6 months, the rehabilitation program then begins to focus on sports-specific agility and movement drills. The goal is to be cleared to return to play between 6 and 9 months depending on the sport.

For patellofemoral lesions, there are numerous modifications, but the principles remain the same. Patients wear a knee immobilizer brace for the first 8 weeks when they are not in the CPM. The CPM initial settings are 0–50° with the same time requirements. Weight bearing is initiated at 30 % of body weight and is progressed to full weight bearing at 2 weeks while in the knee immobilizer. As the patient transitions to the endurance and power strengthening phases, care is taken not to perform exercises at the angle in which the lesion engages in the patellofemoral joint. This angle of engagement should be noted at the time of surgery in order to prevent overloading of the healing area. Sports-specific training should not begin before 6 months, but such training is often delayed if it is a contact sport.

When combining ACL reconstruction with microfracture, the principles of both have to be incorporated into the rehabilitation program. Fortunately, most of the principles initially are the same for variables such as range of motion, swelling control, and quadriceps function. The key consideration for the microfracture is to protect the maturing marrow clot. As long as it is known and communicated to the physical therapist, rehabilitating a simultaneous procedure does not have to be complicated. The progression throughout the rehabilitation process for both microfracture and ACL reconstruction works along a similar timeline with return to sport in the 6–9-month range.

23.6 Published Results

Our institute has published numerous studies on the outcomes of microfracture that have shown encouraging results from the procedure even in high-level football and soccer players [13, 24]. As early as 1994, it was demonstrated that chondral defects improved on average 1.7 grades in patients who do not use postoperative CPM and 2.7 grades in patients who did use CPM [17]. The determination of improvement was made directly from second-look arthroscopy. From this study came the initial intuitive emphasis on postoperative CPM use for 8 h/day for 8 weeks [17].

In 1998, a second study from our institution evaluated microfracture treatment of chondral defects in high-level and recreational athletes [2]. Both groups demonstrated significantly improved functional and symptomatic improvement from preoperative levels. The most dramatic improvement was seen in the first postoperative year with a plateau of results over the ensuing 4–5 years. Of special note, deterioration in functional and symptom scores was not seen in the first 3 years. The athletes who underwent simultaneous ACL reconstruction were analyzed versus patients who did not require ACL reconstruction. Improvement was shown for all outcomes in both groups except for pain in recreational athletes undergoing simultaneous ACL reconstruction and microfracture [2].

A long-term study published in 2003 documented the outcomes of isolated focal chondral defects without concomitant injury treated with microfracture at an average of 11 years follow-up [25]. Pain improved over the initial 2 years following surgery with little change up to 7 years. Swelling followed a similar course with improvement out to 3 years with little change through 7 years. Patients' abilities to do activities of daily living, strenuous work, and sporting activities improved over a 2-year period and remained stable [25]. Consequently, we counsel our microfracture patients that improvement following the procedure is slow but steady with improvement continuing for at least 2 years following the procedure.

Despite the prevalence of chondral lesions with ACL tears and the prevalence of microfracture procedures performed, there is a paucity of literature which specifically evaluates microfracture in conjunction with ACL injury. There are studies which examine simultaneous management of ACL rupture and chondral lesions, but the chondral lesions were treated with ACI, OATs, or periosteal transplantation rather than microfracture [3].

One publication was identified that specifically looked at this combination of procedures. Osti et al. evaluated two cohorts in which patients with an ACL tear, torn meniscus, and an Outerbridge grade 3 or 4 chondral lesion formed group 1 and patients with an ACL tear, torn meniscus, and an Outerbridge grade 1 or 2 chondral lesion formed group 2 [15]. Management of the injured ACL and meniscus was the same in both groups; however, group 1 had microfracture and group 2 had radiofrequency treatment of the respective chondral lesions. The authors reported that at minimum of 5 years follow-up, both groups had excellent clinical and functional improvements according to physical examinations, IKDC scales, Lysholm knee scales, and Tegner activity scales. Despite these significant improvements, the microfracture group with a higher-grade chondral injury at index surgery showed more degenerative changes over time as documented by Fairbank degenerative changes on radiographs and significantly lower WOMAC indices [15].

In our own experience, data from our institute's prospectively collected registry shows that a cohort of 205 ACL reconstructions with an average follow-up of 68 months (range 2–10 years) demonstrated no difference between patients with and without microfracture procedures. The Lysholm scores were 82 in patients who had microfracture and 86 in those who did not ($p > 0.05$). The median Tegner level was 6 ($p > 0.05$) for both groups, and patient satisfaction median was 9 ($p > 0.05$) for both groups. These unpublished data from our registry further confirm that patients with concurrent ACL deficiency and chondral defects can be managed with concurrent ACL treatment and microfracture.

Conclusions

The combination of ACL deficiency and a focal high-grade chondral injury presents a treatment challenge to the orthopaedic surgeon given the paucity of published data currently available for this scenario. A number of techniques have been reported for the management of chondral defects without clear evidence at this time to indicate the definite superiority of one procedure over another. Based on our own extensive research, clinical experience, and documented success, we treat these lesions with microfracture. The importance of this procedure lies not only in the technical aspects during surgery but also in the customized rehabilitation process that promotes the optimal environment for the formation and maturation of the reparative tissue. If both the surgical technique and rehabilitation are followed as we have described, patients do well and can return to their sporting activities.

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The Role of High Tibial Osteotomy in the ACL-Deficient Knee

24

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Contents

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24.1 Introduction

Anterior cruciate ligament (ACL) deficiency in the setting of underlying lower extremity malalignment poses a special clinical challenge for surgeons because of the myriad considerations required to reconstruct a stable, durable, and functional knee. Many clinical and biomechanical studies have examined soft-tissue reconstructions for ACL deficiency, often without consideration for global coronal and/or sagittal plane deformities. Although their relative contributions continue to be debated, malalignment and ACL deficiency, both independently and in combination, can contribute to abnormal knee kinematics, which may hasten the development of osteoarthritis [7, 22, 29, 40]. Therefore, when considering a soft-tissue reconstruction, concomitant assessment of overall alignment is paramount to restoring a functional limb. Several authors have noted that soft-tissue procedures alone have a propensity for failure if concomitant malalignment, particularly varus, is not addressed [32, 34].

In patients with lower extremity varus malalignment and medial compartment gonarthrosis, high tibial osteotomy (HTO) for deformity correction has been associated with delayed progression of arthritis and improved clinical outcomes, especially in patients under 50 years of age [8, 16, 18, 31]. In the younger patient with ACL deficiency and malalignment, HTO in concert with ACL reconstruction (either

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concomitantly or staged) has been shown to improve both knee pain and instability [5, 10, 24, 33]. These procedures, performed in concert, can offset the repetitive abnormal stresses associated with soft-tissue reconstructions in isolation.

24.2 ACL Deficiency and Coronal Plane Malalignment

There is a direct relationship between varus malalignment and ACL tension [26, 27, 44]. In an examination of cadaveric knees loaded in increasing degrees of varus, van de Pol et al. [44] noted tensile forces in the ACL increased from 37.9 to 53.9N. With subsequent resection of the ACL, these same knees demonstrated increasing lateral opening and developed a visible varus thrust with increasing stresses.

Noyes et al. have previously described primary-, double-, and triple-varus knee syndromes [33]. *Primary varus* is defined by a shift of the weight-bearing axis stemming from medial compartment narrowing due to meniscal loss or chondral damage. With progressive medial compartment narrowing, a *double varus* condition develops as the posterolateral restraints become lax, leading to separation of the lateral tibiofemoral articulation. As the varus malalignment becomes more chronic, a hyperextension varus-recurvatum deformity develops. This constellation is referred to as *triple varus*. Although reconstruction of the ACL in a triple-varus knee will alleviate the anterior tibial translation, the underlying varus is not addressed, and consequently, stresses on the reconstructed ACL will be high. High tibial osteotomy in concert with ACL reconstruction can address the triple-varus deformity constellation and minimize stresses on the reconstructed ligament. Additionally, this hyperextension varus-recurvatum deformity can also be accentuated by concomitant posterior cruciate ligament (PCL) and posterolateral corner injuries, requiring special attention and consideration of high tibial osteotomy in the care of multiligamentous instability [23, 25].

24.3 ACL Deficiency and Sagittal Plane Malalignment

Sagittal plane malalignment, such as variations in posterior tibial slope, also has implications for instability in cruciate deficiency. After ACL reconstruction and simultaneous high tibial osteotomy, DeJour et al. [10] noted that postoperative tibial translation was associated with tibial slope. They found a significant positive correlation between anterior tibial translation and increasing posterior tibial slope. Conversely, decreased anterior tibial translation was found with lesser degrees of posterior tibial slope. Giffin et al. [15] further noted increased tibial translation with increasing posterior tibial slope but did not demonstrate altered cruciate kinematics. They concluded that inadvertent alterations of tibial slope during HTO would not alter knee stability or cruciate forces in situ. These findings have been supported by a recent cadaveric study suggesting that large variations of tibial slope can influence the resting position of the tibiofemoral articulation but do not appear to adversely influence the strain environment of the ACL [12].

The posterior tibial slope can be changed by distracting the osteotomy more posteriorly or anteriorly, which changes the resting position of the tibia with respect to the femur. The more posterior slope, the more anterior the resting position. Cruciate-intact knees, however, may be less susceptible to these alterations [12, 15]. It is unclear how alterations of posterior tibial slope affect the integrity of ACL reconstructions in cruciate deficiency, and further studies are necessary to delineate the true effect of sagittal plane adjustment on cruciate kinematics in high tibial osteotomy and ligament reconstruction.

24.4 Indications for Osteotomy

For more than half a century, high tibial osteotomy has been used for correction of lower extremity malalignment and alleviation of unilateral compartment gonarthrosis [19–21]. Coventry [8] initially defined indications for high tibial osteotomy and suggested that the optimal candidate was relatively active, with a stable knee, good range of motion, localized medial compartment osteoarthritis, and age less than 65 years. Due to concomitant surgical procedures, contemporary indications for HTO have expanded to encompass coronal and sagittal malalignment, anteroposterior and varus/valgus instability, and ligamentous deficiency [9, 10, 33, 36]. In patients with ACL insufficiency, symptomatic instability, and coronal and/or sagittal malalignment, the surgeon should consider correction of the underlying malalignment in addition to soft-tissue reconstruction [5, 9, 10, 14, 15, 24, 33]. Table 24.1 summarizes the author's indications for osteotomy in the setting of instability.

When a patient with ACL deficiency also presents with varus overload and medial compartment osteoarthritis, conservative care should be optimized, including activity modification, physical therapy, and unloader bracing. When arthritic symptoms include sequelae of prior meniscectomy, mechanical axis deviation into the medial compartment, and degenerative changes, high tibial osteotomy may be indicated (Fig. 24.1).

Table 24.1 The author's indications for osteotomy, based on clinical instability

Posterolateral or lateral laxity with varus alignment ± thrust
Cruciate deficiency with varus alignment ± thrust
Combined deficiency with varus alignment ± thrust
Repeat failures of cruciate reconstruction

Younger, active patients with ACL insufficiency and symptomatic instability in the setting of underlying or secondary malalignment may be candidates for combined ACL/HTO procedures. Patients who have undergone previous ACL reconstruction, yet maintain an underlying malalignment, may continue to have symptoms of pain, instability, and/or laxity. Furthermore, in the setting of an unsuccessful soft-tissue reconstruction, the surgeon must consider failure to address an underlying malalignment at the index procedure as a contributing factor in graft failure [32, 34]. There is no specific threshold age limit for consideration of these procedures, and the correct approach must be tailored to the patient's specific activity level and expectations.

24.5 Preoperative Evaluation

The preoperative evaluation should include a detailed medical history, physical examination, and appropriate imaging studies. The symptoms and age of the patient demand special attention. In general, the younger the patient, the more active they are likely to be and, therefore, the more likely to have true instability from the ACL deficiency. In the older patient with chronic

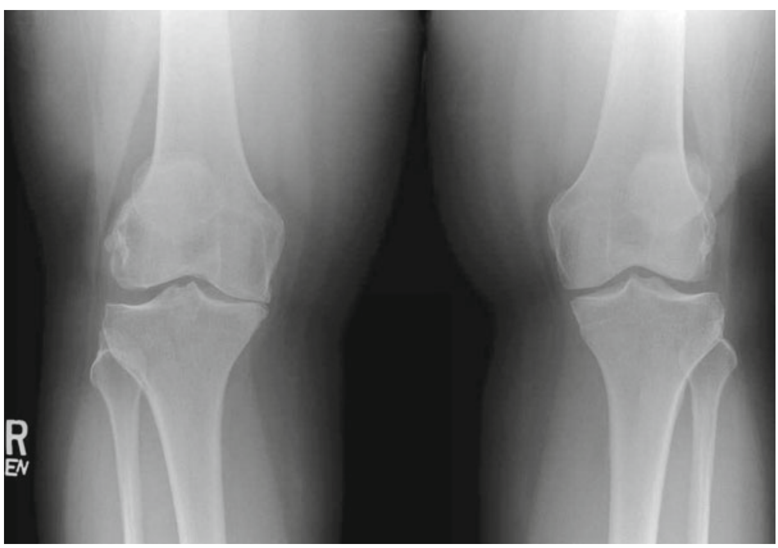


Fig. 24.1 A 42-year old female with ACL insufficiency and medial compartment degeneration from prior meniscectomy and long-standing varus malalignment

ACL deficiency, symptoms may be more likely to originate from degenerative changes. Such patients may benefit from HTO in isolation, without the ligamentous reconstruction. Latterman and Jakob [24] suggested a threshold age of 40 years for this treatment, as many of their older patients did very well with HTO alone, but individual treatment should be tailored to individual patient needs. The younger patient with malalignment, ACL deficiency, and instability would likely benefit from both procedures. The ACL reconstruction and HTO can be done as either a single-stage or two-stage procedure. Several authors have described either one- or two-stage procedures with excellent results [2, 4, 5, 10, 24]. The decision to proceed with single-stage or two-stage surgery is therefore dependent on surgeon preference. However, it should be emphasized that correction of malalignment should be the minimum surgical treatment or as the initial procedure in a staged approach. The ACL reconstruction should be performed secondarily, either as the latter half of a combined procedure or as the second stage of a two-stage procedure. In the setting of malalignment, ACL reconstruction in isolation may lead to inferior results, failures, and progression of osteoarthritic change [32].

Bone quality must also be considered, as it may be challenging to obtain robust fixation in patients with osteoporosis and other diseases that affect bone density and quality. Consideration must also be given to other risk factors for failure, including smoking, corticosteroid dependency, chronic illness, immunosuppressants, etc.

Physical examination findings that may support an osteotomy include abnormal gait patterns, lateral thrust, limb alignment in stance, joint line tenderness, etc. Instability tests including Lachman maneuver, pivot shift, anterior drawer, and so forth should be documented. Presence of the *double-* or *triple-varus* constellations should be noted, if present.

Radiographic evaluation begins with standard knee radiographs, including weight-bearing A/P, lateral, posteroanterior tunnel views in 30° of flexion, and merchant patellar views. The surgeon should assess the extent of knee arthrosis, fractures, retained hardware, etc. Lower extremity alignment should be assessed with weight-bearing long-leg (pelvis to ankle) anteroposterior views, which have been shown to be a simple, reliable, and accurate method for determining the degree of malalignment [17, 35, 38]. The HTO correction can also be calculated from these radiographs according to published techniques [11]. The mechanical and weight-bearing axes are estimated, and the correction to be made is then calculated by shifting this axis just lateral to the lateral tibial spine, at a point representing approximately 62 % of the joint surface as referenced from the medial joint line (Fig. 24.2). Care must be taken in the patient with a large, severe, or complex deformity. In such cases, the accurate correction may be difficult to determine. Mathematical modeling, although complex, can aid in the planning of such osteotomies [39].

Magnetic resonance imaging (MRI) is a useful adjunct in the evaluation of the patient with ACL deficiency and malalignment. MRI can provide the surgeon with useful information regarding subtle osseous abnormalities, soft-tissue injury, and meniscal and chondral pathology that may be less evident on plain radiographs.

24.6 Author's Preferred Surgical Technique

The patient is met in the preoperative area and the operative site is marked. Preoperative prophylactic intravenous antibiotics are administered. After surrendering to anesthesia, the patient is positioned supine and a tourniquet is placed high on the thigh. The limb is then prepared and draped in standard fashion (Fig. 24.3).

We begin with low-pressure arthroscopy of the knee to assess the condition of the cartilage surfaces and integrity of the menisci. We do not perform any meniscal transplantation or cartilage resurfacing procedures at the time of this surgery. These procedures, if indicated, are performed in a staged manner at a later date, with the osteotomy being performed first. At the conclusion of arthroscopy, the extremity is exsanguinated, and the tourniquet is inflated for the balance of the osteotomy procedure.

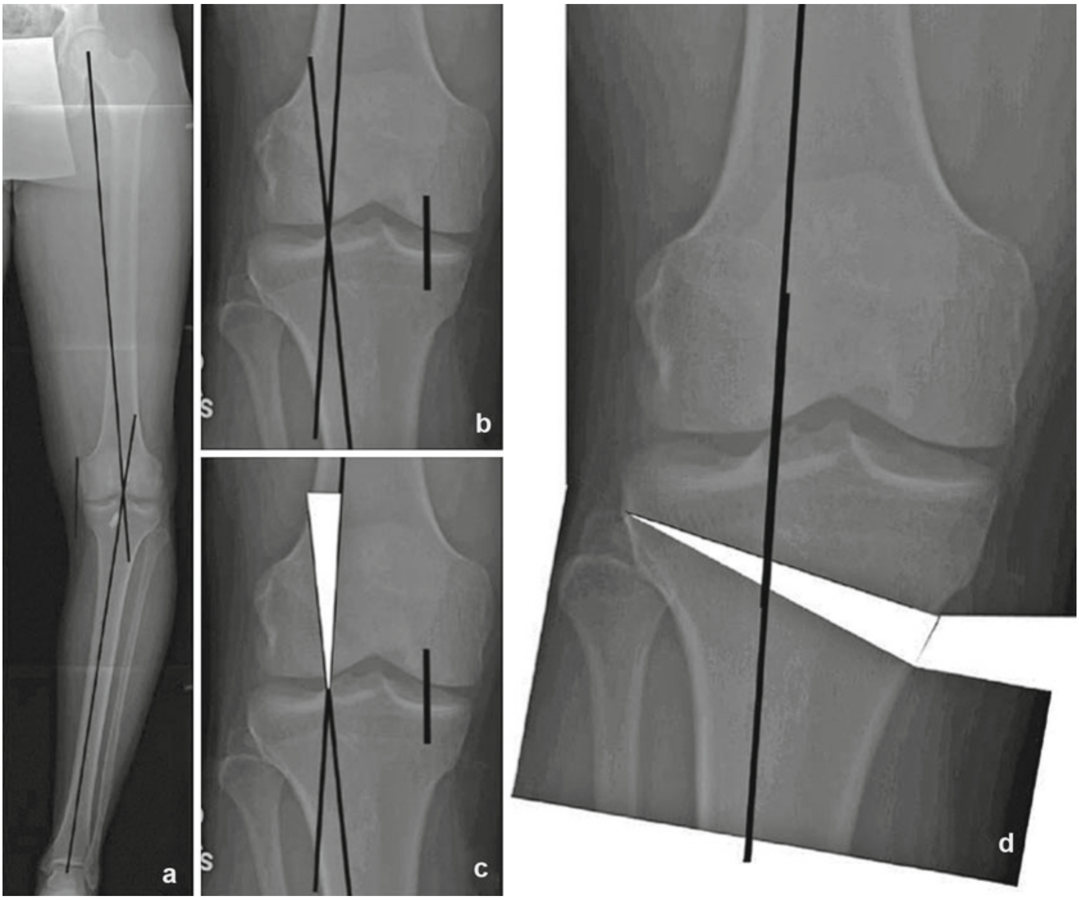


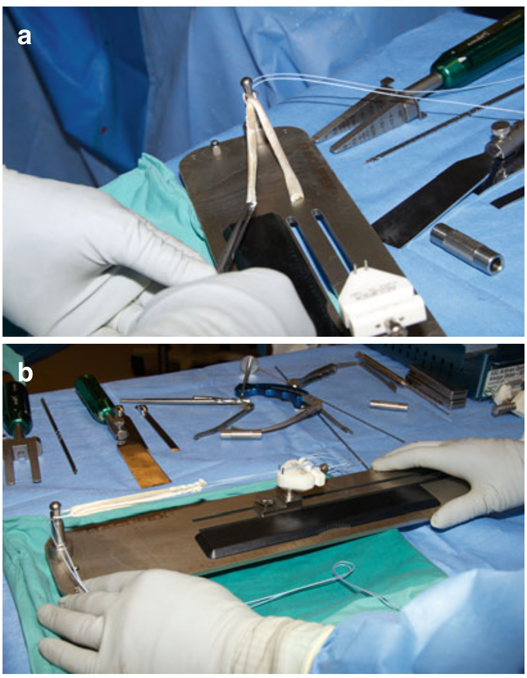
Fig. 24.2 A case of double varus left knee with a failure of previous ACL reconstruction. The patient has both preexisting varus alignment and lateral opening of the knee on a weight-bearing radiograph. (**a**) The right knee was used as a template for the correction of preexisting bony alignment. (**b**) The mechanical axis, shown as a short line, falls into the center of the medial compartment. The new weight-bearing lines are aligned at the point 62.5 % across the width of the tibial plateau, extending proximally to the center of the hip joint and distally to the center of the tibiotalar joint. The size of the opening wedge corresponds to the angle between the weight-bearing lines. (**c**) The medial opening wedge of the proximal tibia is simulated with restoration of the center of the knee joint (**d**) (Figure reproduced with permission from Phisitkul et al. [36])

Fig. 24.3 Patient positioning. The patient is positioned supine, with the foot of the bed extended. An arthroscopy holder or lateral post is employed such that the knee can be flexed off the side of the table for the arthroscopic portion of the surgery

A soft bump is positioned under the leg in order to hyperextend the knee and assist with closing the osteotomy anteriorly. This serves to decrease the tibial slope and therefore anterior tibial translation in the ACL-deficient knee.

A vertical incision is made halfway between the patellar ligament and the posterior border of the tibia, directly over the pes anserinus insertion. Dissection is carried down through skin and subcutaneous tissue to the sartorial fascia (Fig. 24.4). If a hamstring autograft is to be used for the ultimate ACL reconstruction, the gracilis and semitendinosus tendons are harvested at this

Fig. 24.4 Incision. A vertical incision is made halfway between the patellar ligament and the posterior border of the tibia, directly over the pes anserinus insertion. If a hamstring autograft is to be used for the ultimate ACL reconstruction, the gracilis and semitendinosus tendons are also harvested at this time



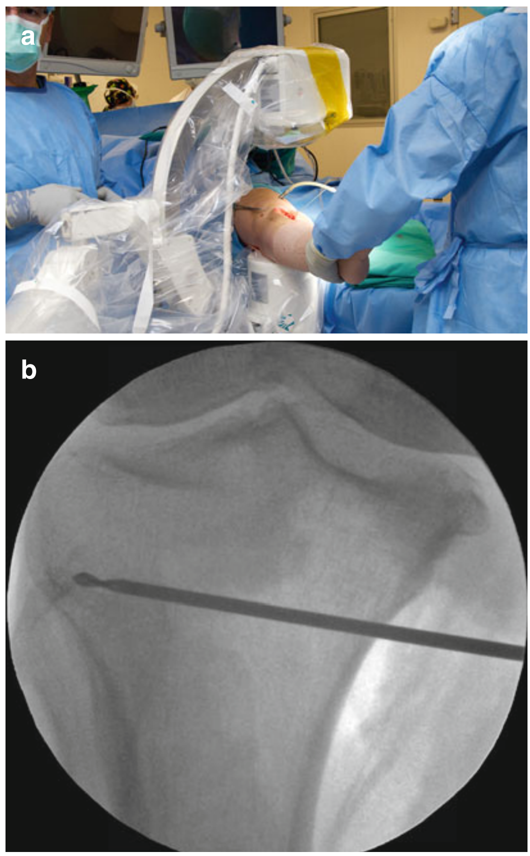
Figs. 24.5 and 24.6 Graft preparation. In this case, a tibialis anterior allograft was used

time. Graft preparation is performed on the back table (Figs. 24.5 and 24.6).

Subperiosteal elevation of the medial collateral ligament (MCL) is performed, and blunt retractors are placed anteriorly behind the patellar ligament and posteriorly in front of the hamstring tendons and superficial MCL.

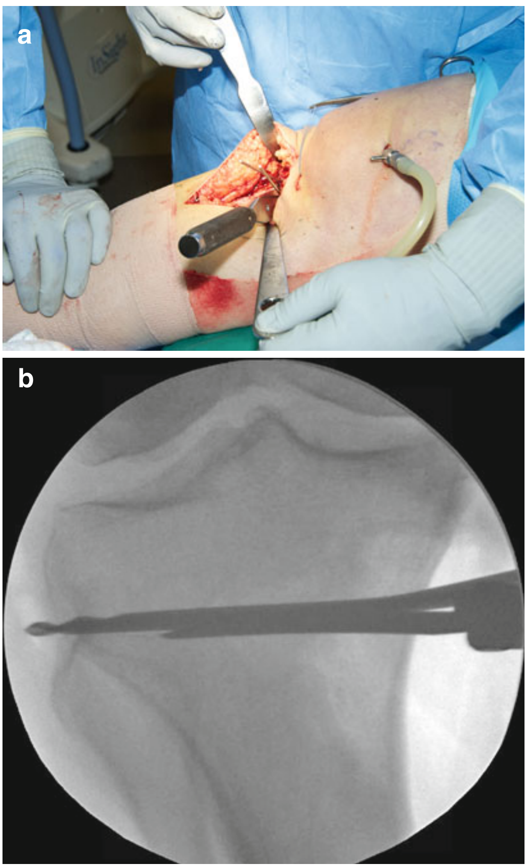
We prefer the medial opening wedge osteotomy for several reasons. The medial opening wedge procedure avoids a secondary osteotomy of the proximal fibula with its concomitant risk of peroneal nerve and posterolateral corner injury [6, 23, 43]. This technique also allows correction in both the coronal and sagittal planes, as hinging through the intact proximal tibiofibular joint decreases the posterior tibial slope [1]. Furthermore, the medial opening wedge incision provides access to the hamstring tendons for autograft ACL reconstruction, as well as convenient positioning of the tibial tunnel.

To perform the medial wedge opening osteotomy, a guide wire is inserted into the proximal tibia from medial to lateral under fluoroscopic

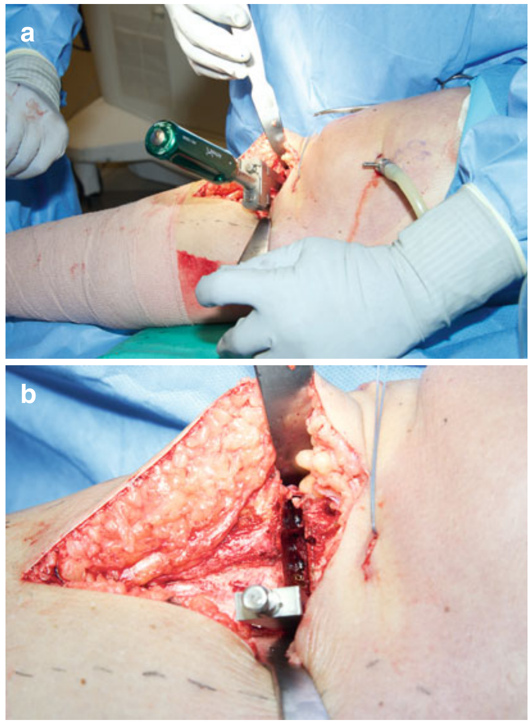


Figs. 24.7 and 24.8 Intraoperative fluoroscopy. The leg can be brought laterally and onto a mini C-arm for radiographic localization

Fig. 24.9 Osteotomy preparation. The proximal guide wires are in place. Retractors protect the medial and posterior soft-tissue structures as well as the patellar ligament. An oscillating saw is used to make the initial shallow cortical cuts



Figs. 24.10 and 24.11 Completion of the osteotomy. An osteotome is used to complete the osteotomy, with positioning confirmed with intraoperative fluoroscopy

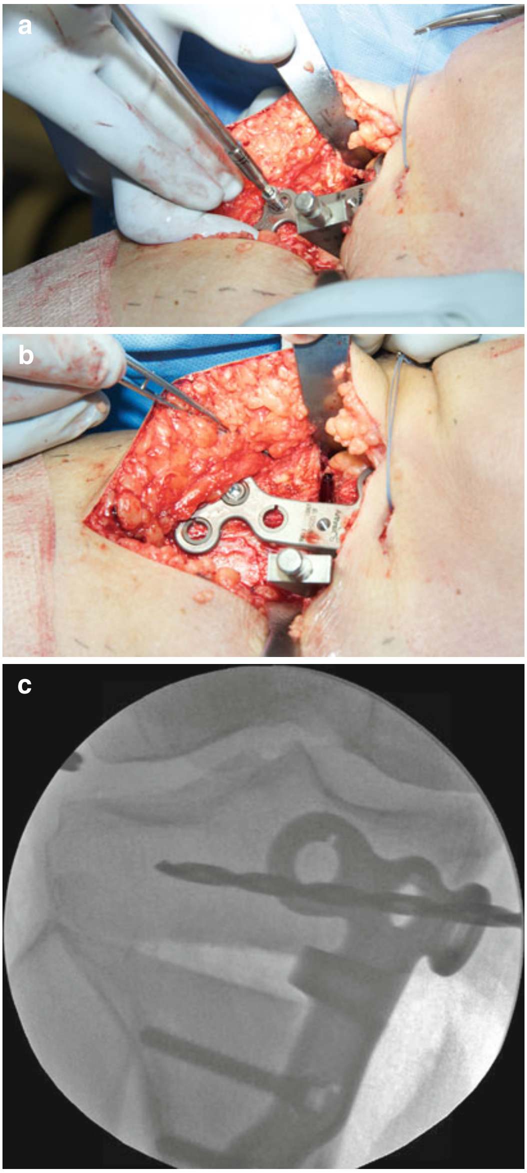


Figs. 24.12 and 24.13 Opening the osteotomy. Temporary wedges (Arthrex, Naples, FL) are employed to open the osteotomy in preparation of fixation

guidance. This wire is oriented obliquely from the superior aspect of the tibial tubercle to a point 1 cm below the lateral joint line at the far lateral tibial cortex (Figs. 24.7 and 24.8). This positioning allows the osteotomy to be proximal to the patellar ligament insertion on the tibia, yet remote enough from the joint to decrease the risk of intra-articular fracture. Furthermore, this allows the osteotomy to be in the metaphyseal region, which is favorable for healing.

The osteotomy is performed with an oscillating saw, oriented just distal to the guide wire to avoid intra-articular extension (Fig. 24.9). Shallow cuts are made with the saw, and the osteotomy is subsequently deepened with flexible and rigid osteotomes, again under fluoroscopic guidance (Figs. 24.10 and 24.11).

The osteotomy is then opened with a medial wedge to a depth predetermined from preoperative radiographic templating (Figs. 24.12 and 24.13). Femorotibial alignment is then estimated by intraoperative fluoroscopy using an



Figs. 24.14, 24.15, and 24.16 Application of the plate. The open wedge plating system (Arthrex, Naples, FL) is used to achieve the desired correction, with screw placement confirmed with intraoperative fluoroscopy

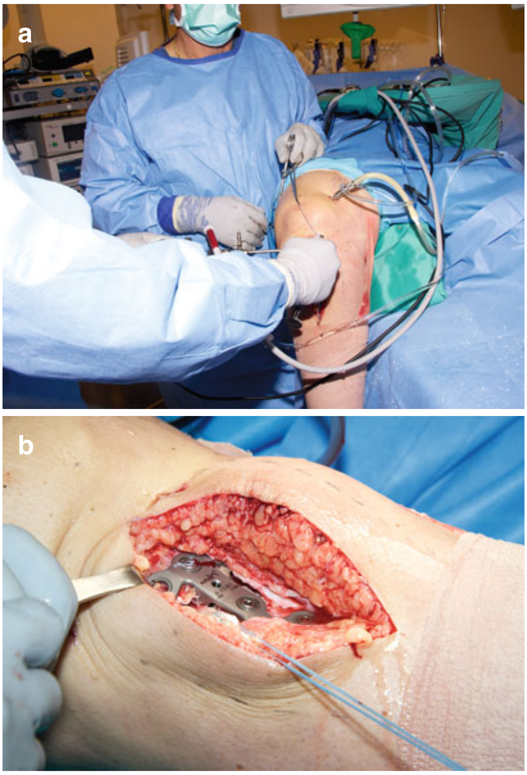
extramedullary alignment guide. Caution must be exercised with these measurements, however, as supine non-weight-bearing estimation of the axis in obese patients or patients with sizable malalignment may not accurately reflect the true mechanical axis [37].

Fig. 24.17 Grafting of the osteotomy. Corticocancellous or synthetic allograft (pictured) is then packed into the osteotomy site

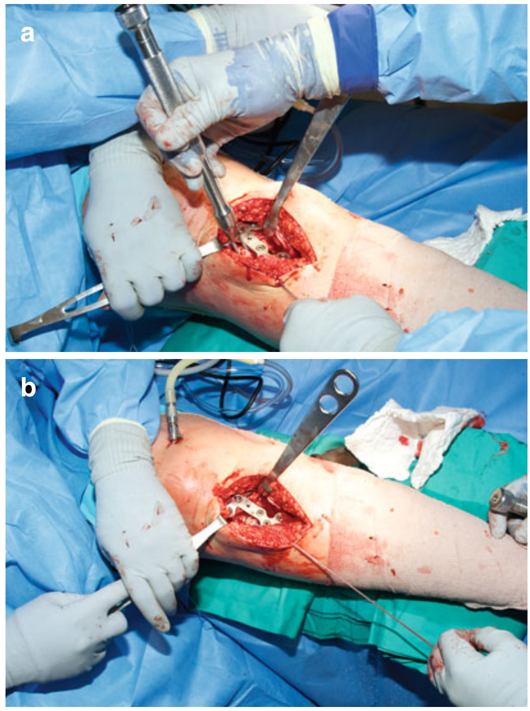
The posterior tibial slope is also assessed fluoroscopically and can be modified by distracting the osteotomy more anteriorly or posteriorly. If there is excessive anterior opening, a tibial tubercle osteotomy may be required to advance the tubercle to the same height as the osteotomy.

With the orientation of the osteotomy complete, an open wedge plating system (Arthrex, Naples, FL) is contoured to the bone and fixed proximally with 6.5-mm cancellous screws and distally with 4.5-mm cortical screws. Screw placement is confirmed with fluoroscopy (Figs. 24.14, 24.15, and 24.16). Corticocancellous allograft wedges (harvested from femoral head allograft) or synthetic allograft wedges are employed to fill the osteotomy site and achieve the desired position (Fig. 24.17).

Having completed the osteotomy, ACL reconstruction then ensues. The osteotomy is performed first to avoid the creation of stress risers in the ACL tunnels and to also avoid inadvertent disruption of the tunnel with the osteotomy. Arthroscopic ACL reconstruction is performed using standard techniques. We prefer to drill the tibial tunnel so that it exits just above the osteotomy site, anteromedially. The femoral tunnel is then drilled, and the ACL graft is passed (Figs. 24.18 and 24.19). We prefer extracortical button fixation for femoral fixation. The tibial side is secured with interference screw fixation above the osteotomy site, with secondary fixation below the osteotomy



Figs. 24.18 and 24.19 Tunnel preparation and graft fixation. The femoral and tibial tunnels are prepared for ACL reconstruction. The ACL graft is passed and secured with extracortical button fixation on the femoral side and with an interference screw on the tibial side, *above* the osteotomy site. The free end of the graft can be seen exiting below the osteotomy site



Figs. 24.20 and 24.21 Secondary tibial fixation. Secondary graft fixation in the tibia can be performed, if warranted. Here, a staple is used to provide backup fixation

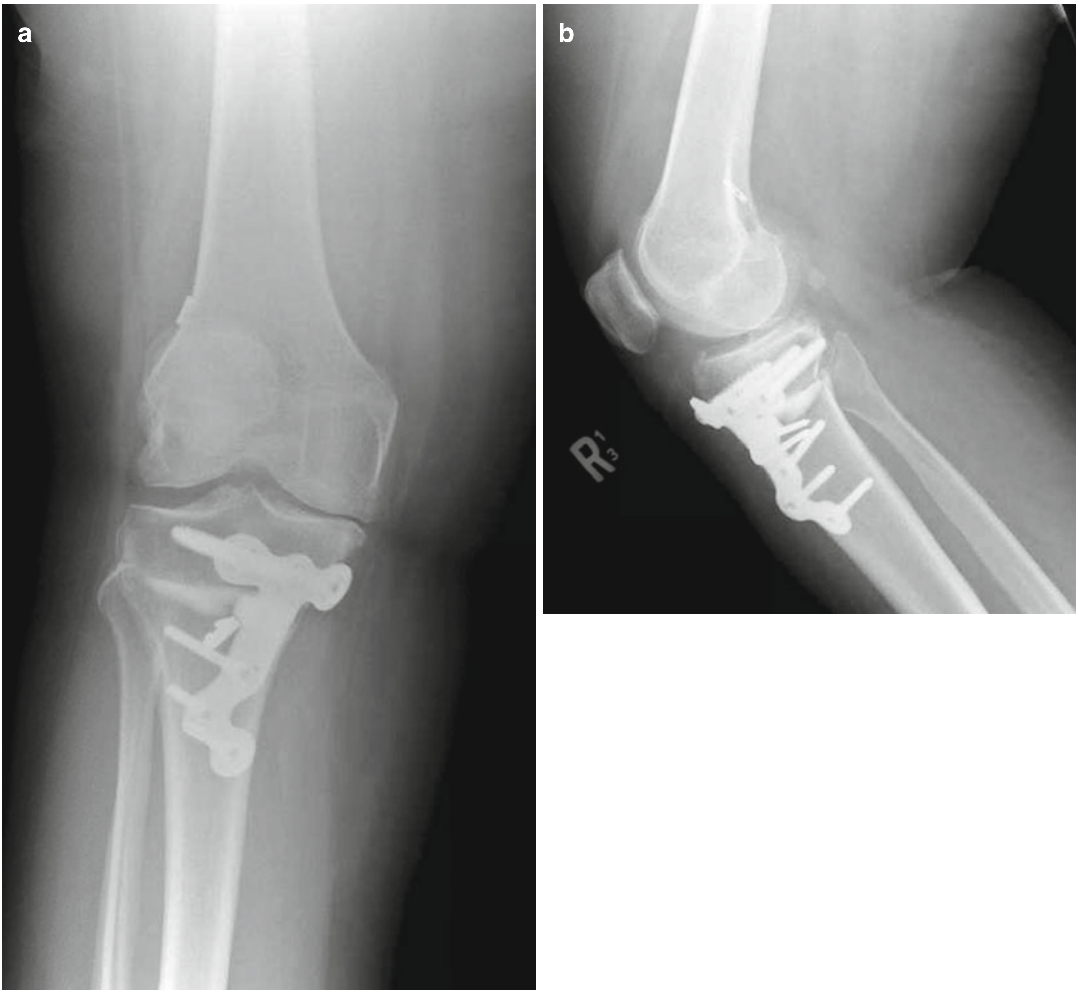
if desired/warranted (Figs. 24.20 and 24.21). The wounds are then closed in layers over a drain.

24.7 Postoperative Care

The majority of patients stay overnight for pain control, serial examinations for evaluation of compartment syndrome, and administration of prophylactic antibiotics. The knee is immobilized in a hinged knee brace. With the brace locked in extension, the patient is allowed toe-touch weight bearing using crutches or a walker for ambulatory assistance. While recumbent, knee range of motion is allowed through a 0–90° arc to decrease the incidence of postoperative stiffness. Sutures are removed within 2 weeks, and radiographs are obtained beginning at the 6-week postoperative appointment (Figs. 24.22 and 24.23). Once there is radiographic evidence of bony consolidation, the brace is discontinued. Full weight bearing, in concert with a formal physical therapy program for strengthening, is then initiated. Radiographs are repeated at the 10-week postoperative visit, and if osseous consolidation has been achieved, then sport-specific rehabilitation is initiated.

24.8 Complications

Surgical and postoperative complications affiliated with HTO include nonunion, hardware failure, fracture, infection, prominent/symptomatic hardware, peroneal nerve palsy, compartment syndrome, vascular injury, thromboembolic disease, and others. Intraoperative fracture of the



Figs. 24.22 and 24.23 Postoperative radiographs

proximal tibia is reported to be as high as 18 % in high tibial osteotomy [41]. Staying distal to the guide pin placed as described in our operative technique can minimize this complication. Instances of intra-articular fracture require anatomic reduction and rigid fixation. Nonunion is reported to range from 0.7 to 4.4 % [3, 41, 42]. Bone grafts, bone substitutes, and growth factors have been used as adjuncts to encourage consolidation at the osteotomy site. We routinely use corticocancellous femoral heal allograft.

The incidence of compartment syndrome in high tibial osteotomy is unknown, but cases have been reported in the literature [30, 45]. Marti and Jakob [28] describe elevated compartment pressures requiring fasciotomy following arthroscopic ACL reconstruction and concurrent high tibial osteotomy. When arthroscopy is employed, lower pump pressures and frequent compartment checks should be performed throughout the procedure. Many of the more common neurovascular injuries, particularly those involving the peroneal nerve, are minimized or obviated by the use of opening wedge osteotomies, which are less likely to result in such complications [13, 41, 43].

24.9 Summary

High tibial osteotomy for correction of varus overload or malalignment should be considered in ACL deficiency, particularly when associated with medial compartment degeneration. This procedure, either in isolation or in concert with ACL reconstruction can provide the patient with stability and improved joint mechanics, which can ameliorate the symptoms of unicompartmental gonarthrosis.

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ACL Injuries Combined with Lateral and Medial Knee Injuries Acute Versus Chronic Injury: What to Do

25

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25.1 Introduction

Acute anterior cruciate ligament (ACL) tears can occur as isolated injuries but more commonly occur in conjunction with injuries to the other structures of the knee, including the knee ligaments and the menisci. Isolated tears of the ACL have a better prognosis following surgical reconstruction, while ACL tears that are combined with damage to the medial and/or lateral structures of the knee have been reported to lead to decreased knee stability and place patients at an increased risk of developing osteoarthritis [2]. Oiestad et al. reported patients with combined ACL injuries to have a significantly increased prevalence of knee OA on plain radiographs compared to patients with an isolated ACL tear (80 vs. 62 %) [48]. It is critical to rule out medial and lateral knee ligament injuries when a patient presents with a torn ACL. Failing to adequately address medial or posterolateral knee injuries prior to reconstructing a deficient ACL has been reported to lead to the ACL reconstruction graft stretching out and/or failure due to increased forces on the reconstructed ligament [23, 41].

The timing of combined ACL injuries (acute vs. chronic) plays a major role in decision-making regarding available treatments as well as timing of procedures. Typically acute injuries are defined as those that occur within 6 weeks of initial treatment. Acute combined ACL injuries are often the result of trauma and the patient can recall a pop or snapping sensation at the time of injury. Acute injuries are accompanied by severe swelling of the knee within a few hours of the

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injury due to hemarthrosis. Treatment of acute combined ACL injuries varies; however, better results are typically obtained when the damaged structures are treated or repaired/reconstructed within 6 weeks of the initial injury. It is important that practitioners allow acute injuries to pass through the initial inflammatory phase prior to surgery to avoid unnecessary complications.

Chronic combined ACL injuries present a multitude of challenges to the practitioner that are not seen with acute injures. Scar tissue, limb malalignment, and osteoarthritis (OA) are the main concerns with chronic injuries. Scar tissue formation can make repairs more complicated and cause practitioners difficulty when trying to decipher the normal anatomy during surgery. Limb malalignment and osteoarthritis can develop when the stability of the joint is compromised due to a combined ACL injury. Malalignment can lead to increased forces on reconstruction grafts if it is not properly addressed prior to combined ACL reconstructions. In some circumstances, patients will require staged procedures to correct malalignment prior to ligament repair/reconstruction to decrease constraint on the knee and prevent reconstruction grafts from stretching out or failing after surgery.

25.2 Anatomy and Biomechanics

The secondary structures most often injured in combination with the ACL are those located on the medial side of the knee (Fig. 25.1). The three main static stabilizers of the medial knee complex are the superficial MCL, deep MCL, and POL [58]. Andersson and Gillquist reported that approximately 18 % of ACL injuries are accompanied by an MCL tear [2]. Conversely, Arthur et al. reported that nearly 95 % of grade III MCL tears are accompanied by an ACL tear [3]. All three ligaments act together to limit valgus angulation, tibial rotation, and anterior-posterior tibial displacement [19]. The POL acts primarily to limit internal rotation near complete knee extension, but it also resists valgus opening of the knee at zero degrees of knee flexion. The superficial MCL is primarily a valgus stabilizer but also functions as a primary external rotation stabilizer, especially at increased knee flexion angles. The more proximal portion of the superficial MCL acts mainly to prevent valgus opening, while the distal portion prevents rotatory instability [20]. The deep MCL has meniscofemoral- and meniscotibial-based portions and acts as a secondary

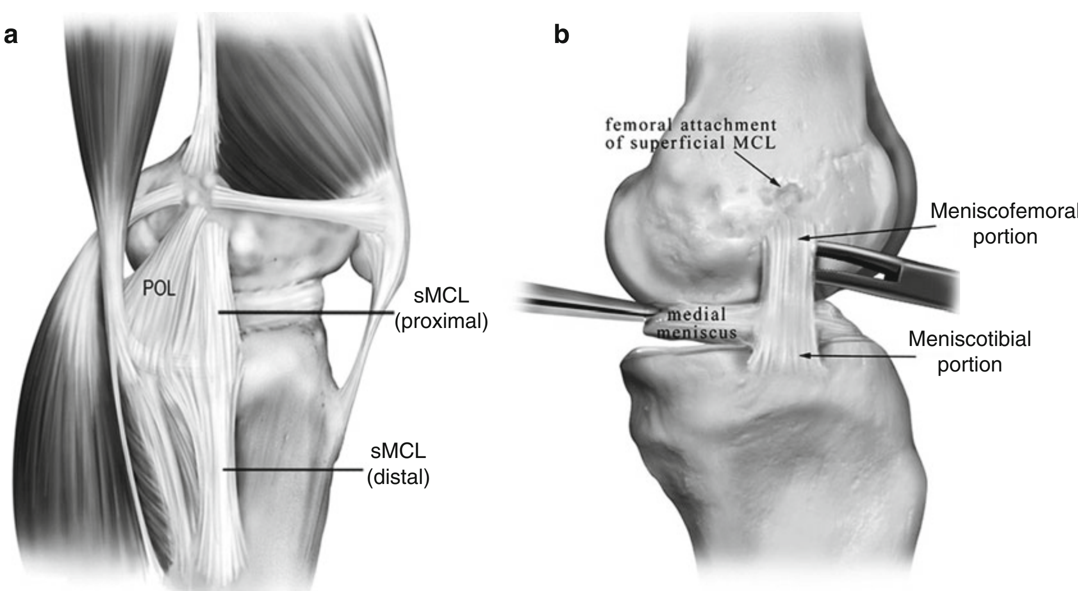

Fig. 25.1 Illustrations of the medial knee anatomy showing the superficial medial collateral ligament (*sMCL*) and posterior oblique ligament (*POL*) (**a**) and the divisions of the deep medial collateral ligament (**b**)

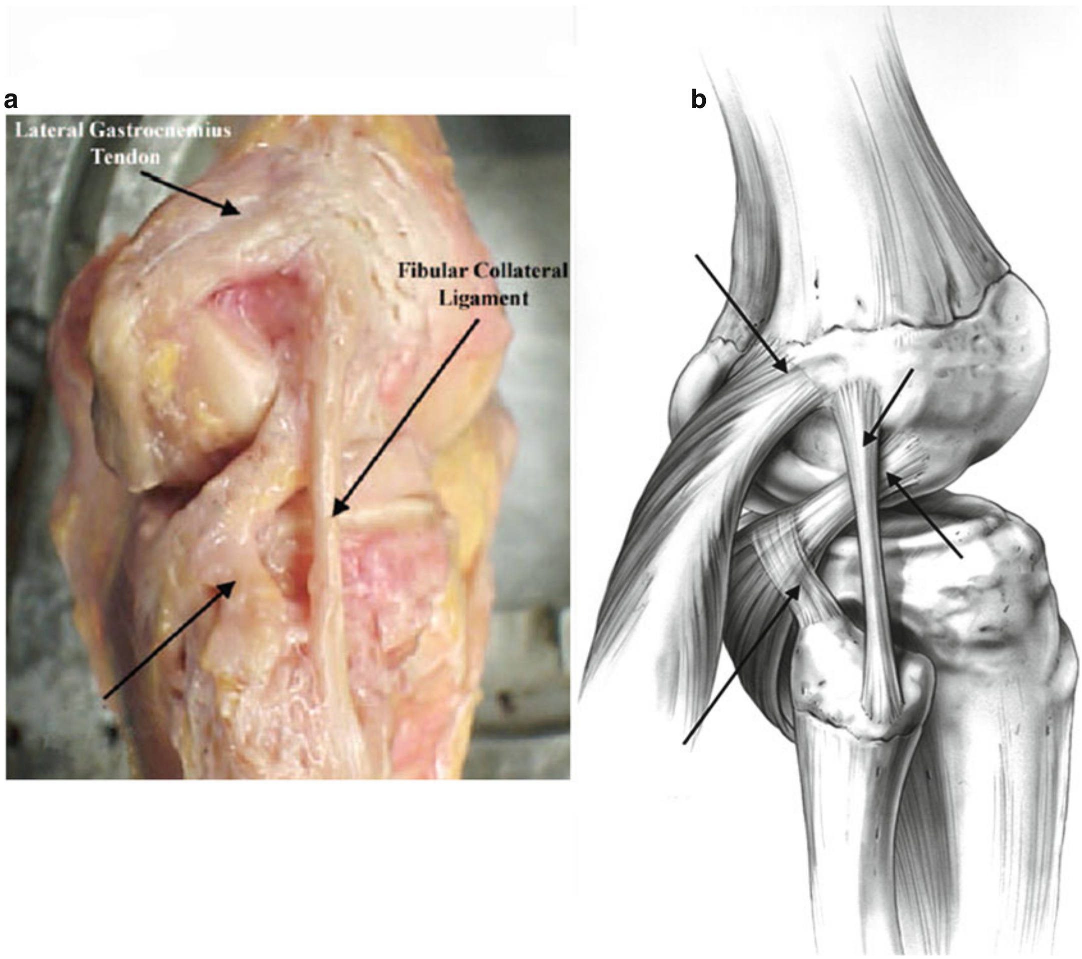

Fig. 25.2 Photograph (**a**) and illustration (**b**) of the posterolateral knee anatomy

valgus and external rotation stabilizer. When the ACL and MCL are injured concurrently, a portion of patients will have also sustained a concurrent meniscal injury, most commonly to the medial meniscus, known as the "unhappy triad." The common mechanism of injury for combined ACL and MCL injuries is a medially directed blow to the lateral side of the knee [49].

Combined injuries to the ACL and posterolateral corner (PLC) are not as common as those to the MCL and ACL. However, combined ACL/PLC injuries can result in serious dysfunction and long-term consequences if not properly addressed. The main anatomic structures contained in the posterolateral knee are the iliotibial band (IT band), long and short heads of the biceps femoris tendon, fibular collateral ligament (FCL), popliteus tendon (PLT), popliteofibular ligament (PFL), lateral gastrocnemius tendon, and the fabellofibular ligament (Fig. 25.2) [31]. The primary static stabilizers of the PLC of the knee are the FCL, PLT, and PFL [16, 22, 40]. Together, these three structures stabilize the lateral knee by restraining varus, external rotation, and combined posterior translation with external rotation [16, 22, 40]. The FCL is the primary restraint to varus, while the popliteus and PFL function as external rotation stabilizers at higher knee flexion angles. Damage to the popliteus ligament and other PLC structures increases varus instability but does not increase anterior translation during deep flexion. An obvious increase in anterior translation can be appreciated near extension, as well as an increase in varus gapping with this type of injury. Anterior cruciate deficient knees with a combined PLC injury will show obvious increased anterior translation from 0° to 30° of knee flexion, which is demonstrated clinically using the Lachman test [60]. Combined injuries to the ACL and PLC are typically the result of a twisting injury to the knee, but noncontact and hyperextension mechanisms have also been reported, as have direct anteromedial contact injuries to a flexed knee [25, 35].

The posterior cruciate ligament has two functional bundles which primarily act to prevent posterior translation of the tibia and secondarily act to prevent increased external rotation. Combined injuries to the ACL and PCL are much less common and are typically involved with a knee dislocation with further damage to one or both of the collateral knee ligaments. Combined ACL and PCL injuries are often the result of high- or low-velocity knee dislocations and may spontaneously reduce prior to evaluation, which makes the actual incidence difficult to know [43]. They will not be discussed here.

25.3 Physical Exam and Diagnosis

When evaluating a patient with a potential ACL injury, it is important to evaluate the entire knee in terms of stability, nerve function, and vascular status. This extensive evaluation is importation in order to avoid overlooking a combined injury. Patients often complain of pain and instability at the joint, and with concurrent nerve injuries, patients may report a foot drop, numbness, tingling, and/or weakness of the ankle dorsiflexors and great toe extensors. Once an ACL injury has been detected via a Lachman test or pivot shift test, it is important to evaluate the medial and lateral stabilizers of the knee for injury. Anterior cruciate ligament injuries that occur in combination with collateral ligamentous injuries can make diagnosis difficult, especially for acute injuries where the patient may be guarding. Injuries to the PCL can lead to a false positive Lachman test, and chronic medial knee injuries can also have a positive dial test [48]. This makes magnetic resonance images (MRIs) and stress radiographs important tools that should be used to aid in the diagnosis.

Table 25.1 Subjective grading of medial knee injuries based on gapping with a valgus stress applied at 0° and 30° knee flexion

Grade	Gapping	Symptoms
I	Absent	Local tenderness with no laxity
II	Gapping with a definite end point	Broader area of tenderness and laxity present with valgus stress
III	Gapping with no definite end point	Increased laxity with valgus stress

Patients with combined medial-sided injuries tend to have a variety of symptoms including swelling, pain, and restricted motion. Localized pain over the meniscofemoral or meniscotibial portions of the MCL has been reported to be indicative of the location of the injury in approximately two-third of patients [27]. Often, meniscal injuries can accompany injuries to the medial structures of the knee, which can also cause joint line tenderness. Anterior cruciate ligament tears have been reported to occur in combination in up to 78 % of grade III MCL tears [54]. Combined injuries to the medial knee and ACL tend to have larger knee effusions and more vague pain rather than localized to a specific area on the joint line. Patients will also typically complain of increased instability with combined ACL damage [15]. Medial knee injuries can be graded based on the amount of medial side joint opening with a valgus stress applied to the knee at both 0° and 30° of knee flexion (Table 25.1). A valgus stress test is considered negative only when there is no difference between the injured knee and the uninjured knee at 0° or 30° of flexion. The degree of gapping at 0° and 30° gives the examiner information regarding which medial structures are injured. Laxity at 30° (but not at 0°) suggests an isolated MCL injury with the POL intact. Laxity at both 0° and 30° represents injuries to both the MCL and POL. Laxity at 0° and 30° also suggests an increased likelihood of a concurrent cruciate ligament injury [15].

Patients with combined ACL and PLC injuries will typically complain of pain and instability at the joint. Concurrent nerve injuries occur in up to 15 % of PLC injuries and may cause symptoms of numbness, tingling and weakness of the ankle dorsiflexors and great toe extensors, or a foot drop [31].

25.3.1 Imaging

25.3.1.1 Radiography

As with any knee injury, a standard series of knee radiographs should be ordered which should include normal anteroposterior (AP) and lateral radiographs, 45° flexion weight-bearing, and sunrise views. These can be helpful in the identification of bony medial knee injuries, such as avulsion fractures and osteochondral fragments, which can change the way a patient is treated. When dealing with suspected combined ACL injuries, knee radiographs are also useful to look for fibular head avulsion fractures, Segond fractures, and ACL avulsion fractures (Fig. 25.3). Bilateral stress radiography, including varus and valgus stress AP radiographs, should be ordered to look for increased medial and lateral gapping (Fig. 25.4) [31, 34]. The radiographs of the injured side should be compared to the contralateral normal side to determine the difference between the two. Opening of the medial and lateral joint spaces can be reliably measured to predict injury pattern according to Tables 25.2 and 25.3, respectively. A side-to-side difference of less than 2.7 mm as

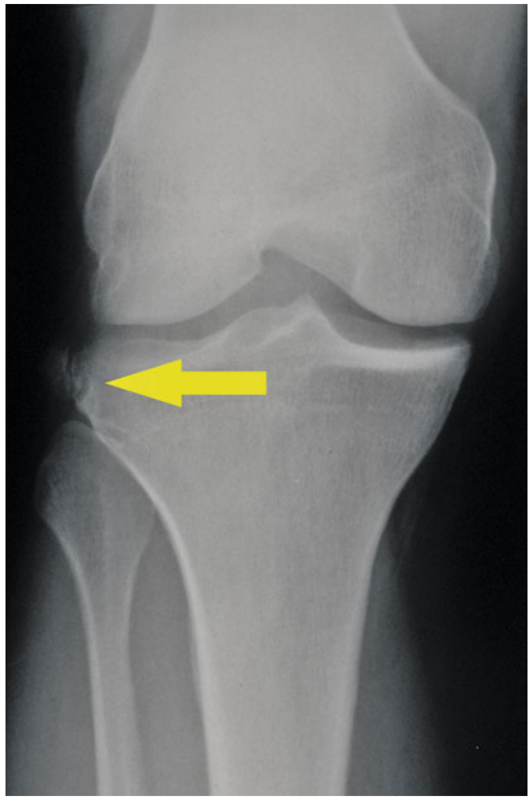

Fig. 25.3 Radiograph of a right knee demonstrating a Segond fracture of the tibial condyle (*yellow arrow*)

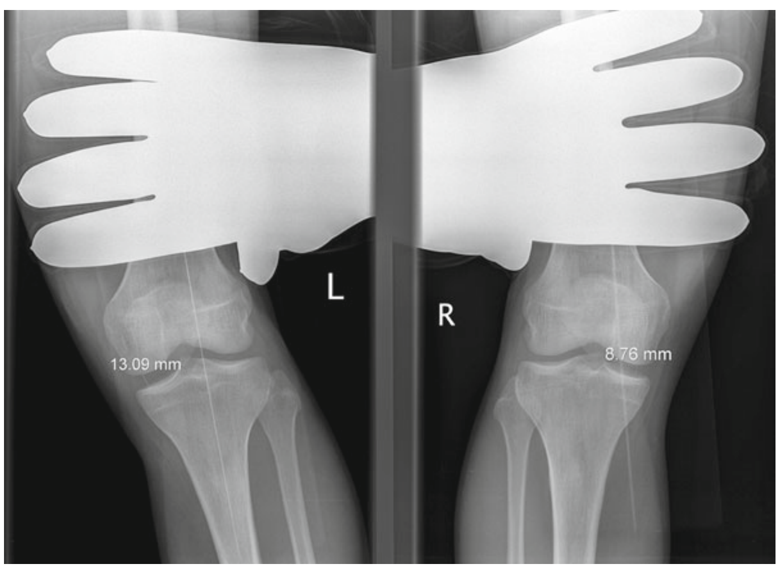

Fig. 25.4 Valgus stress radiographs of an injured left knee and healthy right knee demonstrating greater than 4 mm side-to-side difference in gapping with a valgus stress applied

Table 25.2 Varus stress radiography guidelines for posterolateral injuries

Side-to-side difference (mm)	MRI findings
<2.7	No tear
2.7	Isolated FCL tear
4.0	Grade III PLC injury
6.6	Combined PLC and ACL
7.8	Combined PLC, PCL and ACL

Table 25.3 Valgus stress radiography guidelines for medial knee injuries

Knee flexion angle (°)	Side-to-side difference (mm)	MRI findings
0	1.7	Grade III sMCL injury
20	3.2	Grade III sMCL injury
0	6.5	Complete medial knee injury
20	9.8	Complete medial knee injury

noted with varus stress radiographs suggests no tear or a grade I–II injury. More than 2.7 mm between sides is indicative of an isolated fibular collateral ligament tear, while a difference of more than 4.0 mm correlates with a grade III posterolateral knee injury. Knees that gap open more than 6.6 mm suggest a combined ACL and PLC injury [36]. Valgus stress radiographs at 0° of knee flexion that open less than 1.7 mm indicate a grade I or II injury, while those that open more than 1.7 mm suggest a grade III superficial MCL injury. Gapping to 3.2 mm at 20° of knee flexion also indicates a grade III superficial MCL injury. Knees that open to valgus stress more than 6.5 mm at 0° and more than 9.8 mm at 20° suggest a complete medial knee injury with a torn superficial MCL, deep MCL, and POL. Long leg standing radiographs should be ordered to evaluate chronic combined ACL and PLC injuries (Fig. 25.5). They are useful in preoperative planning with regards to staging procedures for knees in varus alignment. Varus aligned knees will require an opening wedge osteotomy to address the coronal plane malalignment and to lessen the constraint on the knee and prevent the PLC reconstruction grafts from stretching out.

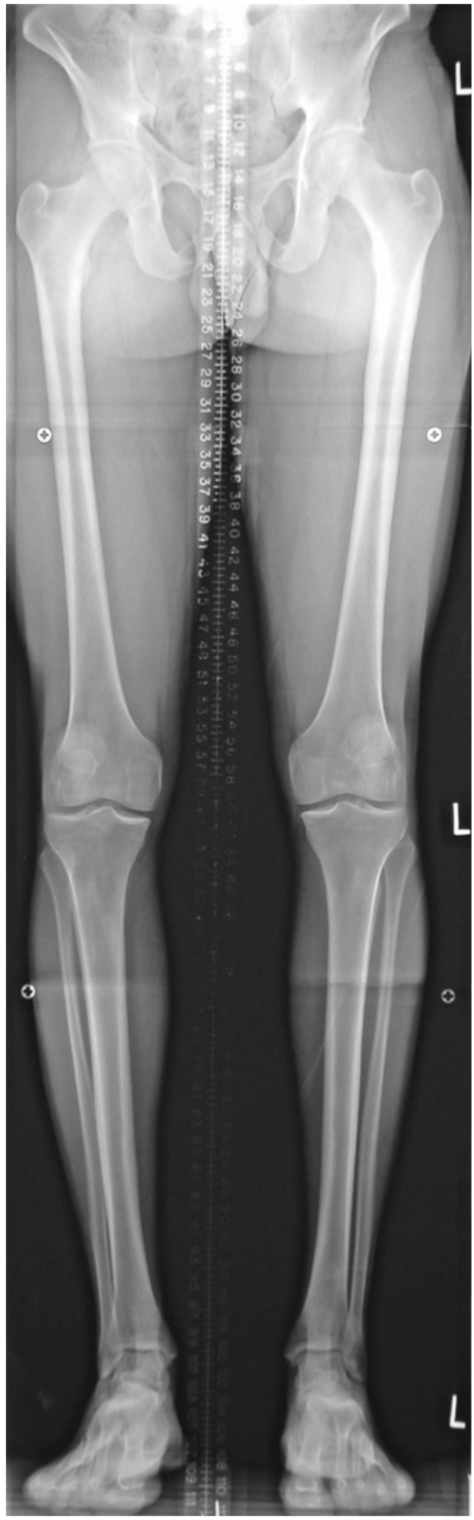

Fig. 25.5 Long leg standing radiographs used to evaluate limb alignment

25.3.1.2 Magnetic Resonance Imaging

High-quality knee MRI images using a 1.5-T magnet or higher magnet strength are useful in diagnosing combined injuries to the ACL and collateral ligaments, especially for acute knee injuries [32]. When looking for injuries to the posterolateral knee, thin-slice (2 mm) coronal oblique images that include the entire fibular head should also be obtained in addition to the standard coronal, sagittal, and axial films. Coronal oblique views should also be included to all for proper visualization of the fibular head and styloid to evaluate the condition of the FCL and popliteus tendon [34].

Trabecular microfractures, or bone bruises, are commonly associated with knee ligament injuries and have been well described for ACL, MCL, and PLC injuries [14, 18, 44, 45, 57]. ACL injuries tend to have bone bruising in the lateral compartment, especially on the anterior or middle lateral femoral condyle and the posterior medial and lateral tibial plateau [18, 57]. MCL injuries are associated with bone bruising located in the lateral compartment due to impact opposite to ligament injury [44]. Injuries to the PLC tend to have bone bruises identified on the anterior medial femoral condyle [14] (Fig. 25.6). In the setting of an ACL injury, the presence of one or more of these bone bruise patterns should increase the level of suspicion for a concurrent medial or PLC knee injury.

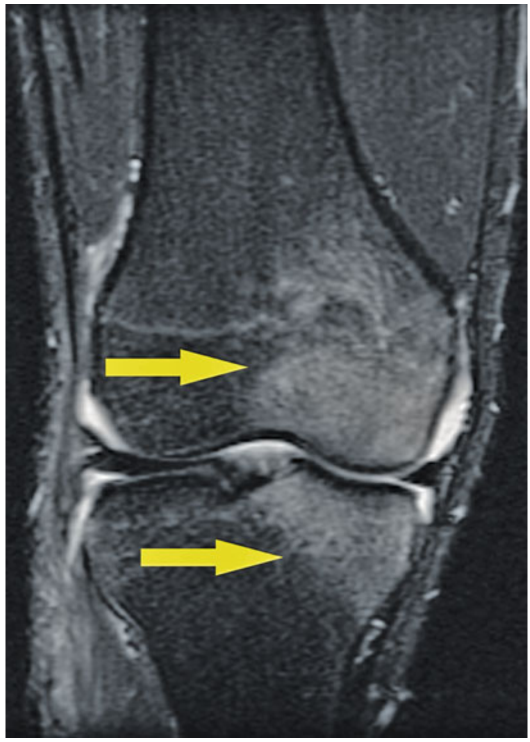

Fig. 25.6 Coronal MRI demonstrating a bone bruise pattern (*yellow arrows*) associated with combined ACL and PLC injuries

25.3.2 Specialized Tests

In addition to a full physical examination of both lower extremities, certain specialized tests should be used to evaluate the ACL along with the posterolateral corner and medial side of the knee for injuries. For each test, it is imperative to compare the injured side to the contralateral normal side to ensure you are not mistaking a normal variation within that patient for an injury.

25.3.2.1 External Rotation Recurvatum Test

The external rotation recurvatum test is utilized to test the structures of the PLC and is performed with the patient lying supine. The practitioner uses one hand to stabilize the distal thigh while using the other to lift the big toe (Fig. 25.7). A positive test occurs when an increased amount of recurvatum, or hyperextension, in the affected knee is seen compared to the healthy side. An increase in recurvatum should alert the practitioner to a high likelihood of a combined injury to the posterolateral corner and cruciate ligaments [26, 39]. When reporting increased recurvatum, a comparison of heel height off the examining table is the most effective measure of difference between the extremities.

25.3.2.2 Varus Stress Test at 0° and 30°

Varus stress testing is utilized to test the lateral restraints of the knee. The patient should be lying supine on the examination table. While holding the ankle or foot, the examiner supports the thigh against the exam table and applies a varus force to the knee joint while flexed to 0°. The examiner's other hand should feel for increased gapping

Fig. 25.7 Photograph of the external rotation recurvatum test used to assess the integrity of the structures of the PLC. The practitioner uses one hand to stabilize the distal thigh while using the other to lift the big toe (**a**); heel heights should be compared to look for a side-to-side difference (**b**)

along the lateral joint space as the knee is stressed (Fig. 25.8a). This test should then be repeated at 30° of knee flexion. The degree of injury can be graded based upon the amount of gapping felt as the joint opens under stress. Grade I injuries cause pain with no gap present, grade II injuries reveal some gapping but with a distinct end point present, and grade III injuries cause significant gapping without a definite end point. Increased gapping at 0° of flexion is indicative of a serious posterolateral injury and carries a high probability of a combined cruciate ligament injury. Grades I and II at 30° of flexion are more typical of partial FCL tears or mid-third lateral capsular ligament injuries, while grade III gapping suggests complete tears of the FCL and damage to other posterolateral structures [31, 32].

Fig. 25.8 Photograph of valgus (**a**) and varus (**b**) stress testing used to gauge the degree of injury to the medial and lateral knee structures

25.3.2.3 Valgus Stress Test at 0° and 30°

Valgus stress testing is performed in a similar manner to varus stress testing. The patient should be lying supine on an examination table with the examiner supporting the thigh against the side of the exam. First, apply a valgus force to the knee joint while holding the ankle or foot at 0° of flexion and then at 30°. As the knee is stressed, the practitioner should feel for increased gapping at the medial joint space (Fig. 25.8b). Gapping can be graded based on the amount the joint opens under stress: grade I causes pain but with no gap present, grade II causes some gapping but a definite end point is present, and grade III causes significant gapping with no definite end point felt. Increased gapping at 0° of flexion indicates a serious medial injury with a high probability of accompanying cruciate ligament involvement. Lower grades of gapping at 30° are more suggestive of partial tears

Fig. 25.9 Photograph showing a dial test used to evaluate the posterolateral corner of the knee which can be performed with a patient in a supine (**a**) or prone position (**b**). The examiner should watch for external rotation of the tibial tubercle of the affected knee and compare the results to the healthy side

of the superficial MCL or posterior oblique ligament, while higher grades indicate complete tears of the superficial and deep MCL in addition to damage to other medial structures.

25.3.2.4 Dial Test (Posterolateral Rotation Test)

The dial test is useful to evaluate the posterolateral corner of the knee and can be performed with a patient in a supine or prone position. A supine patient should flex their knees to approximately 30° off the examination table while the examiner stabilizes the thigh and externally rotates the foot. The examiner should watch for external rotation of the tibial tubercle of the affected knee as the foot rotates and then compare the results to the healthy side (Fig. 25.9). More than 10°–15° difference between the affected and normal extremity is considered a positive test and suggests injury to the posterolateral knee. The test should then be repeated with the patient's knees flexed to 90° off the exam table. Increased rotation at 90° indicates a combined PCL and posterolateral knee injury; however, a decrease in the rotation observed compared to that at 30° suggests an isolated posterolateral [22]. Practitioners should be aware of the possibility of a medial knee injury when a patient has a positive dial test, and they should be careful to fully evaluate the medial knee in both the supine and prone positions as well. There can actually be more increased external rotation on the dial test for a medial knee injury than a posterolateral knee injury, so differentiation between anteromedial versus posterolateral knee rotation must be determined.

25.3.2.5 Posterolateral Drawer Test

The posterolateral drawer test also evaluates PLC stability. The patient should lie on their back with the knee flexed to 90° while externally rotating the foot to approximately 15°. The examiner should stabilize the foot and apply a posterolateral rotation force to the tibia while observing the amount of posterolateral rotation. Increased rotation compared to the contralateral normal side suggests injury to the popliteus complex [10, 31, 32].

25.3.2.6 Reverse Pivot Shift Test

The reverse pivot shift test is useful in evaluating injuries to the posterolateral knee structures and is equivalent to a dynamic posterolateral drawer test. The patient should be lying on their back with their foot externally rotated and their knee flexed between 45° and 60°. The examiner slowly extends the knee while applying a valgus force through the knee. A positive test is signified by a

Fig. 25.10 Photograph showing the figure 4 test used to test posterolateral structures of the knee, especially the popliteus complex and popliteomeniscal fascicles. The patient should flex the injured knee to approximately 90° and then cross the flexed injured leg over the normal side placing the foot across the knee and externally rotating the hip. The examiner pushes the affected knee toward the examination table that imparts a varus stress on the joint to test for stability

palpable clunk felt around 30° of knee flexion as the subluxed knee joint is reduced as the iliotibial band changes from a knee flexor to extensor around 30°. As with any test of knee stability, the injured knee should be compared the contralateral normal side to prevent a falsely positive test [10, 11, 32, 56].

25.3.2.7 Figure 4 Test

The figure 4 test is useful for testing the posterolateral structures of the knee, especially the popliteus complex and popliteomeniscal fascicles. The patient should be lying supine with their injured knee flexed to approximately 90°. The patient should then cross the flexed injured leg over the normal side placing the foot across the knee and externally rotating the hip. The examiner then pushes the affected knee toward the examination table that imparts a varus stress on the joint (Fig. 25.10). This stresses the popliteus complex and popliteomeniscal fascicles as well as the rest of the posterolateral structures. When these structures have been disrupted by an injury, there is no support to stabilize the lateral meniscus, which can then displace medially into the joint resulting in pain at the joint line [55]. Again, the injured side should be compared to the uninjured side [30].

25.3.2.8 Anteromedial Drawer Test

The anteromedial drawer test is used to evaluate for a combined superficial MCL and POL injury. The patient should be lying supine with their injured knee flexed to 90° and the foot externally rotated to 15°. An anteromedial drawer force is applied and the examiner looks for anteromedial rotation of the tibia on the femur. Increased anteromedial rotation seen on the injured extremity compared to the contralateral normal knee suggests a combined superficial MCL and POL injury.

25.3.2.9 Gait Analysis

Practitioners should make certain to examine a patient's gait pattern following a knee injury. Varus thrust gaits are commonly seen in PLC injuries. Since the knee has lost the stabilizers of the lateral compartment, it cannot maintain a normal anatomic position when stressed during gait. As the foot strikes the group, the lateral compartment opens due to stress on the joint and the lack of intact stabilizers, causing the joint to subluxate into a varus position to compensate [11]. Walking with a partially flexed knee will help alleviate the instability, and patients commonly adapt to this style of walking to alleviate their symptoms.

25.4 Treatment

25.4.1 Combined ACL and PLC Injuries

Treatment of combined ACL and PLC injuries depends on the location and severity of the posterolateral corner injuries. Grade I and II injuries to the posterolateral corner have reported positive results with conservative management; however, studies have reported that grade III injuries do not fare well when managed conservatively and will typically need surgical intervention followed by rehabilitation [11, 29, 32]. The optimal time frame for treatment of a combined ACL and PLC injury is usually within the first 3 weeks following the injury. Early surgical management will help to prevent complications due to scar tissue forming on and around the damaged structures. Chronic PLC injuries face additional issues due to the formation of scar tissue and limb malalignment, which typically makes them less amenable to repair and require or necessitate a full reconstruction [11].

25.4.1.1 Nonoperative Treatment of Combined ACL and Grade I and II PLC Injuries

Patients who opt for conservative treatment of a combined ACL/PLC injury will require immobilization of the affected extremity with the knee in full extension to allow the stretched or partially torn ligaments to heal. The joint should remain immobilized and patients should be kept non-weight-bearing for 3–4 weeks to make sure sufficient time has passed to allow healing of the damaged structures. After immobilization, physical therapy may begin with exercises aimed at improving range of motion. At this time, patients are allowed to weight bear on crutches only. Patients are allowed to discontinue the use of crutches once they can walk with a visible limp. Quadriceps strengthening exercises are a focus of physical therapy after the initial immobilization, but isolated hamstring exercises should be avoided for approximately the first 4 months postoperatively. If after 10 weeks of nonoperative treatment the patient still experiences pain or instability, they should be reevaluated for surgical treatment [11, 29, 32]. The appropriate time to determine whether a patient requires or desires ACL reconstruction is once the PLC injury has adequately healed.

25.4.1.2 Operative Treatment: Acute Combined ACL and Grade III PLC Injuries

Ideally, treatment for patients with combined ACL and grade III posterolateral knee injuries should take place within 3 weeks of the initial injury. This will prevent complications due to scar tissue formation on and around the common peroneal nerve and retraction of other ligamentous structures, which can make repair and early postoperative motion difficult. Early treatment also makes identification and repair of the anatomic structures easier [12]. After 3 weeks the structures do not hold sutures as well, and peroneal nerve injuries can be enclosed in scar tissue, which can put the nerve at greater risk during surgery. Anatomic reconstructions or repairs are favored over nonanatomic reconstructions because they have been reported to yield the best outcomes and give patients the best odds to return to normal function [7]. In the posterolateral knee, the FCL, PLT, and PFL are the structures considered for repair or reconstruction, and MRI scans are helpful in determining which structures can be repaired and which will require reconstruction (Fig. 25.11). Acute repairs are possible for the FLC and PLT when they are avulsed off the bone and can be reattached anatomically, and the PFL can be repaired when it has been torn off the fibular head while the popliteus is still intact. All posterolateral structure repairs should be reattached with the knee in full extension because that is the position where the structures are under the most tension. Mid-substance tears of any of the structures should warrant reconstruction, as should other tears that are not easily repaired. Hamstring autografts are typically used when reconstructing either the FLC or PLT. If both structures are damaged and require reconstruction, an Achilles tendon allograft is preferred [8, 37, 38, 42]. With combined ACL and PLC injuries, the posterolateral structures are repaired or reconstructed first, and then ACL graft fixation follows. This will prevent excess external rotation during tensioning of the ACL graft. The ACL should be reconstructed concurrently with the repair or anatomic reconstruction of the damaged posterolateral structures using the surgeon's preferred technique. This will allow the patient to begin a rehabilitation program stressing focused on restoring range of motion, which acts to prevent the development of excessive scar tissue (arthrofibrosis) [32]. The author's preferred method for ACL reconstruction in the acute setting uses an autogenous graft taken from

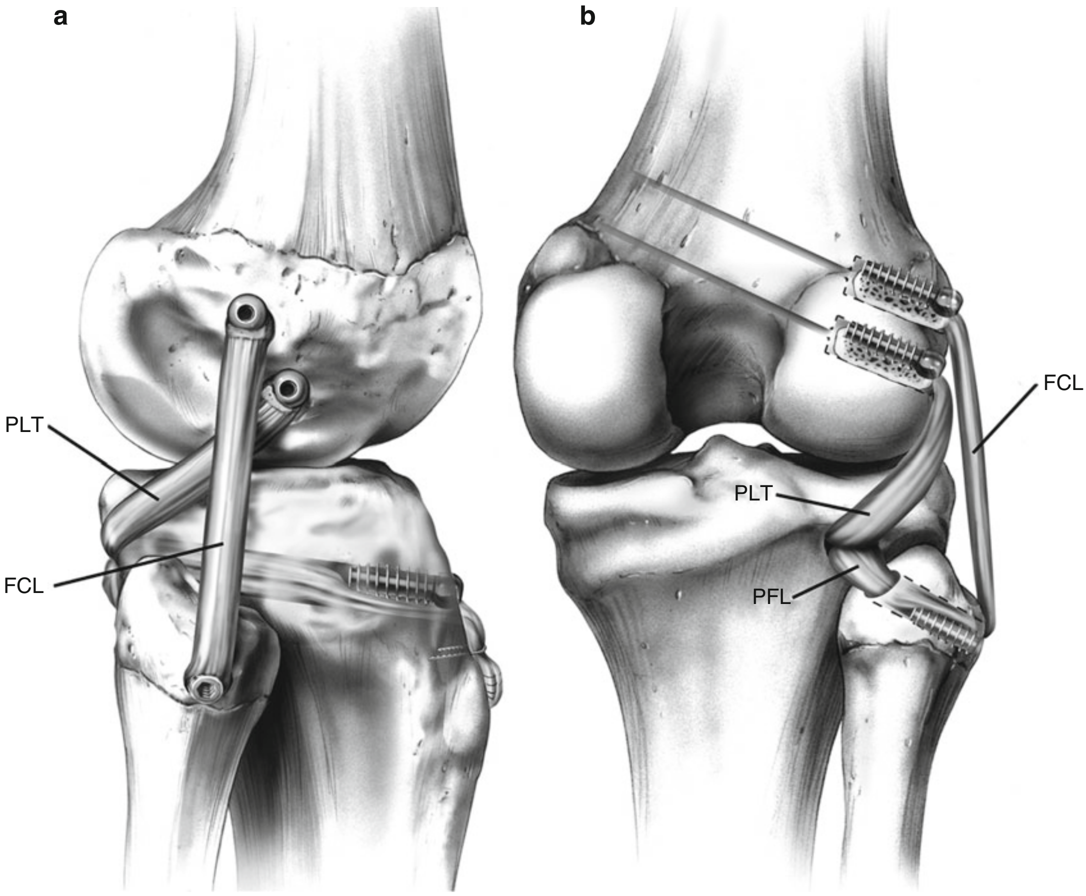

Fig. 25.11 Illustration of an anatomic PLC reconstruction with grafts secured in place; lateral view (**a**) and posterior view (**b**). *FCL* fibular collateral ligament, *PLT* popliteus tendon, *PFL* popliteofibular ligament (Reprinted, with permission, from LaPrade et al. [38], Fig. 2)

the central third of the patient's patellar tendon. The arthroscopic portion of the ACL reconstruction is delayed until after the posterolateral knee approach and identification of the individual damaged posterolateral structures. This prevents difficulty in identifying the injured structures due to fluid extravasation from the arthroscopic procedure. The fascial splitting incisions allow some mild extravasation of fluid during acute posterolateral reconstructions; however, this fluid has not been found to build up in the posterior compartments of the leg or thigh [35].

25.4.1.3 Operative Treatment: Chronic Combined ACL and PLC Injuries

Surgeons should treat a chronic combined ACL and PLC injury as though it was isolated chronic PLC injury by anatomically reconstructing the posterolateral structures with a concurrent reconstruction of the accompanying torn ACL. The multiligament reconstructions should be performed at the same time rather than separately as a staged procedure. A staged procedure not only requires the patient to undergo two complicated knee surgeries with prolonged rehabilitation but also prevents early range of motion, which places the patient at a higher risk of developing arthrofibrosis.

Prior to reconstruction, patients with chronic posterolateral instability must have the alignment of the affected extremity evaluated prior to surgery. Chronic combined ACL/PLC injuries that are found to be in varus alignment on long leg standing radiographs require an opening wedge osteotomy prior to reconstruction of the torn structures. Uncorrected genu varus alignment can often result in repair or reconstruction failure due to excessive tension placed on the lateral structures. This staged procedure will prevent the reconstruction grafts from stretching out or tearing by decreasing the constraint on the knee. An opening wedge osteotomy tightens the posterior capsule and oblique popliteal ligament complex supporting posterolateral stability. Approximately 6 months after the osteotomy, the patient will be reassessed, and if instability is still present, an anatomic multiligament reconstruction of the ACL and PLC will be required [32, 35].

25.4.1.4 Rehabilitation for Combined ACL and PLC Injuries

Rehabilitation following surgery to treat combined ACL and PLC injuries follows similar protocols to those used following repair or reconstruction of isolated PLC injuries. Following surgery, patients should be placed in an immobilizer brace. Exercises are focused on strengthening and regaining full range of motion. Range of motion exercises are started on day 1 postoperatively with an initial goal of 0°–90° during the first day in physical therapy, followed by progressive strength training including quadriceps sets and straight leg raises in the immobilizer. As in nonoperative management, patients should be kept non-weight-bearing for 6 weeks and then transitioned to full weight bearing by using crutches. The immediate goal for range of motion should be full extension, with a progression to 120° of flexion by postoperative week 6. To progress range of motion and strength, patients can begin riding a bike and using a quadriceps machine 6–8 weeks postoperatively. Patients can begin light-weight leg presses to 70° of knee flexion after 6 weeks, but exercises that isolate the hamstring muscles are avoided for 4 months following surgery. Approximately 4–6 months postoperatively, patients can begin more aggressive strength training exercises and progress to light jogging [11, 32].

25.4.2 Combined ACL and Medial Knee Injuries

Treatment of combined ACL and medial knee injuries depends on the severity of the medial knee injury; however, regardless of the severity of the medial knee injury, all combined ACL and medial knee injuries should initially be treated nonoperatively, focusing on decreasing swelling, increasing quadriceps strength, and restoring full range of motion. This initial period is crucial to allow for MCL healing and for the inflammatory phase to subside, which will optimize the timing of ACL reconstruction. Grade I and II MCL injuries have been reported to heal well with little or no residual laxity when treated nonoperatively [47, 51]. This is because the MCL is located outside of the capsule and has an intrinsic ability to heal when the ends of the tear are well approximated. Individuals who underwent ACL reconstruction and conservative MCL management have been reported to achieve superior short-term range of motion and more rapid strength return compared to those who underwent repair of both ligaments [51]. Once the MCL injury has had sufficient time to heal, usually 4–8 weeks, surgical reconstruction of the ACL can take place [4]. The treatment of combined ACL and grade III MCL injuries is a controversial subject. Numerous surgeons recommend nonsurgical management of ACL and grade III MCL tears even when combined with an ACL tear [47, 51, 52]. The current literature does not provide a clear definition for the conditions which require reconstruction of a grade III MCL injury when combined with an ACL tear; however, when there is significant disruption of the superficial MCL (torn ends not close to one another) and the POL has been disrupted, it is not unlikely that nonoperative management will lead to a successful outcome without repair/reconstruction of the medial structures (Fig. 25.12) [6, 51, 53]. In 1978, Fetto and Marshall reported that injuries with MCL gapping in extension usually do not heal, and the authors have found this to be true in their own practice [13].

Patients with continued medial laxity at the time of ACL reconstruction should be evaluated for a concurrent medial knee complex repair, augmentation repair, or reconstruction depending on the injured tissue quality. Meniscofemoral “peel off” lesions with instability in extension and meniscotibial injuries with accompanied

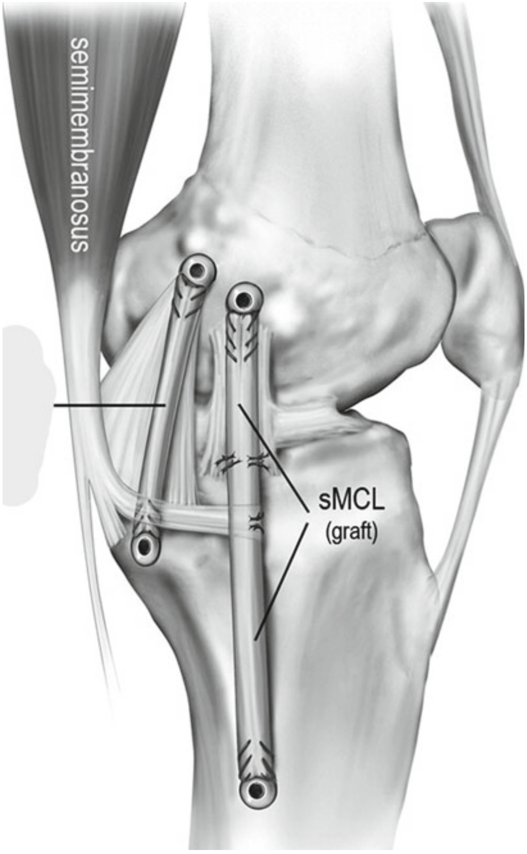

Fig. 25.12 Illustration of an anatomic medial knee reconstruction with grafts secured in place; lateral view. *POL* posterior oblique ligament, *sMCL* superficial medial collateral ligament (Reprinted, with permission, from Coobs et al. [9], Fig. 1B)

rotational instability are prone to developing chronic instability and should be considered for repair/reconstruction. Failure to address medial knee instability has been reported to result in an increased risk of ACL reconstruction failure [5].

25.4.2.1 Nonoperative Treatment of Combined ACL and Medial Knee Injuries

Nonoperative management of grade I, II, and some grade III MCL injuries includes pain and edema control, protective bracing (typically with a hinged knee brace for 6 weeks), immediate range of motion exercises, and progressive strength training. The use of a stationary bike to restore range of motion in the initial weeks following an injury is critical to healing and positive long-term outcomes. Once the medial structures have had adequate time to heal, usually between 4 and 8 weeks, the ACL can be reconstructed using the surgeon's preferred technique. Failure to reconstruct the injured ACL has been shown to limit the success of nonoperative treatment of medial knee injuries [28].

25.4.2.2 Operative Treatment: Acute Combined ACL and Medial Knee Injuries

Operative techniques for acute combined injuries to the ACL and medial knee structures include direct repair, reconstruction or augmentation of the superficial MCL (depending on the tissue quality), deep MCL repair, and POL repair, reconstruction, or augmentation with concurrent ACL reconstruction [9, 17, 24].

A diagnostic arthroscopy, before or after surgical exposure, can be helpful in preventing fluid extravasation. However, in treating more severe medial knee injuries, the operative should be performed first to allow for identification of the damaged medial structures before fluid extravasation, which can make identification of the injury more difficult. For acute combined ACL and medial knee injuries, an arthroscopic examination may reveal a medial "drive-through sign" where there is more than 1 cm of medial opening, which indicates significant MCL laxity and the need for repair or reconstruction. The scope can also be utilized to verify meniscal stability and the location of the injury and to prevent fluid extravasation.

Surgical treatment of complete medial knee injuries involving the superficial MCL, POL, and deep MCL consists of anatomic reconstruction of the two main structures of the medial knee – the superficial MCL and POL. Two separate grafts and four reconstruction tunnels are required to complete the reconstruction. The grafts can be obtained from a single semitendinosus graft split into 16-cm (sMCL) and 12-cm (POL) lengths. The superficial MCL graft should be tightened at 30° of knee flexion and the POL at 0° of knee flexion [9, 33]. This is based on biomechanical studies which report cutting of the medial knee structure at 30° results in the greatest amount of valgus laxity, and the POL plays the largest role in restraint of internal rotation at 0° of knee flexion [21, 50, 58].

25.4.2.3 Operative Treatment: Chronic Combined ACL and Medial Knee Injuries

In chronic combined ACL and medial knee injuries, there are several situations that must be assessed prior to attempting reconstruction of the ACL and repair/reconstruction of the medial knee structures. Pellegrini-Stieda ossification and malalignment are the two main issues to be concerned about with chronic medial injuries.

Pellegrini-Stieda syndrome is characterized by the formation of heterotopic bone due to calcification within the torn superficial MCL near the femoral attachment site. This is seen only in chronic tears and can be readily diagnosed with plain AP radiographs [1]. Mild and moderate cases can be treated with range of motion exercises and/or corticosteroid injections, but more severe cases may require excision of the calcified area when treating the chronic tear [46].

Limb alignment can be assessed via long leg standing radiographs similar to PLC injuries. Patients in valgus malalignment are at an increased risk for ALC reconstruction failure and should have their alignment corrected via a distal femoral osteotomy. This can be performed either as a staged procedure or at the time of ligament reconstruction.

25.4.2.4 Rehabilitation for Combined ACL and Medial Knee Injuries

Postoperative rehabilitation for combined ALC and medial knee injuries is dependent on the patient and the specific injuries treated. Early knee motion and strengthening are essential following surgery to prevent the formation of intra-articular adhesions. The injured knee is placed in a hinged brace in full extension until the patient can regains full, active extension (approximately 6 weeks), and protected weight bearing is typically required for 6–8 weeks. Aggressive range of motion is avoided during the first postoperative week to prevent the reconstruction grafts from stretching out; however, range-of-motion exercises between 0° and 90° of knee flexion and simple strengthening exercises (quadriceps-setting exercises, straight-limb raises, and hip extension and abduction exercises) while wearing the hinged brace are utilized in the first 2 weeks following surgery. In those first 2 weeks following surgery, it is also essential to avoid hyperextension and flexion past 90°, which can place unwanted tension on the grafts. After the 2 weeks, range of motion can progress as tolerated. No resistive or isolated hamstring exercises should be used for approximately 4 months after surgery in order to minimize joint translation, which could stretch out the reconstruction grafts as they heal. Once the patient regains full active extension, an unlocked functional brace is used until at least postoperative week 12. Functional strengthening with low-resistance closed kinetic chain exercises can begin between 4 and 8 weeks, and resistance exercises are gradually increased between 8 and 12 weeks. Two-legged squats can be used, but they should be limited to 70° of knee flexion to prevent joint translation. Isokinetic strengthening is not started until at least week 12. In the majority of patients, full recovery can be expected within 6–12 months [5].

25.5 Results and Outcome

25.5.1 Combined ACL and MCL Injury Treatment Outcomes

The initial treatment following a combined ACL and MCL injury should rely on a nonoperative functional rehabilitation program regardless of the degree of MCL complex laxity/injury. Following 4–8 weeks of rehabilitation, the joint should be reevaluated for medial laxity. If at that time grade II or III laxity is present, operative repair or reconstruction should be performed. Once the inflammatory phase has passed and full range of motion and quadriceps strength have returned to the affected leg, the ACL injury should be reconstructed along with repair/reconstruction of the damaged medial structures in a single procedure. Hughston reported excellent long-term results for acute anatomic repairs of combined medial knee and ALC tears [24].

Chronic combined ACL and MCL injuries are a more complicated problem, and outcomes are not as predictable as with acute injuries. Animal studies in canines have shown that MCL healing is negatively affected in the presence of a deficient ACL [59]. In animals with both the ACL and MCL transected, varus-valgus rotation and the mechanical properties of the ligament did not recover. This shows the importance of early recognition and treatment of combined ACL and medial knee injuries with reconstruction of the ACL to restore stability and allow for proper MCL healing.

25.5.2 Combined ACL and PLC Injury Treatment Outcomes

Chronic combined ACL and posterolateral corner injuries can be complicated by scar tissue and possible limb malalignment, which make treating chronic injuries difficult; however, the goals of reconstruction remain the same as with an acute injury. There is a general consensus supporting better outcomes for patients who undergo reconstruction for a chronic grade III injury to the posterolateral corner of the knee. Geeslin and LaPrade reported significant improvement in patients who underwent anatomic posterolateral reconstructions for both isolated PLC injuries as well as those combined with a cruciate injury [15]. Studies have demonstrated that patients who undergo anatomic reconstructions show no difference between groups requiring a staged procedure with an initial osteotomy versus those who do not [15]. Anatomic techniques that are designed to restore the normal function of the posterolateral knee static stabilizers are recommended for patients with medial and posterolateral ligament injuries. Patients who are treated with anatomic reconstructions have been reported to obtain significant increases in knee stability and function following reconstruction [15, 38].

Conclusion

Treatment of ACL injuries combined with medial or posterolateral knee injuries is a complex and controversial topic that requires a systematic approach to evaluation and treatment. Careful physical examination and the use of stress radiographs are essential to the diagnosis and proper treatment of these injuries. Regardless of the type of injury, it is important to not overlook medial and posterolateral injuries when combined with an ACL tear because they can lead to ACL reconstruction graft failure. Acute combined ACL and PLC injuries have the best outcomes when they are managed with early reconstructions of the ACL and grade III tears of knee structures. Low-grade acute MCL tears combined with an ACL tears may certain cases be treated with bracing and reconstruction of the ACL once the medial injury has healed. Posterolateral corner injuries combined with ACL tears are best treated with repair/reconstruction depending on the injury. Chronic injuries are more of a challenge to treat, often requiring staged procedures to ensure proper limb alignment prior to attempting a reconstruction.

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26 ACL Injuries in Children: Treatment and Outcomes – Personal Experience

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26.1 Introduction

A rising number of anterior cruciate ligament (ACL) injuries are seen in children and adolescents, and the management of these injuries is still a matter of debate [4, 8, 25]. In contrary to the skeletally mature patient where arthroscopically intra-articular transphyseal reconstruction techniques are the standard of care, the treatment of ACL instability among skeletally immature patients remains a controversially debated topic surrounding surgical techniques and risks of growth disturbances [4, 10, 15, 17, 23, 34]. In the past decades, nonsurgical treatment of ACL injuries in the immature patients was considered the most appropriate initial approach until skeletally maturity was reached [34]. The rationale of this approach is to allow the physes to close before a surgical intervention primarily because of the fear of possible growth plate damage associated most notably with transphyseal reconstruction techniques [28, 30, 36].

However deficiency of the ACL in children and adolescents is not a benign condition, and nonoperative treatment has not resulted in good clinical outcomes [16, 24]. To overcome the limitations associated with nonoperative treatment, different surgical strategies have been established in clinical practice including physeal-sparing and transphyseal techniques, but until now, there is no consensus on the optimal surgical technique [2, 15, 18, 20].

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Fig. 26.1 Patient positioning

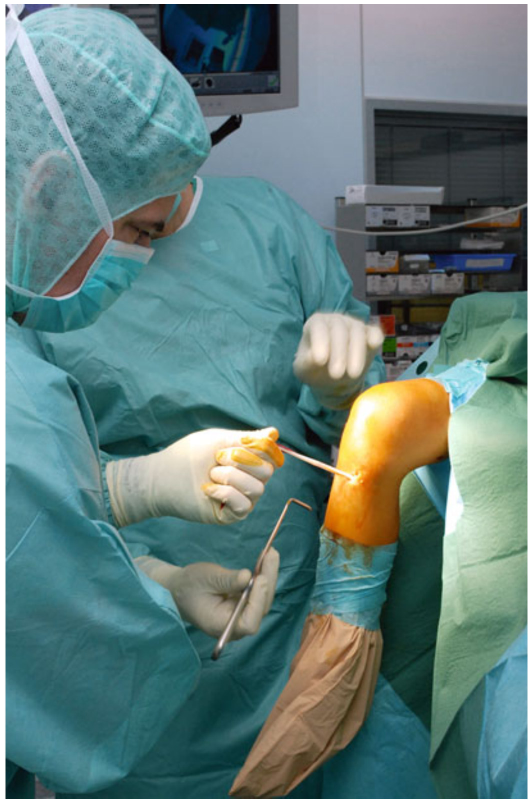

Fig. 26.2 Graft harvest

In our daily practice for several years, a transphyseal anatomical reconstruction with a “physeal respecting” approach has been used to surgically repair the ACL in the skeletally immature patient with favorable clinical results. With this technique, hamstring tendon autograft is used to reconstruct the ACL with fixation techniques performed proximally to the physis in the femur and distally to the physis in the tibia.

26.2 Operative Technique

Surgery is done under general anesthesia with the patient positioned supine on the operating table. The leg is placed in a leg holder and exsanguinated under tourniquet control of 250 mmHg. A special hook under the operating table is used to allow a standardized knee flexion of 130° for drilling of the femoral tunnel (Fig. 26.1).

26.2.1 Graft Harvest and Preparation

Generally the semitendinosus (ST) and gracilis (GT) tendon are harvested through a 1.5-cm slightly diagonal incision over the pes anserinus. The tendons are harvested with an open tendon stripper and finally detached from its insertion (Fig. 26.2). The tendons are prepared on a tendon board. Routinely, a 4-stranded looped graft is prepared with a diameter of 6.5–8.0 mm and a length of 6–8 cm. In patients with sufficient graft length only the semitendinosus tendon is used. The femoral graft end is attached to an endobutton (FlippTack, Karl Storz, Tuttlingen) with non-absorbable 1-mm Ethibond strand (Ethicon, Norderstedt, Germany) as linkage material. The double-looped proximal graft end is sutured together with 2-0 Vicryl (Ethicon, Norderstedt, Germany) absorbable sutures at a point approximately 2 cm from the looped end. The free tibial graft ends are sutured in a running baseball whipstitch mode using no. 1 Terylene (Serag Wiessner, Naila, Germany) nonabsorbable sutures. In the looped tibial graft end (in quadruple grafts), another 1-mm Ethibond strand is used for distal fixation [31] (Fig. 26.3).

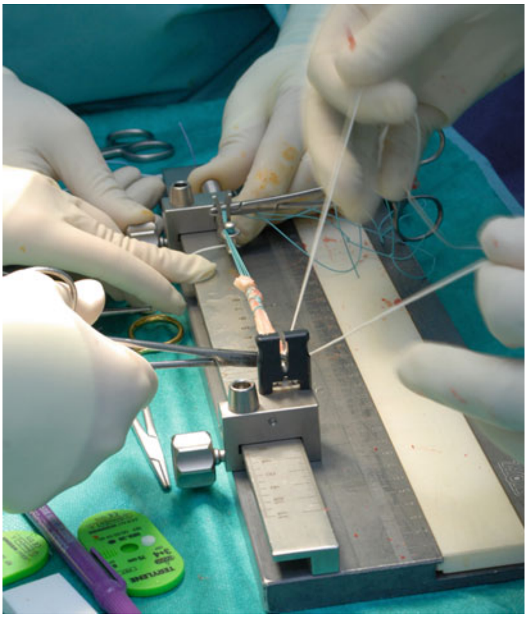

Fig. 26.3 Graft preparation

26.2.2 Arthroscopic Technique

The superior lateral portal and a low medial portal are established as standard portals. Diagnostic arthroscopy is performed and meniscal and chondral injuries evaluated. The intercondylar notch is visualized and remnants of the ACL are partially removed. The femoral insertion area of the native ACL is carefully debrided.

The femoral tunnel is crated first. A femoral offset aiming device is introduced through the anteromedial portal, and the knee is brought to 130° of flexion. The guide is positioned in the center of the femoral insertion area. A guide wire is placed and drilled out through the anterolateral thigh (Fig. 26.4). The guide wire is over reamed with a 4.5-mm reamer through the lateral femoral cortex. The femoral tunnel is then enlarged to the graft diameter using an endobutton reamer or with dilatation to minimize damage to the adjacent femoral epiphysis to a socket of >30 mm depending on the entire tunnel length to allow flippage of the endobutton. The depth of the entire femoral tunnel is measured with a depth gauge (Fig. 26.5) and the respective value is adjusted on the tendon board.

The tibial tunnel is created with the use of a tibial drill guide, and a guide wire is placed in the

Fig. 26.4 Drilling of the femoral tunnel

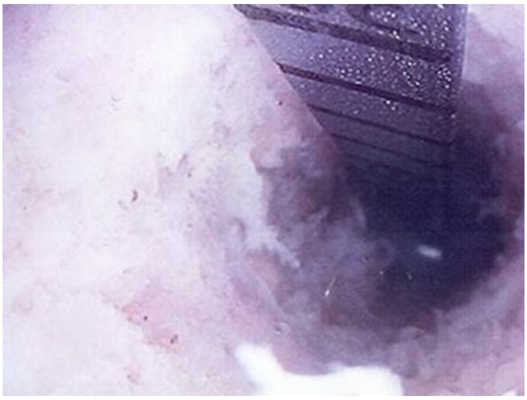

Fig. 26.5 Measurement of femoral tunnel length

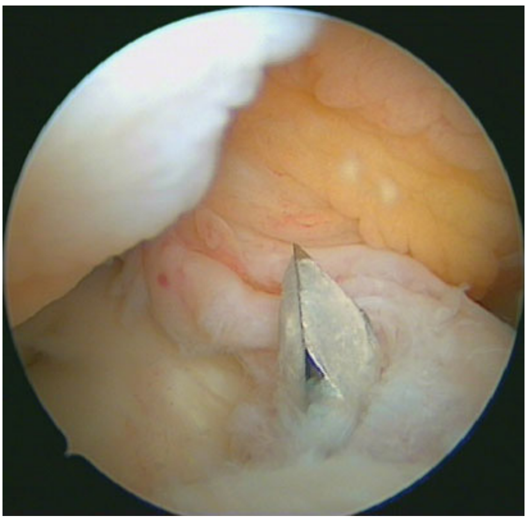

Fig. 26.6 Tibial tunnel placement

center of the native ACL insertion (Fig. 26.6). The tibial tunnel is dilated gradually to the measured graft diameter. The orientation of the tunnel is as vertical as possible in the sagittal and coronal planes. The arthroscope is placed in the tibial tunnel to visualize the proximal tibial physis and define the length proximal to the physis for placement of an epiphyseal bioabsorbable interference screw (Fig. 26.7). The graft is then passed through the tibial tunnel through the joint into the femoral tunnel and the endobutton is flipped (Fig. 26.8a, b). After, femoral fixation tension is applied to the tibial graft end, and the knee is cycled 20 times. Tibial a hybrid fixation technique is used for graft fixation (Fig. 26.9). Either a bioabsorbable 7 × 20-mm PLLA retroscew (Arthrex, Naples USA) or a PLDLLA 6–7 mm × 19-mm interference screw (MegaFix, Karl Storz, Tuttlingen, Germany) is placed in the tibial epiphysis with tension on the graft and the knee in 30° of flexion. Backup fixation is accomplished with a fixation button (EndoTack, Karl Storz, Tuttlingen, Germany; Mini-Suture Disc, Aesculap, Tuttlingen, Germany) or a titanium screw (Fig. 26.10a, b).

Fig. 26.7 Visualisation of the tibial physis

26.2.3 Postoperative Rehabilitation

Postoperatively, only partial weight bearing is allowed for 2 weeks. In case of additional meniscal refixation, 4 weeks of partial weight bearing was carried out. A protective hinge ACL brace (Ipomax, Ortema GmbH, Markgroeningen, Germany) was worn for 12 weeks without motion limit. Physical therapy with lymph drainage, range of motion exercises, and electrical therapy was begun immediately postoperatively, followed by proprioception exercises and closed-chain strengthening exercises within the first 3 months. Return to full activity is not allowed before 6 month after surgery.

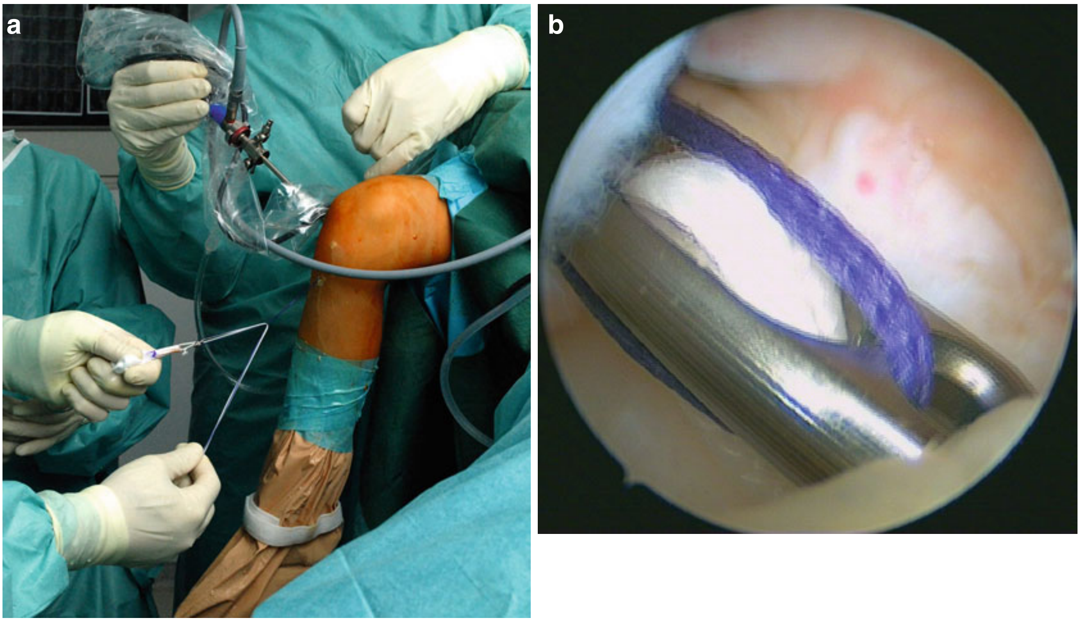

Fig. 26.8 (**a**) Graft insertion. (**b**) Intraarticular passage of the endobutton

Fig. 26.9 Graft tensioning

26.3 Results

26.3.1 Demographic Data

In a clinical study, 42 children and adolescents with open physis who underwent isolated ACL reconstruction were prospectively followed. The median age was 14 years (range: 8–16 years). There were 11 girls and 31 boys. Mean time from injury to surgical procedure was 5.2 months (0.5–57 months). A total of 37 meniscal tears (22 lateral meniscal, 7 medial meniscal, and 4 combined lesions) were seen in 29 of 42 patients (69 %). Lateral meniscal refixation was performed in 14 patients, medial meniscal refixation in 5 patients, and medial and lateral refixation in 2 patients. Patients were evaluated preoperatively for physiologic maturity by assessment of tanner stage and bone age [32, 33]. Nine patients were classified as tanner I, 28 patients as tanner II or III, and 5 patients as tanner IV.

Minimum 2-year follow-up data were available for 40 (95 %) of patients. Mean follow-up time was 27.8 months (24–36 months).

26.3.2 Outcome Measures

Clinical outcome was evaluated preoperatively and on follow-up examination with the International Knee Documentation Committee (IKDC) objective and subjective knee evaluation form [14]. Anterior tibial translation was quantified by measurements with the KT 1,000 arthrometer (MEDmetric Corporation, San Diego, USA) with the joint at 20° flexion.

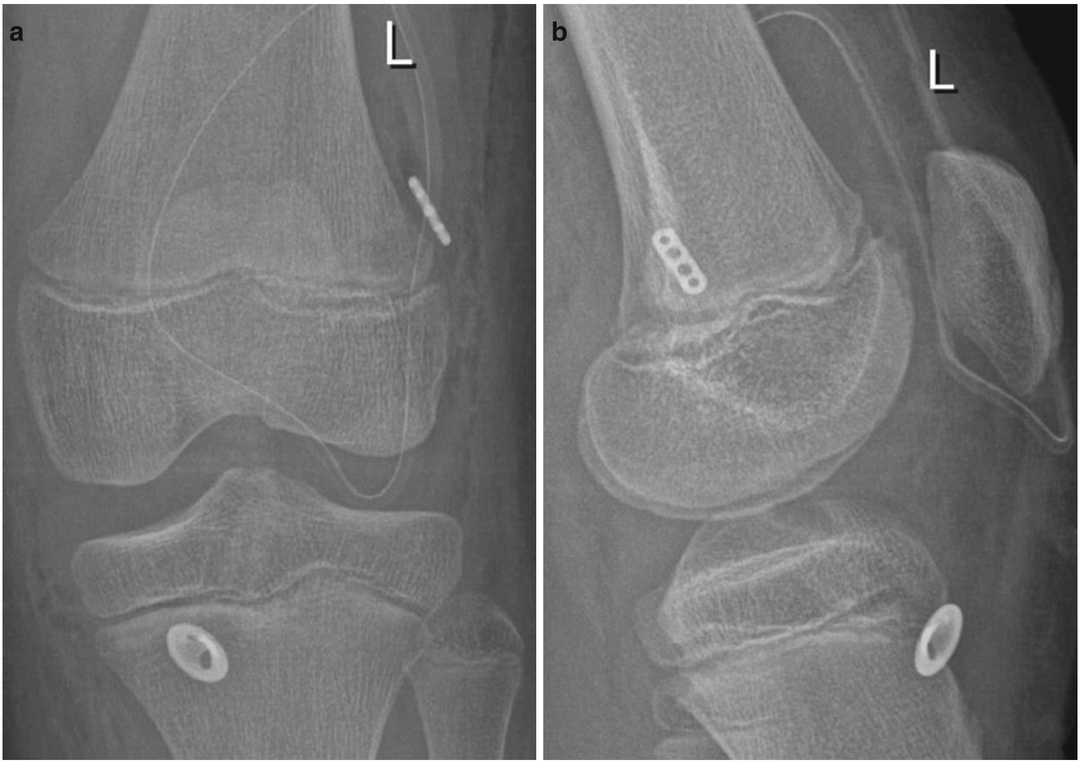

Fig. 26.10 (**a, b**) Physeal sparing fixation

Anteroposterior and lateral knee radiographs of the knee were routinely performed pre- and postoperatively and at 1 and 2 years after reconstruction to identify abnormal physis growth and knee axis deformations. Posterior tibial slope was determined by measuring the angle between the medial tibial plateau and perpendicular to the posterior tibial cortex. Femoral and tibial axis were determined by measuring the anatomic lateral distal femoral angle and the anatomic medial proximal tibial angle.

26.3.3 Results

Preoperatively, all patients were classified in the objective IKDC C (28 patients) and D group (12 patients). KT-1000 measurements exhibited a side-to-side difference of 5 mm in 11 patients of 6–8 mm in 23 patients and >8 mm in 8 patients. Mean subjective IKDC score was 92 ± 6 points (70–99). During latest follow-up examination, 29 patients were classified within the IKDC group A, 9 patients IKDC group B, 1 patient group C, and 1 patient group D. Postoperative KT-1000 examinations exhibited a side-to side difference of <3 mm in 29 patients and of <6 mm in 9 patients. Mean subjective IKDC score was 95 ± 8 points (66–100) at final follow-up.

Postoperative objective stability measurements and functional results significantly improved according to the preoperative status. No patient had clinically visible evidence for varus/valgus malalignment or leg-length discrepancy of more than 10 mm. No abnormal physis growth or premature physis closure was seen during the follow-up radiographs (Figs. 26.11a, b and 26.12a, b). There was no significant change in tibial slope and coronary knee axis measurements. In the two patients with clinically insufficient ACL reconstructions, revision surgery has been performed as skeletal maturity has occurred in the meanwhile.

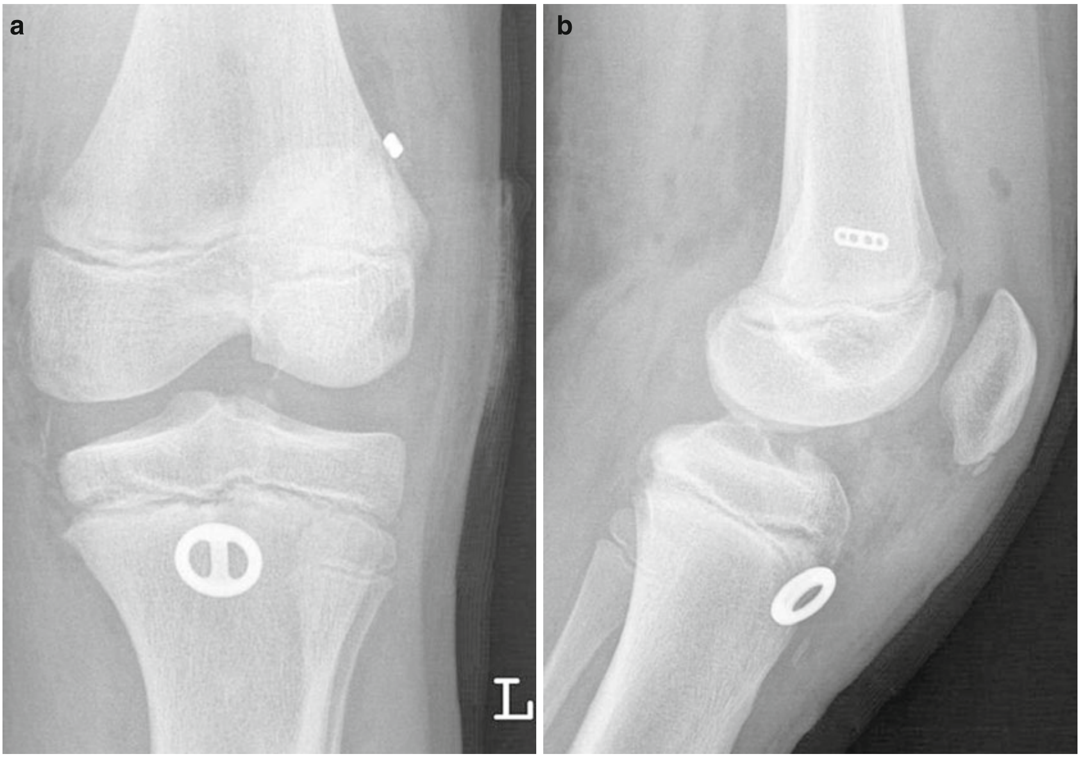

Fig. 26.11 (**a, b**) Postoperative x-rays

26.4 Future Research

Today, there is considerably evidence in the literature that the traditional nonoperative management of ACL injuries in the skeletally immature patients leads to unsatisfactory results [3, 8, 11, 16].

Also, there might be a rationale for a monitored temporary course of conservative treatment including restricted physical activity and the consequent use of an ACL brace in adolescents for subsequent delayed ACL reconstruction as soon as bridging of the physes has occurred [29, 35]; the natural history of this injury is progressive instability leading to further meniscal injury and cartilage damage [1, 22, 26]. Samora et al. reported a prevalence of meniscal lesions of 69 % in skeletally immature patients within 3 months after ACL injury and that a lateral meniscus tear was more common than medial lesions. This is in accordance with our findings and reinforces the fact that meniscal injury is commonly associated with ACL rupture in patients with open physes [27].

Traditionally, transphyseal reconstruction techniques have been avoided because drilling across the growth plate carries the possible risk of physeal injury and subsequent angular and longitudinal deformities [6, 13, 21]. Therefore, physeal-sparing reconstruction, partial transphyseal reconstruction, and extra-articular reconstruction techniques have been used to restore knee stability especially in tanner stage I patients [5, 12, 18, 19]. In a recently published conducted systematic review of different ACL reconstruction techniques in skeletally immature patients by Kaeding et al., no differences in patient-reported outcomes, AP laxity, or leg-length discrepancy or angular deformities between physeal-sparing and transphyseal reconstructions in tanner stage II and III patients was found. For tanner stage I patients, further study was recommended to evaluate efficacy and complication rates with transphyseal techniques [15].

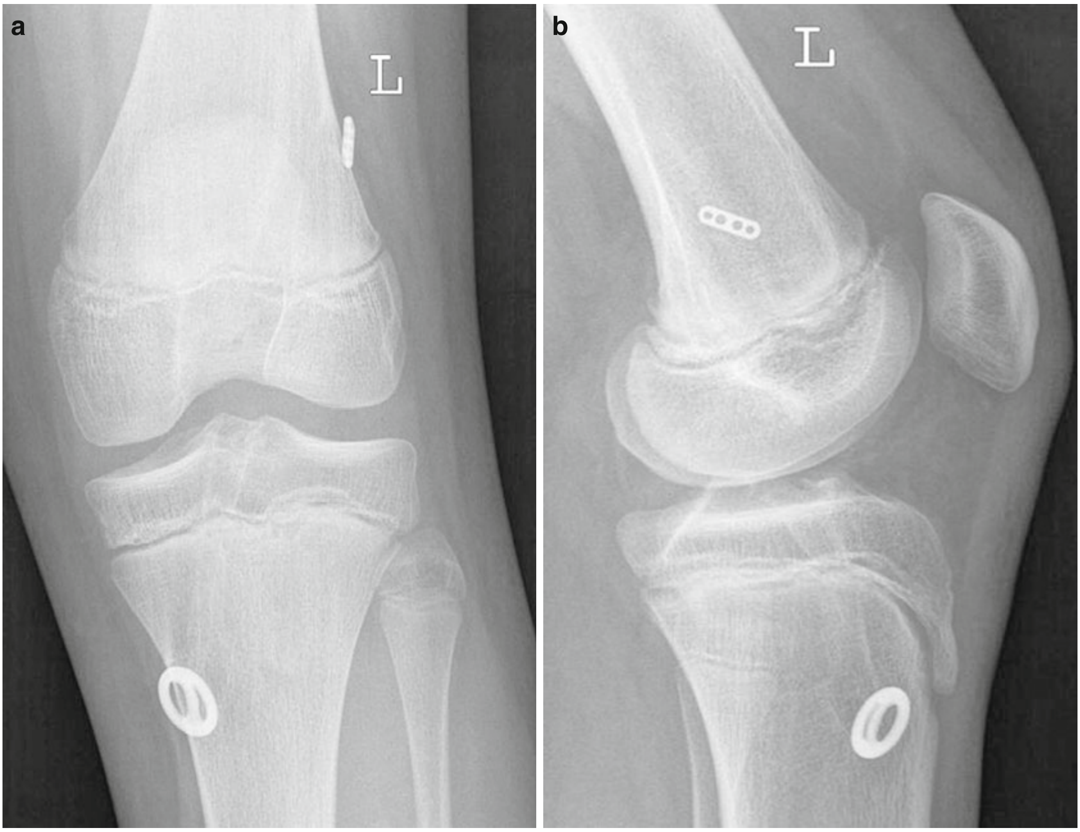

Fig. 26.12 (**a, b**) X-rays 2 years postoperative

However, the lack of anatomical graft placement with some of these techniques may question the long term results [4].

This is supported in a biomechanical study by Kennedy et al. where three different physeal-sparing reconstruction techniques (all-epiphyseal (AE) technique [2], a transphyseal over the top (TT) [18], and an iliotibial band (ITB) reconstruction technique [19, 20]) were investigated. They found that no reconstruction technique was ideal at restoring native knee kinematics. While the ITB reconstruction technique best restored AP stability and rotational control, the technique overconstrained the knee with respect to rotation at higher flexion angles [17]. Also, the safety of ACL reconstructions with respect to secondary growth abnormalities is not completely understood; there is increasing evidence that the risk of growth disturbances with transphyseal surgical techniques is low [7]. In a cadaveric study in sheep, Sail et al. found no growth abnormalities with central growth plate lesions. Posterolateral growth plate lesions with injury of the perichondral structures may lead to valgus and procurvatum deformity. However, this could be prevented if the bony tunnels were filled with tendon graft. They found that ACL reconstructions did not lead to clinically relevant growth disturbances despite consistent physeal damage [28].

These cadaveric results are supported increasingly by clinical investigations. In a recently published meta-analysis of the surgical treatment of ACL ruptures in patients with open physes, Frosch et al. reported low risks (1.8 %) of leg-length discrepancy or angular deformity after surgical treatment of an ACL tear in a skeletally immature individual. They found evidence for a significantly higher risk of angular deformity after physeal-sparing techniques, whereas hamstring tendon transplants may lower the risk [9].

In another published systematic review of the current evidence for management of immature ACL tears, Vavken et al. clearly found out that early surgical treatment results in more favorable outcomes than conservative treatment and recommend surgical stabilization as the first line of treatment. Even for the youngest patients, there was no significant increased risk of growth deformities with surgical treatment, but there were significantly better outcomes for knee stability and function compared with conservative treatment [34].

Conclusion

In conclusion, there is a clear trend to early surgical stabilization of the ACL injured knee in the premature patient. The rationale for this treatment is the high prevalence of meniscal injuries with increasing time from injury. Also there is increasing evidence both from cadaveric and from clinical studies that anatomical transphyseal reconstruction is a safe and reliable procedure even in tanner I patients.

In our opinion, early surgical repair with hamstring tendon autograft and fixation techniques which spare the physis should be considered in the premature patients. We recommend an anatomical transphyseal reconstruction technique. Our described technique has been performed for several years with good clinical outcome and without any signs of growth plate injuries even in tanner I patients.

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Combined Anterior Cruciate Ligament Reconstruction with Patella Tendon Lengthening Following a Complex Knee Injury

27

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Contents

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27.1 Introduction

Patella baja, also called patella infera or infrapatellar contracture syndrome, is frequently found in combination with arthrofibrosis following knee surgery [1–4, 6, 12–15, 17, 20, 21]. It has been described after injuries and operative procedures which interfere directly with the patella (e.g., patella fracture) or peripatellar tissues (e.g., patellar tendon ruptures and harvest of patellar tendon for ACL reconstruction) or as a result of prolonged postoperative limitation of range of motion [13].

According to Dejour [9], surgery is indicated for patella infera with a Caton-Deschamps index inferior or equal to 0.6. Surgery can be performed as a proximalization of the tibial tuberosity; however, if patellar tendon length is less than 2.5 cm, a tendon lengthening procedure is recommended [9].

Rupture of the ACL is a common sports injury. Conservative management was found to be associated with a high risk of cartilage and meniscal damage in patients which are active at high levels of cutting sports [7, 11, 19].

The patient of this case report had both patella infera causing pain with flexion and an ACL-deficient knee with functional instability preventing him to participate in high-level sports activities.

Due to the patient's tight time schedule, the two problems had to be managed in a combined procedure including arthroscopic ACL reconstruction using semitendinosus autograft and patella tendon lengthening.

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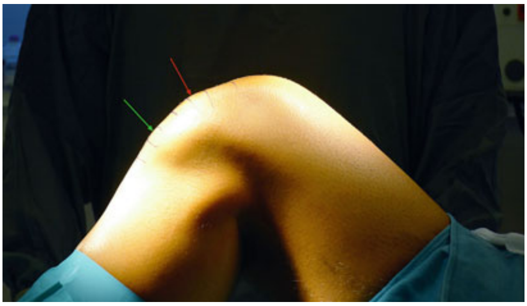

Fig. 27.1 Sagittal view of the preOP knee with visible distalization of the patella (*red arrow* = patella; *green arrow* = tibial tuberosity)

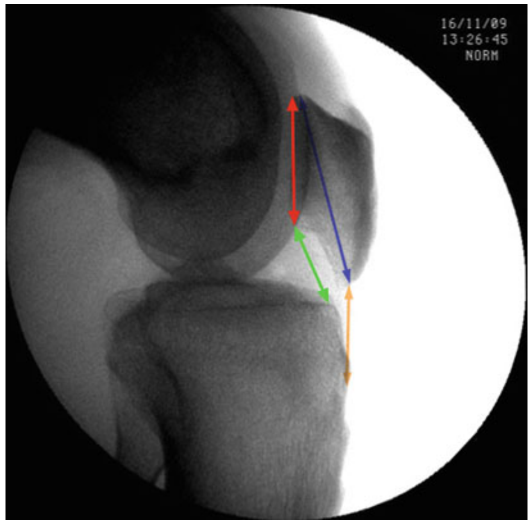

Fig. 27.2 PreOP ipsilateral (Caton-Deschamps index: 0.62: *red and green arrows*; Insall-Salvati index: 0.48: *blue and orange arrows*; Blackburne-Peel index: 0.53)

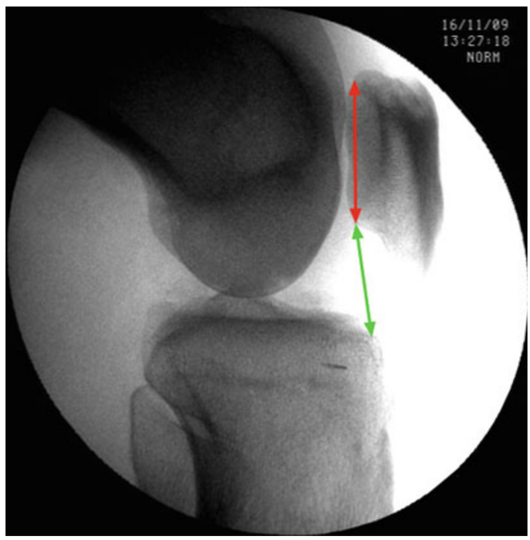

Fig. 27.3 PreOP contralateral (Caton-Deschamps Index = 0.95)

27.2 Case Report

A 44-year-old male patient consulted our office 10 months after his injury – a complex knee trauma while skiing with complete patellar tendon and ACL rupture and a lateral meniscal tear. He has been operated acutely in an outside hospital with patellar tendon repair and open lateral meniscal repair. The ACL has been left untreated. Surgery has been followed by 6 weeks of immobilization and then an intensive physical therapy program was installed. Prior to his injury, he was a semiprofessional mountaineer and extreme alpine skier.

The most prominent complain of the patient at the time of examination was pain with flexion >100°. At this stage, he did not report any giving-way episodes but has not tried to return to his previous sports activities. He basically came for a second opinion on how to proceed with his rehabilitation.

On inspection, he showed a well-healed 15-cm scar longitudinally over the patella and the patellar tendon, a suspected patella baja (Fig. 27.1), and severe atrophy of the thigh muscles.

Clinical examination revealed passive range of motion of 0-0-130° with increasing pain starting at 120°. He had a ++ Lachman and a + pivot shift test. Patella motion was restricted but only associated with minimal pain during palpation. There was no effusion or swelling.

Sagittal X-rays of both knees in 90° of flexion documented patella baja with a Caton-Deschamps index of 0.62 versus 0.95 on the contralateral knee (Figs. 27.2 and 27.3).

The patient was advised to continue his physical therapy program with a focus on muscular strengthening of the quadriceps using open- and closed-chain exercises but not exceeding 90° of flexion and hamstring strengthening.

About 1 year later, the patient returned for another consultation. Symptoms regarding pain with flexion did not change, but additionally he had experienced several instability episodes of his knee. His thigh circumference was equal to the contralateral side. He could not mountain climb on the same level due to pain with increased flexion and was unable to ski in difficult terrain due to knee instability. Clinical examination was almost equal to the previous examination with some increase of tenderness around the patella and a mild effusion. Patellar height on X-ray was similar to the previous examination.

Since the patient had the desire to return to his extensive sports activities, he was offered surgical intervention. Because he has been self-employed, time was extremely crucial to him.

In order to address both of his major complains – pain with deep flexion and anterior knee instability – surgery including ACL reconstruction in combination with patella tendon lengthening was planned simultaneously. For ACL reconstruction, an arthroscopic procedure using ipsilateral semitendinosus tendon autograft was performed and followed by patellar tendon lengthening with a modified z-plasty.

The patient was positioned supine and the leg fixed in an electric leg holder.

In order to determine the correct position for the patella, a lateral view in 90° of flexion from the contralateral knee was performed and saved with a fluoroscope.

After inflating the tourniquet, a 10-cm incision was placed excising the old scar from the middle of the patella to the tibial tuberosity. The semitendinosus tendon was when harvested for ACL reconstruction.

A diagnostic arthroscopy was performed revealing no cartilage pathology in all compartments, a repaired lateral meniscus that had healed, and an incomplete longitudinal tear of the medial meniscus about 1.5 cm in length. The patella was distalized with prominent scar formation in the area of Hoffa's fat pad and some scar formation in the suprapatella recess. There were only minor remnants of the ACL visible.

The medial meniscal tear was repaired using one all-inside FasT-Fix™ (Smith & Nephew) suture.

Then the femoral tunnel was drilled inside out through the anteromedial arthroscopic portal. The tibial tunnel was drilled outside-in using an Arthrex guide. The semitendinosus tendon was fixed with Nr.2 FibreWire™ (Arthrex) in web stitch technique at both ends and used as a four strained graft. After measuring the length of the femoral tunnel (35 mm), it was mounted to a 15-mm continuous loop Endobutton™ (Smith & Nephew). Graft diameter was 8 mm proximal and 8.5 mm distally.

On the tibial side, the graft was fixed in hybrid technique, with an 8 × 28-mm bioabsorbable interference screw and tying the sutures over a bony bridge.

Following ACL reconstruction (Fig. 27.4) the shortened patellar tendon was exposed. A straight longitudinal cut from the inferior patellar pole to the center of the tibial tuberosity was performed. The two resulting reins were then separated diagonally and detached on one side proximal at the patellar insertion and on the other side distal at the tibial insertion (Figs. 27.5, 27.6, and 27.7). The patella was then mobilized and the fibrotic Hoffa as well as scar tissue in the suprapatellar recess was excised.

Two holes (2.5 mm) were drilled parallel through the patella and the tibial tuberosity from medial to lateral, and a Nr.5 FibreWire™ suture was pulled through. The knee was flexed to 90°, and under fluoroscopic control, the FibreWire™ loop was tightened with the patella at the same height than the contralateral side. The tendon reins were adapted by Vicryl sutures. Finally, the wound was closed in layers. Tourniquet time was 90 min.

The patient was mobilized with partial weight-bearing and a hinged knee brace with full extension and flexion limited to 60° on the first postoperative day. He was discharged from the hospital at day 4.

The brace was adjusted to 90° of flexion at 3 weeks and weight-bearing was increased gradually. At 6 weeks, we allowed full weight-bearing

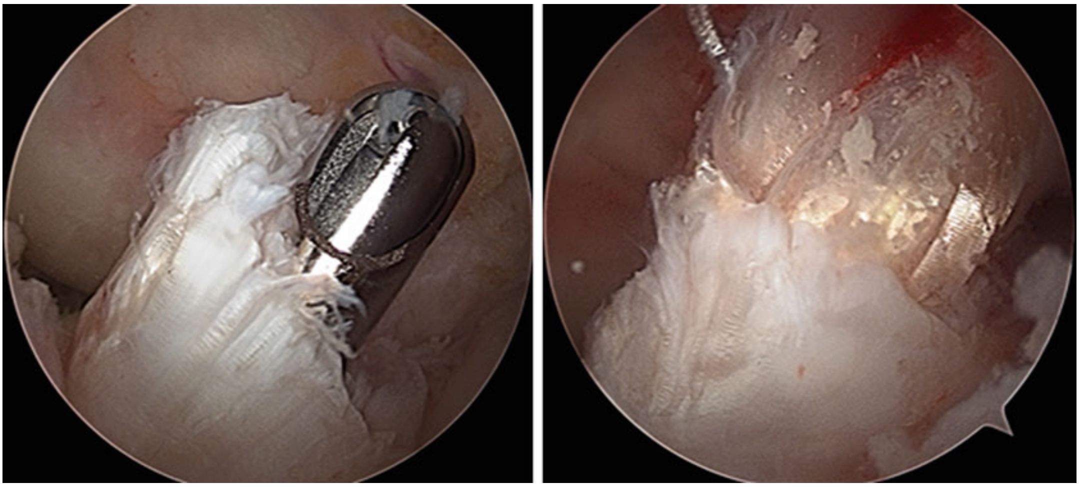

Fig. 27.4 Hamstring autograft positioned in the center of the old ACL stump

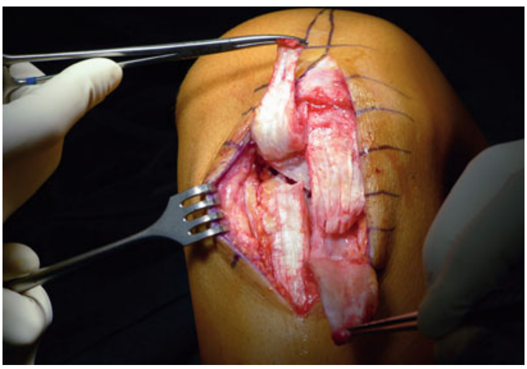

Fig. 27.5 Medial and lateral reins divided into a deeper and upper layer

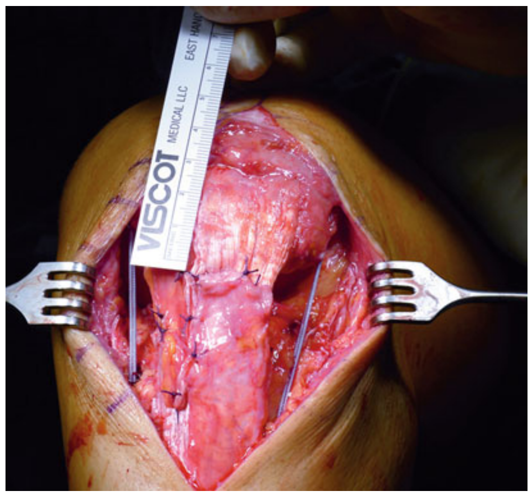

Fig. 27.6 Adopted and sutured patellar tendon after modified z-plasty with nearly 3 cm of tendon lengthening. The patella position is secured by a doubled FibreWire™ Nr.5 traversed through the distal patella and the tibial tuberosity

and unrestricted range of motion. Muscle strengthening was gradually implemented, and at 8 weeks, he was able to ride a stationary bike without problems.

At 6 months postoperative, the patient had a ROM of 0–140°. The patella position had remained constant with a Caton-Deschamps index of approx. 1.0 (Fig. 27.8). He had a negative Lachman and negative pivot shift test. He still had a muscular deficiency of the thigh musculature.

At 12 months, the patient was back to full activity with some minor pain and no instability even with strenuous sports activities. He was very satisfied with the result (Fig. 27.9).

27.3 Discussion

Patella baja is a rare but severe problem complicating knee surgery. The radiographic measurement of patella height has been discussed in the literature [16]. The five most common indices used are the Caton-Deschamps (CD), Insall-Salvati (IS), modified Insall-Salvati (mIS), Blackburne-Peel (BP), and Labelle-Laurin (LL)

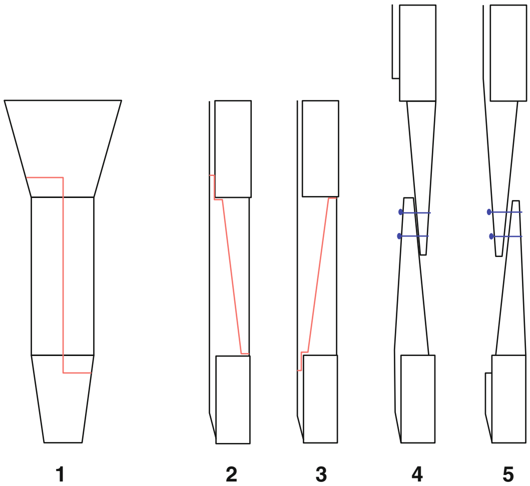

Fig. 27.7 Schematic figure of the modified z-plasty. *Black lines* = bony patella and tibial tuberosity; *grey lines* = patellar tendon; *red lines* = target cuts; *blue* = sutures. *1*: anteroposterior target cuts through the patellar tendon and its insertions. *2*: sagittal view with cuts of the left sided rein in (1). *3*: sagittal view with cuts of the right sided rein in (1). *4*: sagittal view of adopted ends of the left sided rein. *5*: sagittal view of adopted ends of the right sided rein

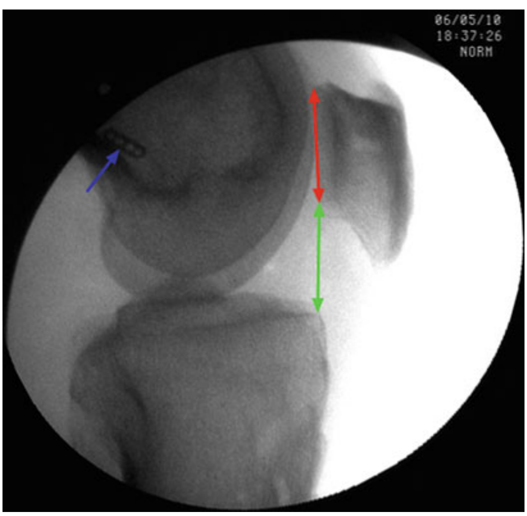

Fig. 27.8 Six months postOP (Caton-Deschamps index: 1.01) *blue arrow*: Endobutton™ (Smith & Nephew)

ratio. They do show varying results. Seil et al. [16] concluded that IS ratio shows the lowest number of normal patella height, CD ratio the lowest number of patella alta, and LL method revealed the highest number of patella alta. The BP ratio leads

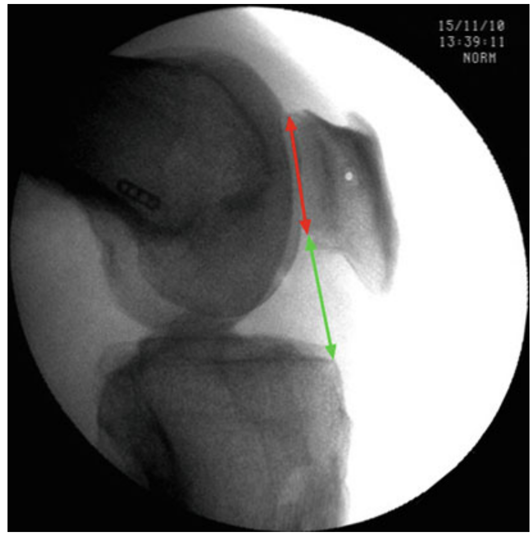

Fig. 27.9 Twelve months postOP (Caton-Deschamps index: 1.02)

to intermediate results for both patella alta and baja, being the most moderate method.

Several operative techniques have been published with varying outcome [5, 10, 18, 22]. Proximal advancement of the tibial tuberosity [8] is a sufficient technique but if the patellar tendon is shortened severely, it is necessary to gain as much length as possible. In this case or if the patellar tendon is partially destroyed, allograft replacement or a reconstruction using quadriceps or hamstring autograft may also be an option.

We have used this modified z-plasty technique, which allows to nearly double the tendon length, in ten cases of isolated patella baja with extremely satisfying outcome. In the combination with an ACL reconstruction, we thought this would be the best solution.

Due to functional instability, ACL reconstruction was indicated in this patient. The high activity level of this patient and the variety of different sports (ski mountaineering, climbing, cycling, mountain biking, etc.), however, have required unrestricted knee flexion and knee stability. So the goal of this surgery was to restore both of these modalities as closely as possible. For ACL reconstruction, a hamstring graft was the ideal graft choice over patella tendon (which was clearly impossible in this case) and quadriceps tendon. An allograft would have been a good alternative but was not available to us.

The major concern to us was to perform both surgeries combined in order to save recovery time. We were afraid of putting too much surgery to the knee joint at once.

In order to achieve a good result in such a complex case, it is necessary to have a compliant and motivated patient who is willing to undergo an extensive rehabilitation protocol.

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Part III

Complications After ACL Reconstruction: Can We Do Better? – Prevention and Treatment

ACL Graft Failure

28

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28.1 Introduction

In accordance with the rising number of primary ACL reconstruction, we are faced with an increasing number of revision surgeries [1, 23]. Revision ACL surgery for the patients means another time-consuming event, including weeks of impairment, absence from work or sports, and long hours of rehabilitation. Like in total joint surgery, revision ACL reconstruction represents an even higher challenge to the orthopedic surgeon.

Changing and evolving techniques in primary ACL surgery (e.g., double-bundle ACL reconstruction) may be responsible for better outcomes but may also create new challenges in the revision situation.

In ACL revision, the surgeon is faced with an additional problem that clinical results have been found to be inferior to primary reconstruction [2–4, 21, 27] and patient expectations especially in sports are still extremely high.

Therefore, ACL revision surgery does not mean to duplicate the previous procedure but to find a perfect solution using most of the time a different graft and a modification of the reconstruction technique.

28.2 Analysis of Graft Failure

The reported rate of traumatic reinjuries (Fig. 28.1) following ACL reconstructions varies between 3.6 and 32 % [13, 15, 23, 37]. Therefore, other reasons are more important for ACL graft

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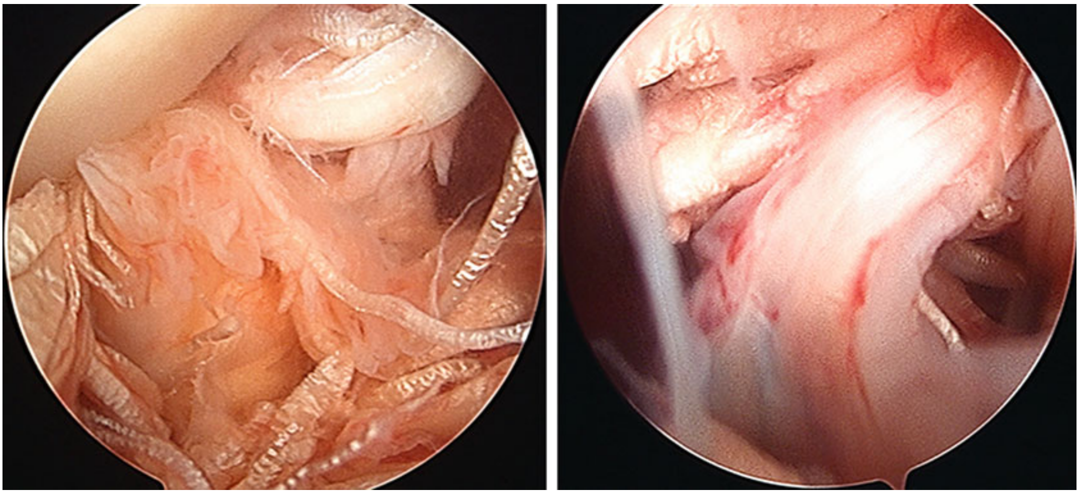

Fig. 28.1 Traumatic graft rupture

failure than reinjury. Failure due to technical problems in primary ACL, reconstruction seems to be the most frequent reasons for revision surgery [3, 5, 7, 8, 16, 26]. Injury to the graft during harvest or fixation [15], malpositioning of the bone tunnels, and problems with fixation are common.

In most studies [16, 17, 27], femoral tunnel malposition was the most common technical failure (Fig. 28.2). The femoral tunnel influences graft kinematics the most. Anterior placement leads to high graft stress in flexion, resulting either in graft loosening or in increased risk of re-rupture [17].

Tibial misplacement has less influence on graft kinematics, but is associated with different forms of impingement. There may be bony impingement with the graft interfering with the condyles (too far medial or too far lateral) or the intercondylar notch (too far anterior) or soft tissue impingement on the posterior cruciate ligament (PCL) (too far posterior). The latter has been found more frequently in association with endoscopic single-bundle techniques (in order to reach the desired position on the femur, the tibial tunnel is moved posterior) and with double-bundle reconstructions in small knees.

Vertical graft placement (most common in transtibial drilling techniques) may lead to good anteroposterior (ap) stability as represented by a negative Lachman test with firm endpoint. However, it may be associated with rotational laxity (positive pivot shift test).

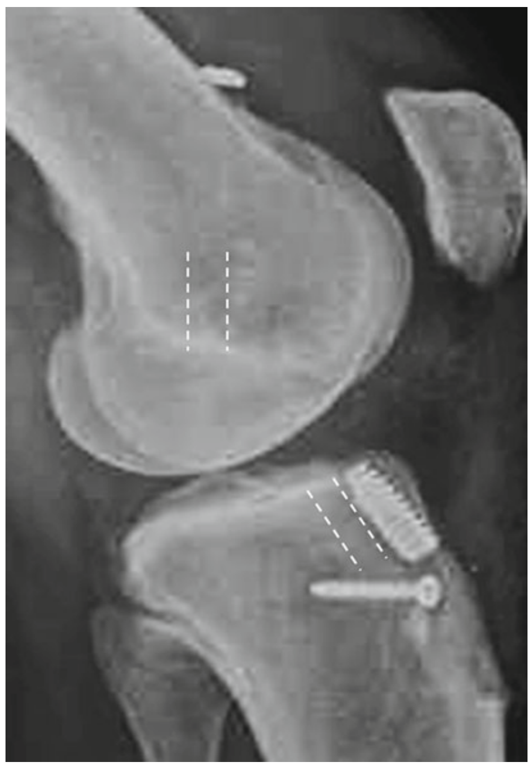

Fig. 28.2 Misplacement of the bone tunnels – femoral and tibial too anterior. White dashed line outlining the bone tunnels

Biologic graft failure is also a common reason for graft failure, but the term has not been well defined in the literature up to date [8, 14, 15]. The definition by the MARS group [23] seems useful for clinical practice: Biologic failure is classified as lack of incorporation of the graft as evidenced by early failure without a significant traumatic episode or obvious significant technical problems with the previous reconstruction. Using this definition, the authors attributed 7 % to this type of failure in their study [23].

Additional ligamentous pathologies leading to rotational instabilities are not infrequent either [3, 10, 41]. Unaddressed posterolateral instability (10–15 % in chronic ACL instability) [10, 20], for example, was found to be associated with prolonged ACL graft failure.

Increased tibial slope [13] places a higher stress on an ACL graft and could be a risk factor for graft failure.

Infection following ACL reconstruction is another risk factor for graft failure [13]. Additionally, it has been documented that in the revision situation, the amount of degenerative cartilage changes and meniscal lesions is higher than in primary ACL reconstruction [6].

28.3 Clinical Evaluation

Because of the multifactorial reasons for graft failure, patients with recurrent instability following ACL reconstruction have to be evaluated systematically.

Time and duration of complaints (sudden onset vs. gradual worsening) are as important as the quality of complaints.

For a successful outcome of revision surgery, it is essential to distinguish patients' symptoms between pain and instability. ACL revision surgery can sufficiently address instability but rarely directly addresses pain. Pain is rather a sign of additional injuries (e.g., meniscus lesions) or degenerative cartilage pathology. There may also be complaints of "instability" due to pain. Especially disorders of the patellofemoral joint (e.g., patella instability, patellofemoral osteoarthritis) are sometimes associated with "giving-way" episodes due to pain-related muscle inhibition.

To gather as much information about the previous surgery and the postoperative course as possible is helpful planning the revision operation (e.g., previous patients' history and operative reports). However, this information is not always accessible.

Clinical examination has to include a meticulous assessment of range of motion (ROM), swelling, effusion, tenderness, and laxity.

The evaluation of laxity should not only include a Lachman test but also has to be extended to anterior drawer (90° of flexion) in neutral, internal, and external rotation (to assess rotational instability); posterior drawer (to exclude posterior instability); and pivot shift test.

Instrumented laxity test like the KT 1000 [30], the Rolimeter [30], and the newer instruments to objectively evaluate the pivot shift test [25] may also be helpful.

28.4 Imaging

Imaging plays a critical role in planning revision surgery. The goals of imaging are to detect additional pathology and to clearly define previous bone tunnels and implants. Imaging is the foundation to plan the revision surgery with respect to timing (one- or two-stage procedure) and operative techniques.

The need for this complex information may require all modalities such as plain radiographs, magnetic resonance imaging (MRI), and computed tomography (CT) scans.

28.4.1 Radiography

Conventional X-rays give an "overview" of the situation which includes an estimation of the size and location of previous tunnels. Metal implants can be clearly identified.

Weight bearing ap and lateral views are important to assess the joint space if degenerative changes are suspected.

Long-standing films are not only necessary to evaluate the alignment in the case of degeneration but also in the situation of additional ligamentous laxity (posterolateral or posteromedial).

Fig. 28.3 MRI of failed ACL reconstruction with a metal interference screw on the tibia

28.4.2 MRI

MRI is ideal to assess additional pathologies (e.g., meniscal lesions, cartilage lesions, bone marrow edema) and the current graft situation (e.g., graft impingement, structure, partial graft ruptures). Bioabsorbable implants can also be identified. Commonly, MRI is superior to plain radiographs to characterize position and size of preexisting tunnels. However, in case of metal implants or due to edema around bioabsorbable implants, the MR signal may be highly compromised (Fig. 28.3).

28.4.3 CT

In order to exactly define bone tunnels (shape, size, location), CT scans with sagittal, coronary, and/or 3D reconstructions [20, 24] are the "gold standard" and superior to MRI regardless of the implant material (Fig. 28.4).

28.5 Graft Selection

Although several studies [12, 32, 36, 38] have shown that there are no statistical differences in subjective and clinical outcome between autologous patellar tendon, hamstring, and quadriceps grafts for primary ACL reconstruction, every surgeon has a "personal" graft preference.

Revision surgery, however, requires flexibility and familiarity with all different grafts. For many years (during the times when the patellar tendon graft was seen to be the gold standard for primary ACL reconstruction), "reuse" of a previously harvested patellar tendon for revision as early as 6 months after the initial surgery was common [20]. Today, this practice has been mostly abandoned due to the fact that the repair tissue of the defect was found to have inferior biomechanical properties [18, 29] and that there is a general acceptance that other grafts function just as well.

Autologous grafts are available from the injured as well as the contralateral leg. The decision which graft to use is dependent on several factors: (a) transplant used for the primary reconstruction, (b) previous transplant fixation technique, (c) size of previous bone tunnels, and (d) patients' choice.

The contralateral leg is a possible source for several grafts, but not all patients do accept that.

Allografts are an excellent possibility for revision surgery [15]. They do have the advantage of reduced morbidity and more flexibility in size. Availability of allografts, however, is very restricted in many countries in Europe.

Therefore, in revision ACL surgery, the surgeon has to give up his graft preference for primary ACL reconstruction in order to adapt the graft best suitable to the current situation.

28.6 One-Stage or Two-Stage Procedure

28.6.1 One-Stage Surgery

In every revision situation, the first question to ask is if the problem can be solved in one operation without compromising anatomical tunnel placement, transplant fixation, or ingrowth.

The more versatile and experienced the surgeon referring to graft choice, drilling of the bone tunnel (e.g., outside-in, retrograde, transtibial,

Fig. 28.4 Comparison of plain radiography and CT scan in the same patient. Tunnel enlargement on the femur cannot be judged on the X-ray

anteromedial), and fixation techniques, the more frequent a revision situation can be solved in one stage. If a surgeon wants to keep to his preferred technique and fixation method, then only few revision situations can be handled in one operation [9, 22, 39].

28.6.2 Two-Stage Surgery

Filling of preexisting misplaced or enlarged bone tunnels with cancellous bone may finally result in a situation which comes close to a primary reconstruction (provided that there is no coexisting pathology).

The major disadvantage, however, is the time delay until the final reconstruction.

At least 3–6 months are necessary for the cancellous bone to heal in completely [22, 39]. Cost of the operation and the risks of an additional surgery have also to be taken into account.

In professional sports as well as manual labor where patients depend on the stability of their knee, this time delay may result in significant problems for these patients.

28.7 Classification of Revisions

In order to provide a possibility for comparison of outcomes and to facilitate surgical planning, a classification system for the various revision situations is necessary. Pässler et al. [28] described a classification system which is based on the amount of tunnel enlargement. We further modified this classification and included other relevant factors for the revision reconstruction [11] (Table 28.1).

Table 28.1 Classification of ACL revision [11]

Type A
None or minimal tunnel enlargement, anatomical placement of the tunnels or tunnel completely off the anatomical location
One-stage procedure
Graft choice not relevant (preference of surgeon or patient – autologous graft from the opposite leg or different transplant from the same leg)
Possible modification of fixation technique
Type B
Massive tunnel enlargement, anatomical placement of new tunnels impossible
Two-stage procedure (bone grafting the tunnels first)
Type C
Bone tunnels slightly off the anatomical position (with or without tunnel enlargement), anatomical placement of new tunnels possible with technical modifications
Single-stage procedure
Graft choice relevant
Modified placement of tunnels (e.g., outside-in, retrograde, squared tunnels)
Possible bundle augmentation (AM or PL)
Type D (complex revision)
Additional pathologies (ligamentous laxity and/or degenerative changes)
ACL revision plus osteotomy
ACL revision plus additional ligament reconstruction (medial/lateral)
ACL revision plus meniscus allograft/implant

28.8 Surgical Technique

28.8.1 Implants

Implant removal from previous ACL surgery can be difficult and time-consuming. Therefore, these implants should only be removed if they compromise anatomical tunnel placement in revision surgery. If metal interference screws are present, a "universal screw removal set" (includes screw drivers for every metal screw on the orthopedic market) provided by several companies should be available in the OR in order to avoid unnecessary complications.

Staples used on the tibia for fixation of soft tissue grafts are sometimes extremely difficult to remove. They never compromise tunnel placement and should only be retrieved if they are painful for the patient.

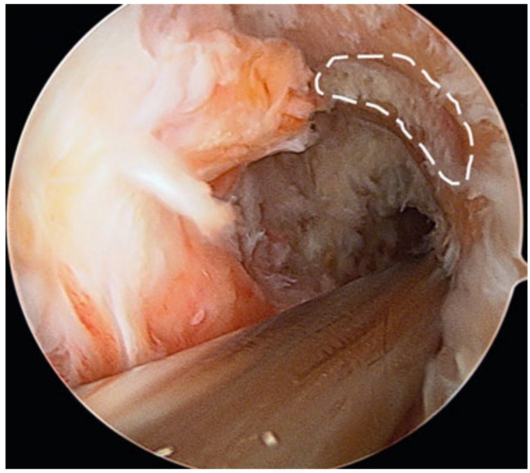

Fig. 28.5 Placement of a new femoral tunnel through anteromedial arthroscopy portal. The previous tunnel, placed transtibial, is still visible. White dashed circle outlining the previous bone tunnels

28.8.2 Tunnel Placement

If the tunnels of the initial reconstruction are in a nonanatomical position (more than one tunnel diameter off), placement of the new tunnels is of no difficulty (Fig. 28.2).

If misplacement is less than one tunnel diameter, changing the angle of the new tunnel can be sufficient. If the initial ACL reconstruction was performed by transtibial drilling technique, the starting point for the tibial tunnel is medial on the tibia close to the insertion of the MCL. Using a steep tunnel more central on the tibia close to the tuberosity and placing the femoral tunnel through the anteromedial arthroscopy portal (Fig. 28.5) usually result in sufficient tunnel divergence (Fig. 28.6).

On the femur tunnel, divergence may also be achieved using outside-in placement [37] (Fig. 28.7) or retrograde drilling techniques (RetroDrill™ oder FlipCutter™ from Arthrex Inc.).

It is always helpful to gradually ream the new tunnel to the desired diameter and inspect the new tunnel using the arthroscope (Fig. 28.8). Thus, a coalition with the old tunnel is recognized early, and the old tunnel may be grafted with a bone cylinder in the same session.

In case of two-stage revisions when enlarged tunnels have been bone grafted, it is recommended to ream the tunnel 2 mm smaller

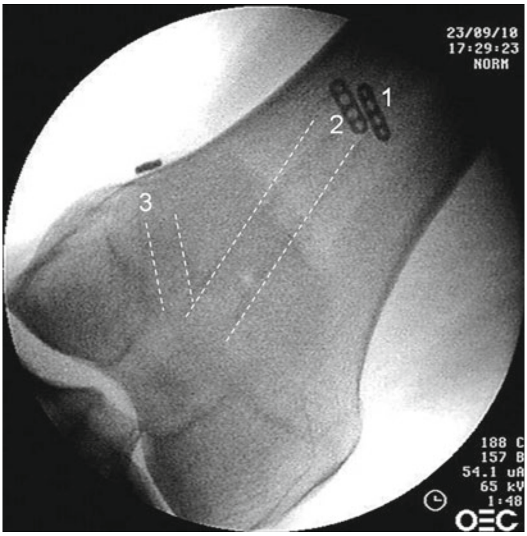

Fig. 28.6 Primary ACL reconstruction 2008 (*1*). First revision (re-trauma) using the same tunnel 2009 (*2*). Third revision (due to increasing rotational instability) 2011 (*3*). White dashed line outlining the bone tunnels

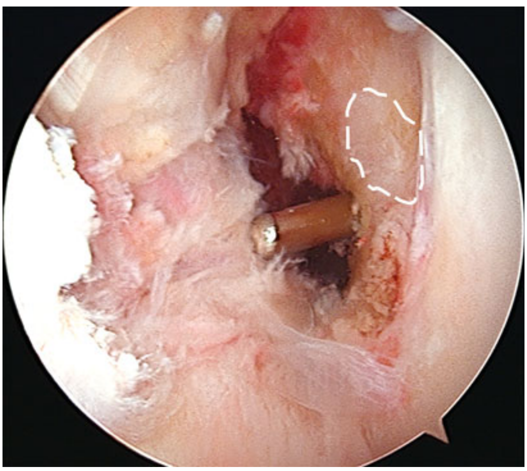

Fig. 28.7 Outside-in placement of a new femoral tunnel. White dashed circle outlining the previous bone tunnels

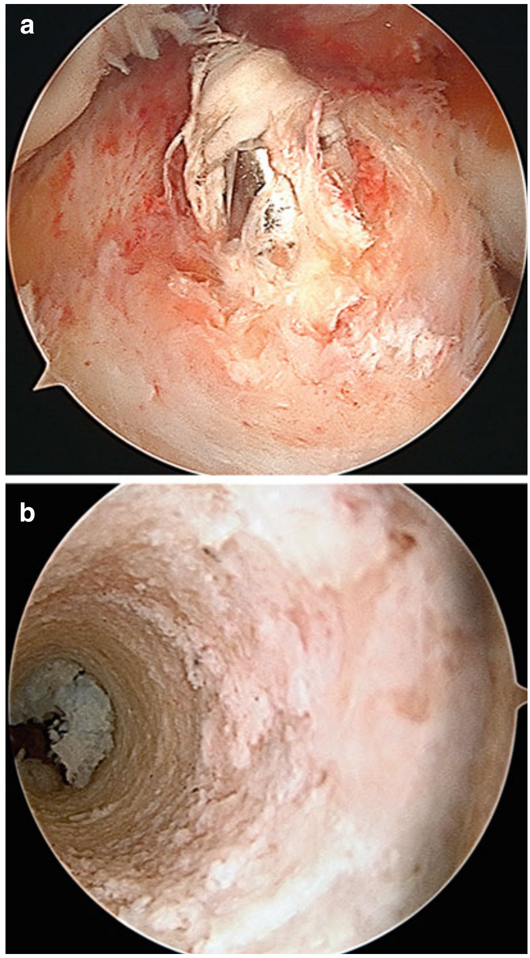

Fig. 28.8 (**a**) Placement of the tibial tunnel using a 6-mm drill to start and gradually increasing in size by 1 mm to the definitive diameter (the remnants of the graft are seen). (**b**) Inspection of the bone tunnel with the arthroscope

than the planned diameter and impact the additional 2 mm by using cannulated dilators. This leads to good compression of the normally soft cancellous bone.

28.8.3 Graft Preparation

If allografts are available, patellar tendon or Achilles tendon allografts with bone blocks can be used sufficiently to fill enlarged preexisting tunnels.

If autografts are being used, patellar tendon as a bone-tendon-bone graft or the quadriceps tendon with a bone block from the patella allows some flexibility in size [26, 38]. In order to limit harvest side morbidity, the diameter of a patellar bone block should be limited to a maximum of 10 mm and the tibial bone block to a maximum of 12 mm. However, in several revision cases, it has been proven superior to use a smaller square-shaped bone block, which equals the measures of the harvested tendon graft [11, 35] (Fig. 28.9).

In our technique [11], the bone tunnel is not reamed but created using a cannulated rasp and then dilated with a squared dilator of the appropriate size (KARL STORZ GmbH & Co. KG). Using this technique allows to place a new anatomical tunnel in the situation of only slightly misplaced tunnels (Fig. 28.10) or even in the case of massive tunnel enlargement (Fig. 28.11).

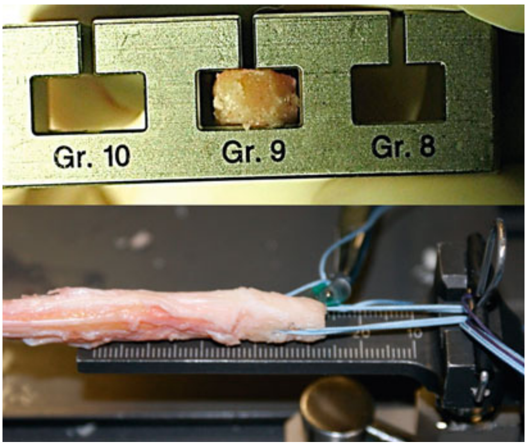

Fig. 28.9 Preparation of a squared bone block in the cross-sectional dimensions of a quadriceps bone-tendon graft (KARL STORZ GmbH & Co. KG)

28.8.4 Double-Bundle ACL Reconstruction Technique

There are different opinions about the revision situation of double-bundle ACL reconstructions, with some surgeons stating that revision of a double-bundle construct is a "nightmare." As a summary, there is no evidence in the literature that the revision situation of a primary double-bundle ACL reconstruction is more complicated than revision of an initial single-bundle surgery.

Similar to single-bundle revision, the revision strategy is dependent on the type of fixation used, the amount of tunnel enlargement, and placement. The same rules apply concerning the analysis of failure mode and surgical planning.

In some situations, it may be an advantage to add a "second bundle" in the revision situation [19, 33]. In cases that the original graft is placed vertical and therefore approximates the direction of an anteromedial (AM) bundle (the patient presents with a negative Lachman but positive pivot shift test and functionally with giving-way episodes), a posterolateral (PL) bundle might be added to improve rotatory instability. This technique is demanding and necessitates a profound knowledge of knee kinematics and familiarity with primary double-bundle reconstruction techniques.

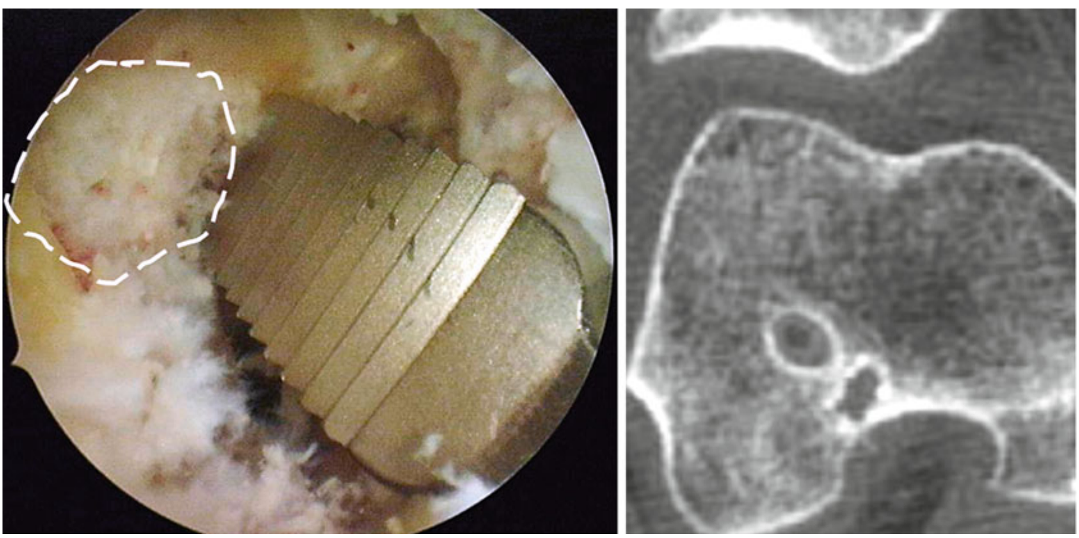

Fig. 28.10 A rasp correspondent to the dimensions of the graft is used to place a new anatomical tunnel. On CT the tunnel position is documented. A conventional round tunnel would have interfered with the preexisting tunnel (*white*). White dashed circle outlining the previous bone tunnels

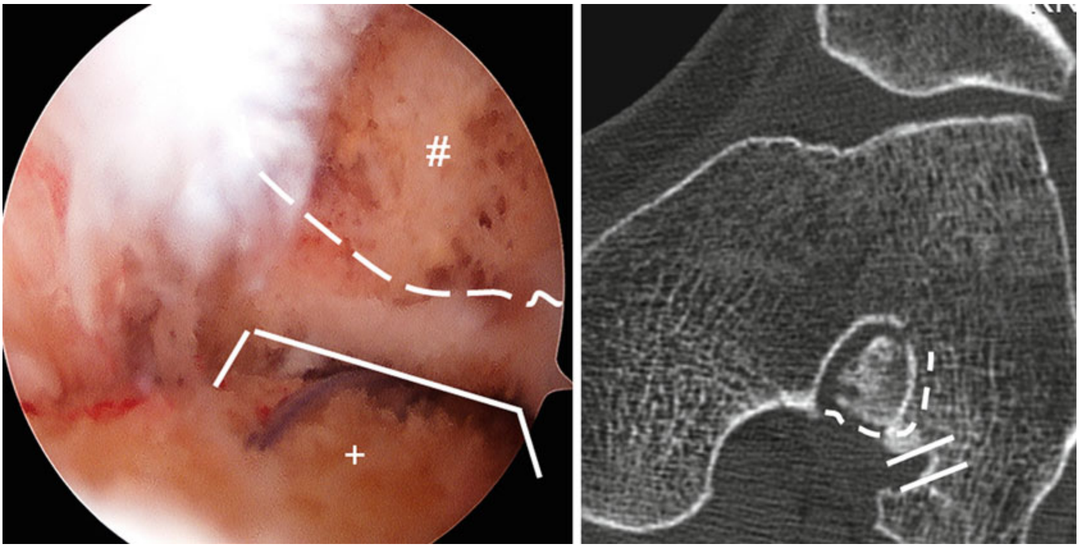

Fig. 28.11 A squared tunnel for a quadriceps bone-tendon graft was positioned on the femur, and a massive enlarged bone tunnel was grafted in the same session. CT control 3 months postop. #, pre-existing bone tunnel-grafted; + new squard bone tunnel

28.8.5 Grafting of Bone Tunnels

Grafting of preexisting tunnels is important whenever a new tunnel cannot be placed anatomical without impairing fixation and/or compromising graft incorporation.

Allograft bone in different forms (bone chips, granulated pieces, or blocks) may be used if available.

If a surgeon prefers or is dependent on autologous grafts, cancellous bone cylinders taken from the iliac crest are ideal for grafting enlarged tunnels. There are a variety of instruments on the market which allow for precise and minimal invasive harvest [31] of those cylinders.

Before grafting a tunnel, remnants of previous grafts or implant materials, such as sutures, have to be removed. Sclerotic tunnel walls should be over-reamed or perforated with a microfracture ale in order to provide better vascularization and graft incorporation.

For grafting a femoral tunnel, bone cylinders can be introduced through the anteromedial arthroscopic portal (Figs. 28.12 and 28.13).

Alternatively, the cylinders can be grinded and filled in a 1- or 2-ml syringe where the tip was cut off. The bone granular is then introduced in the tunnel and compressed [34].

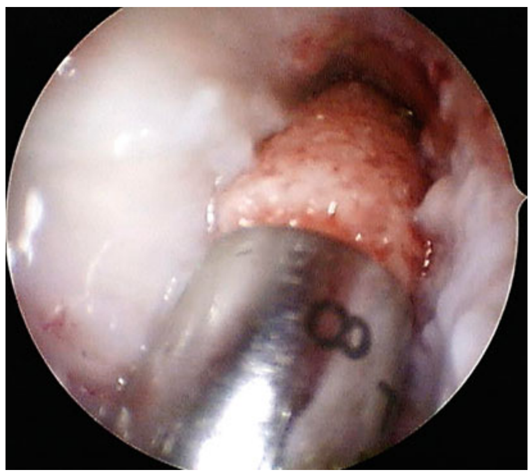

Fig. 28.12 Bone grafting a femoral tunnel with a bone cylinder from the iliac crest

The same techniques can also be used for grafting tibial tunnels. For larger tunnels on the tibia, however, a cortico-cancellous bone block from the iliac crest may be utilized.

Incorporation of the bone grafts takes about 3–6 months. For the timing of the definitive surgery, CT scans may help to assess the bone quality within the grafted tunnels (Fig. 28.14).

There are rare situations where new tunnels can be placed anatomically despite grossly

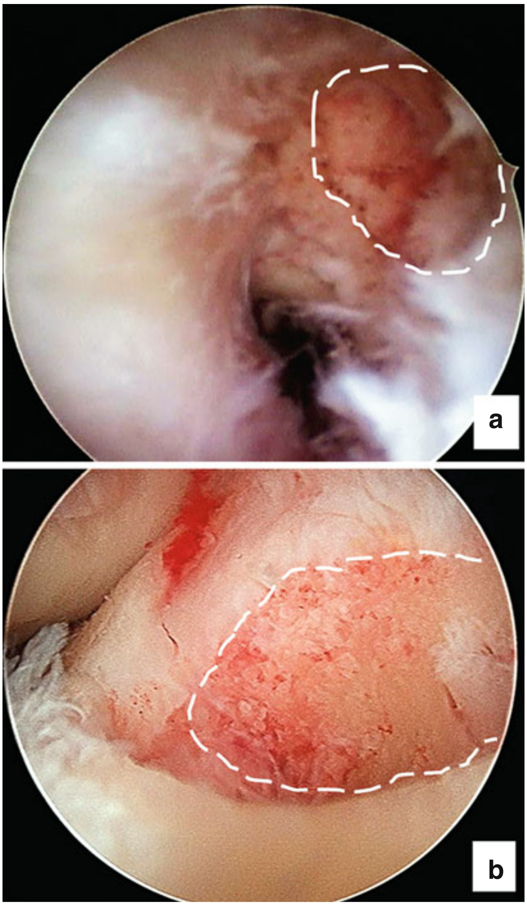

Fig. 28.13 Finalized bone graft. (**a**) Femoral tunnel, (**b**) tibial tunnel. White dashed circle outlining the bone grafted tunnels

Fig. 28.14 CT scan 4 months following bone grafting. circle is making the bone grafted tunnel

enlarged preexisting tunnels. In these selected cases, ACL revision surgery can be performed in one stage, but nevertheless, the old tunnels should be bone grafted simultaneously (Fig. 28.10).

A new interesting approach for revision surgery is to fill the defects with calcium phosphate cement and drill a new tunnel right through. This is currently only in the experimental stage, and clinical data are not available yet [43].

28.8.6 Transplant Fixation

The revision surgeon has not only to be flexible with graft choice but also with graft fixation. Interference screws with diameters larger (up to 11 mm) than commonly used in primary procedures should be available as well as implants which allow for extracortical fixation. Because of soft bone mainly on the tibia but also on the femur in case of previous bone grafting hybrid, fixation (joint line and extracortical) might be necessary.

28.8.7 Additional Surgical Procedures

For a successful ACL revision surgery, it is essential to address all relevant additional pathologies.

Patients with degenerative cartilage changes (>ICRS II°) in combination with varus or valgus alignment (>5°) will benefit from an additional corrective osteotomy [13]. Although open wedge osteotomy is most common on the tibia today to correct varus alignment, there are situations in revision ACL surgery in which closed wedge techniques offer an advantage. If massive tibial tunnel enlargement is present, an open wedge osteotomy would mean creating an additional bone defect. If a closed wedge technique is performed, however, the excised bone wedge can be used to graft the old bone tunnel. Care has to be taken not to increase the tibial slope (CAVE: open wedge osteotomy) because this would put additional stress on the ACL graft.

In the case of chronic lateral instability, limb alignment has to be evaluated carefully. In a varus situation, lateral reconstruction alone might not be sufficient, and a corrective osteotomy has to be performed instead or in severe cases of instability additionally to the ligamentous reconstruction.

If the revision operation has to be staged, it is recommended to perform an osteotomy always first and maybe graft the bone tunnel simultaneously.

If a posterior instability is present, this has to be corrected first by PCL reconstruction before ACL revision surgery.

28.9 Clinical Results

The clinical outcome of ACL revision surgery in general is not as good as the outcome of primary ACL reconstruction [2, 4, 14, 21, 40, 42]. One of the reasons is that the result of revision ACL surgery is greatly influenced by additional pathologies. Study results are difficult to compare because the patient collective is extremely heterogenic with respect to the type of revision, duration of symptoms, cause of failure, and operative techniques used.

Despite the prolonged recovery time, there was no difference in the outcome of single- versus two-stage revisions [22]. However, because no classification system of the revision situation was applied, this study might compare different things. In order to improve the study designs in the future, a standardized classification system has to be introduced [11]. Since the patient population will remain very heterogenous, a multicenter approach like the one proposed by the MARS group [23] seems the right direction in order to include a large number of patients.

Nevertheless, it is extremely important to counsel the patients carefully about the expected outcome of revision surgery. Patient expectations and demands might be unrealistic to achieve even with the best planned and performed revision procedure [21].

28.10 Take Home Message

ACL graft failure resulting in revision surgery represents a challenging task to the orthopedic surgeon. The key to success in revision surgery is careful planning of the procedure. This consists of analyzing the causes of failure (atraumatic vs. traumatic reasons), evaluating the index procedure (implant fixation, graft choice, tunnel placement, tunnel enlargement), and detecting additional pathologies (other components of laxity or degenerative changes). Imaging is extremely important, and all modalities such as plain radiographs (for limb alignment), MRI (for additional pathology), and CT (for tunnel morphology) are valuable.

The decision for a single or staged procedure is mainly determined by the size and location of the primary bone tunnels. Anatomical placement of the new tunnels is the main goal and not to be compromised. The advantage of a staged procedure is that revision ACL reconstruction may be performed similar to a primary procedure. However, the major disadvantage is the time delay of 3–6 months resulting in a prolonged instability period for the joint and prolonged time until the patient can sufficiently return to work or sports activity. Therefore, for the benefit of the patient, it should be evaluated if a revision situation can be sufficiently solved in a single-stage procedure. In revision situations, the surgeon has to be flexible and familiar with all available graft choices and multiple fixation techniques.

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Reducing the Risk of a Reinjury Following ACL Reconstruction: What Factors Should Be Used to Allow Unrestricted Return to Sports Activities?

29

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Contents

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29.1 The Problem: Reinjuries After ACL Reconstruction

Anterior cruciate ligament (ACL) injuries most commonly occur in athletes under 25 years of age who participate in high school, collegiate, or league sports. The immediate goals and expectations of ACL reconstruction for these individuals are to stabilize the knee to prevent future reinjuries and allow a safe return to previous levels of activity. Long-term goals include maintenance of an active lifestyle and the prevention of osteoarthritis that is frequently found in ACL-deficient knees, especially those that undergo meniscectomy [41, 56].

The rates of failure following ACL reconstruction from the authors' review of 11 studies with a minimum of 5 years of follow-up range from 3 to 19 % (Table 29.1). These studies also reported that contralateral ACL ruptures occurred in 5–24 %. Wright et al. [67] recently published a systematic review of level I and II studies of injury rates to either knee a minimum of 5 years after patellar tendon and hamstring autograft reconstruction. This investigation found that ipsilateral ACL graft rupture rates ranged from 1.8 to 10.4 % and contralateral ACL injury rates ranged from 8.2 to 16.0 %. In young athletes, reinjuries and failed ACL reconstructions have a potentially devastating impact. These individuals will most likely require further surgery, return to lower activity levels, and have a higher risk of developing future knee joint arthritis.

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Table 29.1 Rates of reinjury to the ACL in reconstructed and contralateral knees in studies with a minimum 5 years of follow-up

Author, journal, year, level evidence	No. patients, follow-up	ACL graft, no.	Failed ACL reconstruction[a]	Injured ACL contralateral knee	Overall ACL reinjury rate, both knees	Factors statistically associated with reinjuries, ACL graft failures
Hui et al. [29]	90	BPTB auto	7 (8 %)	22 (24 %)	29 (32 %)	Coronal graft inclination angle <17° (vertical graft placement) for ACL-reconstructed knee
Level IV	15 years					Age <18 years for contralateral knee
Shelbourneet al. [57]	1,415	BPTB auto	61 (4 %)	75 (5 %)	136 (10 %)	Age <18 years and participation in basketball or soccer for either knee
Level II	5 years					Female gender for contralateral knee
Sajovic et al. [55]	54	BPTB auto – 30	3 (10 %)	3 (10 %)	6 (20 %)	Not analyzed
Level I	5 years	STG auto – 31	3 (10 %)	2 (6 %)	5 (16 %)	
		Total – 61	6 (10 %)	5 (8 %)	11 (18 %)	
Nakata et al. [40]	68	Allogeneic free tendon	7 (10 %)	4 (6 %)	11 (16 %)	Not analyzed
Level IV	10 years					
Pinczewski et al. [50]	180	BPTB auto – 90	7 (8 %)	20 (22 %)	27 (30 %)	Increased laxity for ACL-reconstructed knees
Level II	10 years	STG auto – 90	12 (13 %)	9 (10 %)	21 (23 %)	Age<21 years for contralateral knee
		Total	19 (11 %)	29 (16 %)	48 (27 %)	
Keays et al. [30]	51	BPTB auto – 29	0	2 (7 %)	2 (7 %)	Not analyzed
Level II	6 years	STG auto – 27	2 (7 %)	3 (11 %)	5 (18 %)	
		Total – 56	2 (4 %)	5 (9 %)	7 (12 %)	
Salmon et al. [56]	67	BPTB auto	9 (13 %)	15 (22 %)	24 (36 %)	Age<21 years and meniscectomy for ACL-reconstructed knee
Level IV	5–13 years					
Drogset et al. [21]	42	BPTB auto	4 (8 %)	5 (12 %)	9 (21 %)	Not analyzed
Level I	16 years					
Roe et al. [53]	180	BPTB auto – 90	4 (4 %)	16 (18 %)	20 (22 %)	Not analyzed
Level II	7 years	STG auto – 90	9 (10 %)	9 (10 %)	18 (20 %)	
		Total – 180	13 (7 %)	25 (14 %)	38 (21 %)	
Myklebust et al. [39]	57	BPTB auto	11 (19 %)	6 (11 %)	17 (30 %)	Return to team handball
Level IV	6–11 years					
Deehan et al. [17]	90	BPTB auto	3 (3 %)	10 (11 %)	13 (14 %)	Not analyzed
Level II	5 years					

ACL anterior cruciate ligament, *BPTB* bone-patellar tendon-bone; *auto* autograft, *NA* not available, *STG* semitendinosus gracilis, *AJSM* American Journal Sports Medicine, *Int Ortho* International Orthopedics, *JBJS* Journal Bone Joint Surgery, *KSSTA* Knee Surgery, Sports Traumatology, Arthroscopy

[a]++Pivot shift and/or Lachman tests, Grade C or D International Knee Documentations Committee ligament grade, >5 mm on knee arthrometer testing, or required ACL revision

Factors that may account for ACL graft failures and postoperative reinjuries include patient age of either <18 years [29, 58] or <21 years [51, 57]; return to high-risk sports such as soccer [58], basketball [58], and team handball [39]; meniscectomy [57]; and surgical technique in terms of graft placement (Table 29.1). Borchers et al. [13] reported that the factors of allografts and return to high sports levels were significant risk factors for ACL graft failure in 21 of 322 patients followed for just 2 years postoperatively. Paterno et al. [50] reported that alterations in neuromuscular control of the hip and knee during a drop jump and postural stability predicted ACL injury upon return to activities after reconstruction in 43 athletes followed for 1 year postoperatively. Ten of the 13 patients who suffered a reinjury in that investigation did so to the contralateral knee. There exist other reasons for ACL graft failure that have been previously described in detail, including use of low-strength grafts, inadequate graft fixation, impingement of the graft in the intercondylar notch, excessive or insufficient graft tensioning at surgery, biologic failure of the graft, deficiency of other knee ligaments, postoperative infection, and inadequate rehabilitation [38, 43].

The reasons for rupture of the ACL in the contralateral knee are unknown and have not been scientifically determined. Some authors believe this problem may be due in part to insufficient rehabilitation in the contralateral limb after surgery [27, 65]. Postoperative rehabilitation plays a critical role in returning patients to athletic or demanding occupational activities as safely as possible. Unfortunately, few studies have determined the ability of rehabilitation programs to restore normal muscle strength and neuromuscular indices required for high-level athletic activities such as pivoting, twisting, and jumping. Because of the extensive documentation of neuromuscular deficits in both limbs following ACL injury and reconstruction [4, 16, 22, 25, 28, 35, 36, 48, 50, 62], failure to address and fully rehabilitate both knees may be part of the reason for the high reinjury rates in ACL-reconstructed and contralateral limbs shown in Table 29.1.

One problem is that studies that have attempted to identify factors responsible for reinjury rates have not taken into account the athletes' bilateral muscle strength, ACL function, and neuromuscular control upon return to sports. The possibility exists that many athletes have not regained normal indices in both lower limbs and that the release to unrestricted activities was premature. Many questions and a lack of consensus exist regarding the appropriate criteria for releasing patients to unrestricted sports activities postoperatively.

29.2 Systematic Review: Published Criteria to Allow Return to Sports

The authors conducted a systematic review of ACL clinical studies to determine the published criteria used to allow athletes to return to unrestricted sports activities over the last decade [7]. Inclusionary criteria were English language, published between April 2001 and April 2011, original research report (any level of evidence), primary ACL reconstruction (any graft type), minimum 12 months follow-up, and skeletally mature populations. Exclusionary criteria were articles that included revision ACL reconstructions or dislocated knees; major concomitant procedures such as high tibial osteotomy, meniscus allograft, and other knee ligament reconstructions; follow-up of less than 12 months; and other types of articles such as reviews, case reports, abstracts, and technical notes. Of 716 articles initially identified, 264 were included in this review.

Of the 264 studies, 105 (40 %) failed to provide any criteria for return to sports following ACL reconstruction. A total of 158 studies (60 %) listed the amount of time postoperative that patients were allowed to return to sports activities, which varied widely (Table 29.2). In 84 studies (32 %), the amount of time postoperative was the only criteria provided. In 40 studies (15 %), subjective criteria (that could not be measured) were also stated (Table 29.3). Only 35

Table 29.2 Time postoperative return to sports allowed according to graft type[a]

Time postop	BPTB autograft no. studies	STG autograft no. studies	QT autograft no. studies	Double-bundle grafts no. studies	Other grafts[b] no. studies	Total no. studies
≥12 weeks	–	1	–	–	1	1
3–4 months	1	2	–	1	–	2
4 months	–	–	–	–	2	2
4–5 months	–	1	–	1	1	2
4–6 months	1	3	–	–	1	4
>4 months	2	2	–	–	–	3
≥5 months	1	3	–	–	–	3
5–6 months	2	1	–	–	1	2
≥6 months	45	51	5	8	49	84
6–7 months	1	1	–	–	–	1
6–8 months	3	2	–	–	–	4
6–9 months	5	3	–	2	2	8
6–10 months	2	5	–	1	2	5
6–12 months	1	–	–	–	–	1
7–9 months	1	–	–	–	1	1
≥8 months	2	3	–	–	–	4
8–9 months	–	2	–	–	–	2
≥9 months	4	10	–	–	2	11
9–10 months	–	1	–	–	1	2
9–12 months	2	–	–	–	–	2
10 months	–	1	–	–	–	1
10–11 months	–	1	–	1	–	1
10–12 months	3	1	1	–	2	4
≥12 months	4	4	–	2	2	8

From Barber-Westin and Noyes [7]
BPTB bone-patellar tendon-bone, *STG* semitendinosus gracilis, *QT* quadriceps tendon
[a]There were multiple grafts observed in 54 of the 158 studies that provided time postoperative criteria
[b]Allografts, primary repair, synthetic ligaments

studies (13 %) noted objective criteria that were required for return to athletics (Table 29.4). These included muscle strength (25 studies, Table 29.5), effusion and/or range of knee motion (15 studies), single-leg hop testing (10 studies, Table 29.6), objective knee stability (1 study), and validated questionnaire responses (1 study).

This systematic review suggests that noteworthy problems and a lack of objective assessment methods exist for release to full sports activities after ACL reconstruction in the published literature. Only 35 (13 %) articles cited objective criteria that patients had to achieve before unrestricted athletics were allowed. In addition, only 1–2 criteria (other than time postoperative) were included in the majority (33) of these studies.

29.3 Time Postoperative Should Not Be the Sole Criteria for Return to Sports

Even with modern operative techniques and rehabilitation programs, there is strong evidence that deficits in balance, proprioception, muscle strength, and neuromuscular control exist for many months postoperatively [16, 22, 25, 28, 35, 36, 48, 50, 63]. For instance, sensory and motor deficits were found in one study in ACL-reconstructed knees that were 12–30 months postoperative compared to matched controls [12]. Numerous investigations have found altered knee joint kinematics exists between 4 and 12 months postoperative during single-legged hop landings

Table 29.3 Subjective criteria provided for release to sports activities[a]

Criteria as stated by investigators	No. studies
Good firm anterior tibial stop	1
Good firm point on clinical evaluation	1
Knee stability confirmed clinical exam	3
Stable knee	1
Good stability	1
Normal laxity of the knee	1
Satisfactory stability	1
Pass sports-specific tests such as cutting, squatting, jumping	1
Knee function normal or nearly normal on clinical exam	1
Satisfactory clinical exam	1
Confirmation recovery of quadriceps strength	2
Functional quadriceps control	1
Sufficient muscle recovery after specified athletic training accomplished	1
Depending on functional capacity	2
Good recovery range of motion, muscle strength, stability	1
Regained full subjective functional stability	5
Regained full functional stability	9
Regained full functional strength and stability	2
Full functional stability in terms of strength, coordination, balance	3
No significant side-to-side deficits	1
If all parameters met	1
Depending on individual progress	1
After ACL accelerated rehab program	1
No problematic symptoms in knee joint	1
Only after rehab goals met	1
Controlled functional training had been performed without difficulty	2
Good muscle coordination in agility training, balance equal to opposite side	1
If patient's rehabilitation of limb and stability warrant	1
Satisfactory performance on agility drills	1
Depending on functional ability, including run-to-sprint intervals, sidestep cutting, and timed recreational drills	1
Close to full range of motion and muscle strength	1

From Barber-Westin and Noyes [7]
[a]Multiple subjective criteria given in 10 of the 40 studies included

Table 29.4 Objective criteria provided for release to sports activities[a]

Criteria categories	No. studies
Time postoperative, muscle strength	16
Time postoperative, muscle strength, range of motion/effusion	3
Time postoperative, thigh circumference, single-leg hop test	3
Time postoperative, range of motion/effusion	4
Time postoperative, muscle strength, single-leg hop test	2
Time postoperative, muscle strength, range of motion	2
Time postoperative, Lachman rating, effusion	1
Time postoperative, muscle strength/thigh circumference, single-leg hop test	1
Time postoperative, muscle strength, single-leg hop test, range of motion/effusion	1
Time postoperative, muscle strength, 4 single-leg hop tests, range of motion/effusion, validated questionnaires	1
Single-leg hop test	1

From Barber-Westin and Noyes [7]
[a]In 35 studies that provided objective criteria for return to sports

[18, 24, 64], downhill running [62], and forward lunging [49] and walking [23]. Chmielewski [14] reviewed asymmetry documented in ACL-reconstructed knees from several studies during squatting, stair climbing, single-leg hopping, and drop vertical jumping. Although this problem may not persist past a few months with normal daily activities, asymmetry may still be present for more than a year in higher-demand activities. This author expressed concern that the serious short-term consequence of asymmetrical loading may increase the risk of reinjury to either limb postoperatively. Hartigan et al. [26] proposed a rigorous criteria for return to activity and warned that return to sports should not be based solely on the amount of time that had elapsed since surgery. Kvist [34] in a review of rehabilitation studies noted that many authors decided on a timeline to return to sports first and developed the rehabilitation program according to that criteria only, which is not a desirable approach. Return of normal muscle strength and neuromuscular function are considered more vital indices than time to allow release to high-level sports activities.

Table 29.5 Muscle strength criteria for return to sports according to graft type[a]

Muscle strength criteria (compared to opposite side)	BPTB autograft no. studies	STG autograft no. studies	Double-bundle grafts no. studies	Other grafts[b] no. studies	Total no. studies
>90 % isokinetic strength	9	5	2	1	11
≥85 % isokinetic strength	3	3	2	3	7
>80 % isokinetic strength	2	3	0	1	5
≥90 % quadriceps index	0	3	0	1	1
≥90 % weighted leg extension	1	0	0	1	1

From Barber-Westin and Noyes [7]
BPTB bone-patellar tendon-bone, *STG* semitendinosus gracilis
[a]There were multiple grafts observed in 15 of the 25 studies that provided muscle strength criteria
[b]Allografts, BPTB + Ligament Augmentation Device

Table 29.6 Single-leg hop test criteria for return to sports according to graft type[a]

Single-leg hop test criteria (compared to opposite side)	BPTB autograft no. studies	STG autograft no. studies	Double-bundle grafts no. studies	Other grafts[b] no. studies	Total no. studies
>90 % single hop	4	3	1	1	6
≥90 % on 4 tests: single hop, triple hop, crossover hop, timed hop	0	1	0	1	1
≥85 % single hop	0	2	0	2	2
>90 % "hop/jump testing"	1	0	0	1	1

From Barber-Westin and Noyes [7]
BPTB bone-patellar tendon-bone, *STG* semitendinosus gracilis
[a]There were multiple grafts observed in 7 of the 10 studies that provided single-leg hop test criteria
[b]Allografts

29.4 Published Recommendations to Determine Return of Normal Knee Function

A few authors have proposed rigorous testing criteria for return to sports activities, although clinical data were not provided to demonstrate the effectiveness of these recommendations in reduced reinjury rates. For instance, Hartigan et al. [26] required 90 % or greater scores on the quadriceps strength index, four single-leg hop tests (single hop, triple hop, triple crossover hop, timed hop), the knee outcome survey activities of daily living scale, and a global rating of overall knee function for return to sports. In addition, patients had to have less than a 1+ knee effusion and full knee motion on examination.

Kvist [34] reviewed 34 studies on the outcome of ACL surgery published between 1998 and 2003 and concluded that the criteria for release to sports activities varied widely. Proposed criteria from this author's review included rehabilitation factors (<10–15 % deficit muscle strength and single-leg hop test; no pain or effusion, full ROM, functional knee stability evaluated by objective measurements such as motion analysis), surgical factors (static knee stability measured by KT-1000), and other factors (social factors, psychological factors, and associated injuries).

Van Grinsven et al. [63] conducted a systematic review of the rehabilitation literature published between 1995 and 2006 in order to develop an evidence-based postoperative ACL program that would allow a return to athletics within 6 months. These authors recommended the following for return to sports criteria: full knee motion, ≥85 % on strength (quadriceps and hamstrings) and single-leg hop tests compared to the opposite leg, <15 % deficit on hamstring/quadriceps strength ratio, no pain or swelling with sport-specific activities, and a stable knee in active situations.

29.5 Authors' Recommendations for Reducing the Risk of Reinjury and Factors to Assess to Allow Return to Sports

Preoperative, intraoperative, and postoperative factors are all considered paramount in reducing the risk of reinjury and graft failure after ACL reconstruction [27, 43]. Before surgery, patients are treated with rehabilitation until pain and swelling subside and knee motion, muscle strength, and gait are restored to normal or nearly normal levels. The only exception is in patients with a mechanical block to knee motion from a displaced meniscus tear, in which case surgery is performed within 2 weeks to repair the meniscus tear. The delay in surgery markedly reduces the problems of postoperative knee motion limitations and muscle weakness and allows the patient to mentally prepare for surgery and the subsequent extensive course of rehabilitation.

The reconstructive procedure itself is of paramount importance, as a nonanatomic or vertically placed graft carries a high risk of failure even without return to strenuous activities [37]. Many investigations have reported that errors in surgical technique are one of the most common causes of failure of ACL reconstruction [3, 19, 20, 46]. The use of allografts in young, athletically active patients has been associated with a higher failure rate than autografts [13, 60]. The authors prefer to use bone-patellar tendon-bone autografts for athletes, placed in central tibial and femoral tunnels located in the native ACL attachments. The identification of the recommended native attachments and surgical techniques to avoid a vertical ACL graft has been discussed in detail elsewhere [43]. An ideally placed single-graft construct provides control of the combined motions of anterior tibial translation and tibial rotation, thereby avoiding the necessity for a complex double-graft reconstruction.

The postoperative physical therapy program, described by the authors in detail elsewhere [27], should be structured and gradually intensified to be effective without causing problems such as anterior knee pain or tendinitis. As well, consideration is required of any major concomitant procedures such as meniscus repairs or other knee ligament reconstructive procedures, which require modifications to the protocol. In addition, patients with noteworthy articular cartilage deterioration of grade 2B or 3A–B according to the Cincinnati Knee Rating System [5] are not considered candidates to return to high-impact sports activities. Progression through the rehabilitation program is based on the continual evaluation of the patient's response to surgery and the exercise regimen. Athletes in the authors' clinic who desire to return to high-risk sports may enter a running program when they demonstrate at least 70 % isokinetic muscle strength of the quadriceps and hamstrings compared to the opposite side, have ≤3 mm of increase of anteroposterior displacement on knee arthrometer testing, and are at least 9 weeks postoperative. It is important to note that the majority of athletes are approximately 16–20 weeks postoperative when the running program is initiated. Upon successful completion of this program, basic plyometric training is performed in the clinic. This training consists of five levels and is done under supervision to ensure correct technique and posture are maintained with each jump. Then, advanced neuromuscular jump retraining (Sportsmetrics, Cincinnati Sportsmedicine Research. and Education Foundation) is done when the patient demonstrates the following: (1) negative pivot-shift test, (2) ≤3 mm increase in anteroposterior displacement on knee arthrometer testing, (3) <20 % deficit peak torque hamstrings and quadriceps on isokinetic testing, and (4) <20 % deficit in lower limb symmetry on single-leg hop testing. This program lasts for at least 6 weeks and has been described in detail elsewhere [6]. An example of a jump with correct technique and form is shown in Fig. 29.1. Patients then undergo the tests to be described next to determine if they may be released to begin sports training. The authors acknowledge that future studies are required to determine if advanced rehabilitation programs that include comprehensive neuromuscular retraining are effective in reducing the reinjury rate after surgery.

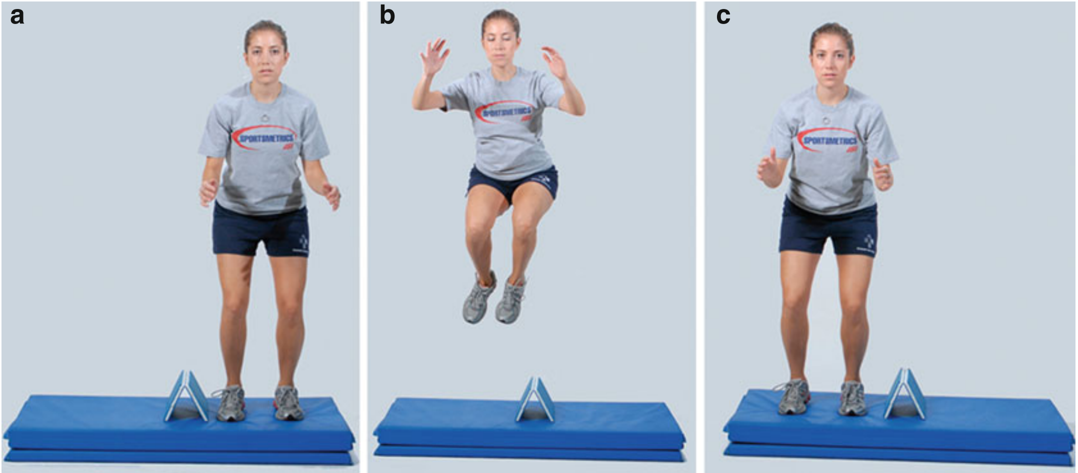

Fig. 29.1 An example of advanced plyometric neuromuscular retraining is shown using the mattress side-to-side jump. A cone or barrier is placed on a cushioned surface approximately 2 in to 3 in deep. The athlete performs a double foot jump from one side (**a**) over the barrier (**b**) to the other side (**c**). The feet are kept together and the athlete is instructed to begin and end the jump in the same amount of knee flexion (Reprinted with permission from Barber-Westin and Noyes [6])

Table 29.7 Functional criteria for return to sports activities following ACL reconstruction

Functional test	Indice tested	Minimum accepted result
Isokinetic test 180°/s, 300°/s or 1 repetition maximum test	Hamstring, quadriceps strength	<10 % deficit compared to contralateral side
Single-leg hop tests (single hop, triple hop, triple crossover hop, timed hop)	Lower limb symmetry	<15 % deficit compared to contralateral side
Video drop-jump test	Lower limb neuromuscular control	>60 % normalized knee separation distance
Single-leg squat test 0–90°	Lower limb neuromuscular control	No valgus motion of knee, no medial/lateral movement of knee
Knee arthrometer test	Anteroposterior tibial displacement	<3 mm increase compared to normal, contralateral side
Lachman, pivot shift tests	ACL function	<3 mm Lachman, grade 0–1 pivot shift
Knee examination	Range of knee motion, Joint effusion, Patellar mobility, and crepitus	Full knee motion, no effusion, normal patellar mobility, no/slight patella crepitus
Trial of function during running, plyometrics, sports-specific drills	Lower limb function	No pain, swelling, or giving way

From Barber-Westin and Noyes [8]

The functional criteria recommended to allow release to unrestricted sports activities are shown in Table 29.7. Muscle strength, lower limb symmetry, knee motion, and joint effusion are considered paramount in this assessment. If isokinetic test equipment is not available, a 1-repetition maximum bench press and leg press may be done [32, 54]. Lower limb symmetry is measured according to the difference in distance hopped between limbs as previously described (Fig. 29.2) [42]. In addition, a qualitative assessment may be made of the athlete's ability to control and hold the landing on single-leg tests such as the triple crossover hop (Fig. 29.3).

It is important to note that approximately two-thirds of all ACL tears are noncontact in nature

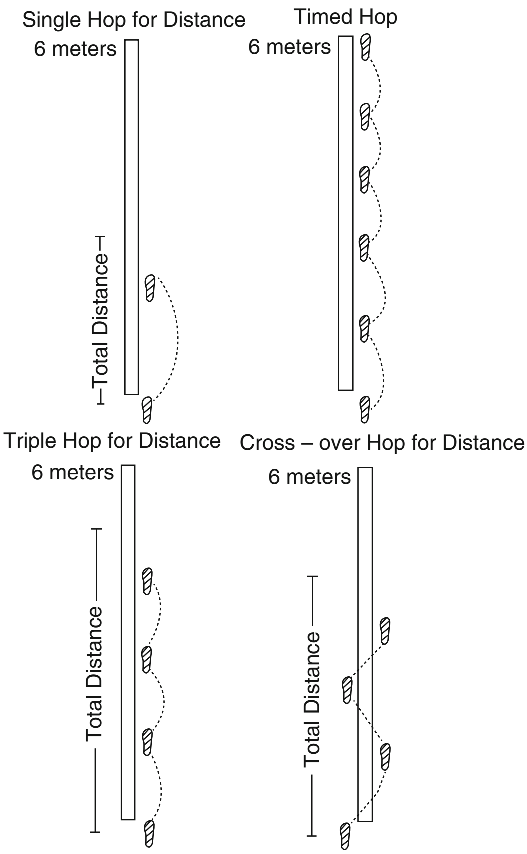

Fig. 29.2 Four single-leg hop tests that may be done to measure lower limb symmetry. At least 2 of these tests should be conducted. Normal lower limb symmetry is identified by <15 % deficit between limbs in the distance hopped (From Noyes et al. [42])

and occur during cutting, pivoting, accelerating, decelerating, or landing from a jump [10, 59]. Fatigue appears to increase the risk of ACL injury [9, 31]. Abnormal mechanics seen during ACL ruptures includes reduced knee flexion angles, increased hip flexion angles, valgus collapse at the knee, increased hip internal rotation, and increased internal or external tibial rotation [11, 33]. Due to these problems, we believe additional tests that assess dynamic neuromuscular control such as the drop jump [44] and the single-leg squat test [2, 15] are important to conduct prior to release to sports activities. The drop-jump test offers a simple method of determining lower limb alignment in the coronal plane. Performed with one video camera, this test clearly demonstrates a valgus lower extremity alignment on landing (Fig. 29.4). The single-leg squat test has been noted by others to be a reliable clinical tool to assess dynamic knee control and hip muscle function [2, 61, 66]. Consideration should also be made of the multi-stage fitness test to determine VO_2max [52], and the 60-s sit-up test [1] or other core strength measures [47] to measure fitness levels. It is acknowledged that once the surgeon and therapist have released the patient to full activities, it is then the responsibility of the coaching staff to progress the patient through sports-specific activities and build endurance. Patients are counseled to seek medical advice if knee symptoms develop.

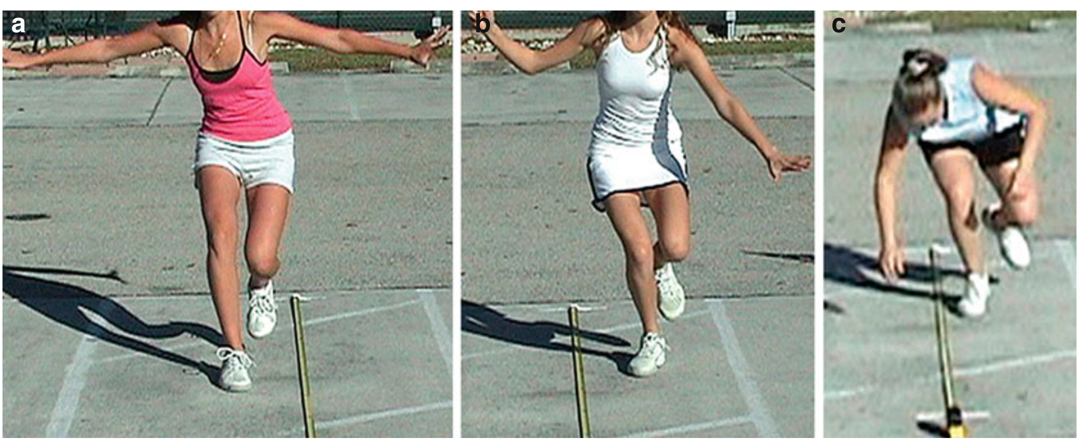

Fig. 29.3 The single-leg hop for distance test may be used to provide a qualitative assessment of an athlete's ability to control the upper and lower extremity upon landing, which may be rated as either good (**a**), fair to poor (**b**), or complete failure, fall to ground (**c**) (Reprinted with permission from Barber-Westin and Noyes [6])

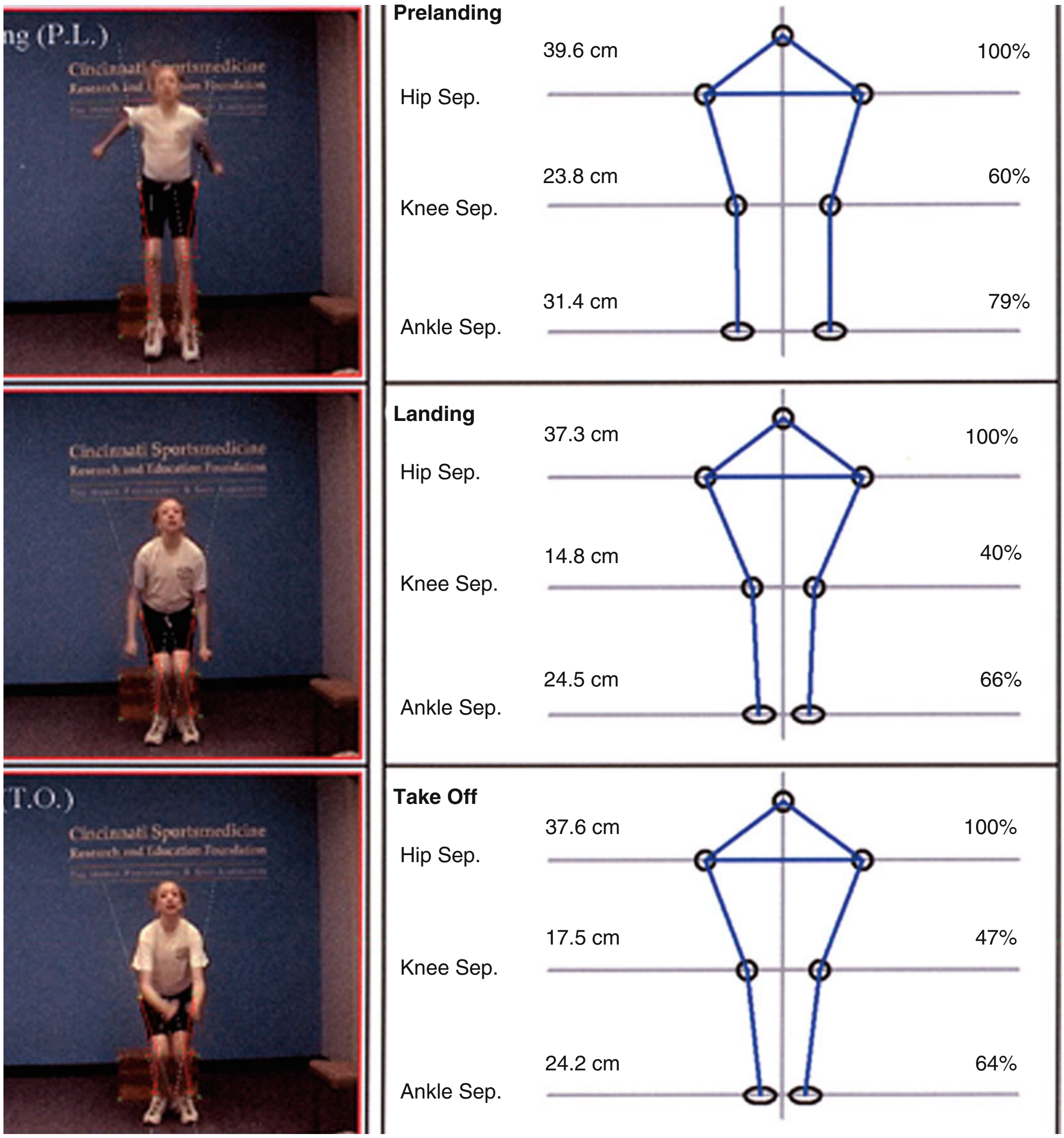

Fig. 29.4 The three phases of the drop-jump test. The cm of distance between the hips, knees, and ankles is calculated along with normalized knee and ankle separation distance (according to the hip separation distance). Shown is the test result of a 14-year-old female who demonstrates poor lower limb alignment, indicated by 17 cm of absolute knee separation distance and 47 % normalized knee separation distance (From Noyes et al. [44])

29.6 Summary

Following ACL reconstruction, the rates of graft failure range from 3 to 19 % and the rates of contralateral ACL ruptures range from 5 to 24 %. While there are many potential causes for failure of this operation, a lack of consensus exists in the sports medicine literature regarding the criteria to use for releasing patients to unrestricted sports activities after ACL reconstruction. The premature return to strenuous athletics before restoration of normal muscle strength and neuromuscular indices in both limbs may represent a major risk factor for reinjury. A systematic review of the literature was conducted to identify the factors investigators have used to determine when return to athletics is allowed. Of 264 studies that met the inclusionary criteria, 105 (40 %) failed to provide any measures for return to sports after surgery. Only 35 studies (13 %) included objective criteria which consisted of the categories of muscle strength or thigh circumference, general knee examination, single-leg hop tests, Lachman rating, or validated questionnaires. The results of this systematic review show noteworthy problems and a lack of objective assessment prior to release to athletics.

Even with modern operative techniques and rehabilitation programs, there is strong evidence that deficits in balance, proprioception, muscle strength, and neuromuscular control exist for many months postoperatively. Therefore, the factor of the amount of time that has elapsed since surgery should not be used as the sole criteria for return to athletics. Preoperative, intraoperative, and postoperative factors are all paramount in reducing the risk of reinjury in athletes after ACL reconstruction. The restoration of normal or nearly knee motion, muscle strength, and gait before surgery aids in the prevention of postoperative complications. Use of a high strength graft placed in the anatomic central tibial and femoral attachments will prevent a vertical graft position that has a high risk of failure. Postoperative rehabilitation is structured and gradually intensified based on the patient's progression and response to surgery. Advanced neuromuscular jump retraining is recommended before release to sports activities.

Recommendation is made to measure muscle strength, lower limb symmetry, lower limb neuromuscular control, and ACL function before release to unrestricted activities. Minimum acceptable results of these indices are provided. Future studies are required to determine if advanced rehabilitation programs and the demonstration of return of normal muscle strength, neuromuscular indices, and ACL function are effective in reducing reinjury and failure rates after surgery.

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Anterior Knee Pain After ACL Reconstruction: How to Avoid It

30

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30.1 Introduction

Anterior knee pain (AKP) is a frequent complaint and well-documented problem after anterior cruciate ligament (ACL) reconstruction [1, 10, 11, 14, 17, 19, 20, 22–24, 27, 28, 30, 33, 41, 42, 47, 48, 50, 52–58, 61]. AKP is a diagnosis based on symptoms and clinical signs. The severity of pain ranges from a mild nuisance to severe pain that prevents one from performing daily living activities. Thus, depending on pain severity, it could be considered as a complication or a normal postoperative outcome. The presence of AKP can interfere with patient's satisfaction after ACL reconstruction. In fact, AKP is an outcome predictor after ACL reconstruction. Thus, Bartlett et al. [4] have observed that the grade of patient satisfaction after ACL reconstruction correlates more strongly with the absence of pain than with any other variable assessed. Also, Heijne et al. [20] have shown that a low degree of AKP is the most important predictor for a good clinical outcome 12 months after ACL reconstruction.

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Therefore, prevention of AKP after ACL reconstruction would be a crucial key for surgery success.

This chapter expresses our experience and reviews the literature on AKP after ACL reconstruction. This topic is clinically relevant because given the upsurge of all kinds of sports, ACL injuries have become increasingly common, and therefore, their surgical treatment is currently a commonplace in orthopedic surgery. It is therefore interesting to carry out a detailed analysis of the sources of AKP after ACL reconstruction, underscoring the importance of treatment, and especially, prevention.

30.2 Is Anterior Knee Pain Related to the Choice of Graft Material?

It has been suggested that AKP is related to the graft chosen. Many graft options are available for ACL reconstruction: autografts (bone-patellar tendon-bone (BPTB), hamstring tendons (HT), and quadriceps tendon) and allografts. Currently, the two most commonly grafts used for ACL reconstruction are autogenous BPTB and the HT grafts. Many orthopedic surgeons, based on clinical personal experience and retrospective studies, maintain that AKP is much more frequent after ACL reconstruction using BPTB autografts than with the use of HT autografts. Moreover, the use of HT in theory should reduce the incidence of AKP because with this graft, we avoid the direct approach over the anterior knee aspect and we do not interfere with the extensor mechanism of the knee. However, we must point out that surprisingly, there are few prospective randomized clinical trials (level I of evidence) that can confirm this statement.

Ejerhed et al. [10], Laxdal et al. [27], and Svensson et al. [56] have found more cases of AKP in patients with an ACL-reconstructed knee using a BPTB than in those with an HT autograft. The power of these studies is the prospective randomized design (level I of evidence) and the evaluation of AKP before and after ACL reconstruction. This is very important because we cannot evaluate, from a scientific point of view, the degree and incidence of postoperative AKP if we do not consider the preoperative degree and incidence of AKP. However, the way AKP is measured is also crucial. These authors evaluated AKP using the "kneeling" and "knee-walking test" described by Juri Kartus. More recently, Wipfler et al. [61] in a prospective randomized study have also found that kneeling and knee walking were better in the HT group compared with the BPTB group. However, the knee-walking test is a nonphysiological test, given that very few patients walk on their knees in daily life. Therefore, if we ask a patient who never walks on his or her knees to walk on them after an ACL reconstruction with BPTB autograft, it is not surprising that he or she reports pain. Thus, we agree with Mikkelsen [33], who believes that it would be more realistic to use a functional AKP score to evaluate the pain, as the Werner functional knee score [29], a modification of the Lysholm knee scoring scale, which covers different activities with which AKP patients have problems such as stair walking, squatting, sitting with flexed knees, etc. Moreover, it would be interesting to also evaluate the degree of pain using for instance the visual analogue scale (VAS). In another prospective randomized study by Shaieb et al. [47] the authors have found a higher incidence of AKP in the BPTB patients at 6 months after surgery than in the HT patients (48 vs. 20 %). At 2 years of follow-up, the incidence of AKP was 42 and 20 %, respectively. An interesting finding in this study is that 52 % of the patients in the BPTB group and 27 % in the hamstring tendon group had loss of motion. This could explain the high incidence of AKP in the BPTB patients as we discuss in the next section. In another prospective randomized controlled trial (level I of evidence) comparing BPTB and quadruple-strand HT, Maletis et al. [30] found in the HT group fewer patients with sensory deficits (14 vs. 83 %) and fewer patients with difficulty kneeling (6 vs. 20 %). In the following sections, we analyze the importance of sensory deficits in the genesis of AKP. Finally, in a level II systematic review, Magnussen et al. [29] comparing BPTB and HT autografts demonstrated that AKP was more frequent in the BPTB group. In the same way, Freedman et al. [14], in a meta-analysis study comparing BPTB grafts and HT grafts in arthroscopic ACL reconstruction, showed that BPTB autograft reconstructions resulted in an increased rate of AKP than HT autografts (17.4 vs. 11.5 %).

On the contrary, there are also prospective randomized clinical trials (level I of evidence) that demonstrated no significant differences between the BPTB and HT autografts groups regarding AKP. Jansson et al. [23] have not found statistically significant differences regarding Kujala patellofemoral score and isokinetic muscle torque measurements for BPTB and HT autograft ACL reconstruction at 2 years after surgery. Lidén et al. [28] have analyzed the donor-site morbidity after BPTB and HT autograft in the form of knee-walking ability, kneeling ability, and area of disturbed anterior knee sensitivity. These authors have not found significant differences in terms of donor-site morbidity between both groups 7 years after ACL reconstruction. Eriksson et al. [11] demonstrated no significant differences between the BPTB and HT autografts groups regarding the AKP scores except in the subscore "kneeling," in which the patients with HT grafts had fewer problems. Samuelsson et al. [43] have shown that BPTB produces more AKP and kneeling pain than the HT graft, but the difference disappears with time. Siebold et al. [50] have not found differences in AKP in a study comparing HT and BPTB ACL reconstruction in females although there was greater kneeling pain in the BPTB patients. However, in a randomized controlled trial (level I of evidence) comparing BPTB versus HT autografts, Taylor et al. [57] have not found significant differences in kneeling pain. Heijne and Werner [19] have not found differences in AKP in patients with HT graft compared with BPTB graft. Finally, Sajovic et al. [42] in a randomized controlled trial (level of evidence 2) comparing ACL reconstruction using HT autograft and BPTB autograft have not found statistically significant differences between both groups with respect to AKP at 11-year follow-up.

It would be logical to think that if AKP depends on the graft harvest, the patients on whom allografts are used should not have AKP. However, AKP has been also reported after using allografts. Stringham et al. [54] have shown that patellofemoral signs and symptoms were absent in 40 % of autograft patients versus 44 % of allograft patients.

Geib et al. [17] have shown that the central quadriceps free tendon autograft is a low-morbidity autograft alternative in ACL reconstruction with equivalent results when compared with BPTB autograft. According to these authors, the quadriceps tendon autograft group has less AKP (4.56 vs. 26.7 %), less anterior numbness (1.5 vs. 53.3 %), and better extension (mean loss, 0.55° vs. 2.77°) when compared with BPTB autograft. Gorschewsky et al. [18] have also seen that the autologous quadriceps tendon has less donor-site morbidity than the BPTB group. They have shown that the central quadriceps free tendon autograft would be a good alternative for patients with activities involving kneeling or prolonged flexion of the knee joint.

In conclusion, it is evident that the answer to our question remains unclear, and the controversy continues. Maybe, AKP could be related to inadequate rehabilitation techniques rather than to the graft choice.

30.3 Importance of Postoperative Quadriceps Weakness, Restriction in Range of Motion, and Loss of Anterior Knee Sensitivity in the Genesis of Anterior Knee Pain

Several authors have suggested that AKP is related to the loss of motion rather than to the graft material [1, 41, 48]. In this way, Mikkelsen attributed the low incidence of AKP in her series after ACL reconstruction using BPTB autografts to the postoperative rehabilitation [33].

The influence of loss of knee extension after ACL reconstruction in the genesis of AKP is widely accepted. Sachs et al. [41] first observed that AKP was present in 19 % of patients operated on ACL using BPTB grafts, and it correlated positively with flexion contracture. They stated that the loss of extension contributes to AKP.

Therefore, these authors concluded that postoperative rehabilitation programs must emphasize the avoidance of flexion contracture to prevent AKP. Aglietti et al. [1] have also found a significant correlation between AKP and extension loss greater than 5°. Kartus et al. [24] have found an extension deficit greater than 5° in 13.4 % of patients with an ACL-deficient knee operated on with BPTB autografts. These authors have shown that AKP is related to the loss of range of motion and anterior knee sensitivity. They have demonstrated that those patients with a full range of motion and a minimal loss (≤4 cm^2) of anterior knee sensitivity had significantly less AKP than patients with isolated flexion or extension deficits or combined flexion and extension deficits. The median loss of anterior knee sensitivity in their patients with BPTB autografts was of 16 cm^2 (range 0–288). Shelbourne and Trumper [48] demonstrated that AKP after ACL reconstruction is not an inherent complication associated with BPTB harvesting. Moreover, these authors have shown that regaining full knee extension or hyperextension postoperatively, if hyperextension exists in the contralateral knee, is the key to decreasing the incidence of AKP after ACL reconstruction using any type of graft. Furthermore, restoring immediate full knee hyperextension after autogenous BPTB ACL reconstruction does not adversely affect the ultimate stability of the knee [40]. However, the return of full range of motion might not always be possible. If full hyperextension is not obtained in the early postoperative period, it can be difficult to regain it later. Mikkelsen et al. [34], in a prospective randomized study, demonstrated that extension deficit after ACL reconstruction can be prevented using a brace set at −5° of hyperextension. Fisher and Shelbourne [12] documented in a group of patients with symptomatic flexion contracture of the knee after ACL reconstruction a significant improvement in AKP after arthroscopic scar resection and restoration of full knee hyperextension. Finally, Kartus et al. [24] reported more pain and loss of motion both in flexion and extension after ACL reconstruction using both BPTB and HT autografts if the patients underwent concomitant meniscal resection, than if the patients had intact menisci.

The influence of loss of flexion on AKP is controversial. Kartus et al. [24] have stated that the loss of flexion causes significantly more AKP than the loss of extension, and Aglietti et al. [1] have found a significant correlation between AKP and flexion loss greater than 10°.

Finally, Sachs et al. [41] showed that quadriceps weakness is intimately related to AKP. However, Mikkelsen [33] has not found a correlation between the degree of AKP and the quadriceps torque (level II of evidence). In the study by Sachs et al. [41], the mean strength quadriceps index (side-to-side comparisons) was 66.2 %. The strength index is the ratio of the peak torque of the involved leg to the uninvolved leg multiplied by 100. However, in the study by Mikkelsen, [33] it was of 75 %. This could explain why Mikkelsen did not find a correlation between quadriceps weakness and AKP. Mikkelsen [33] concludes that the less difference in quadriceps index, the less AKP. Therefore, we must make an effort to improve thigh muscle strength, especially of the quadriceps muscle. In this way, we must note that harvesting the hamstring tendon does not affect the strength of the quadriceps as we can see when we analyzed the morbidity of an isolated autogenous hamstring graft harvest [51]. However, the ACL reconstruction procedure itself reduces quadriceps and hamstring strength in the operated limb regardless of tendon graft chosen [51]. According to Soon et al. [51], this could explain the initial decrease in quadriceps strength observed in their hamstring graft group patients.

30.4 Sources of Anterior Knee Pain After ACL Reconstruction

AKP after ACL reconstruction may have a large variety of causes. The first question we must ask ourselves before proposing a treatment is: which is the source of the AKP in our patient? In most cases, AKP arises in the anterior aspect of the knee and in the intercondylar notch. But we must not forget the possibility of AKP arising in the popliteal aspect of the knee [45].

30.4.1 Anterior Knee Pain Related to Fixation Devices

30.4.1.1 Migration of Tibial Interference Screw Fixation

The bioabsorbable interference screw is a safe and well-accepted technique used for tibial attachment of hamstring tendons and BPTB graft during arthroscopic ACL reconstruction. Migration of tibial interference screw is a well-known cause of AKP after ACL reconstruction (Fig. 30.1) [46]. The treatment consisted of screw removal after graft healing.

Fig. 30.1 Migration of tibial interference screw fixation

30.4.1.2 Lateral Protrusion of Cross-Pin Fixation

Bioabsorbable cross-pin fixation is a safe and well-accepted technique used for femoral attachment of hamstring tendons during arthroscopic ACL reconstruction that affords high initial fixation strengths while limiting subsequent complications from permanent hardware [36, 38, 59, 60].

Femoral transverse device lateral protrusion has been previously published. Clark et al. [8] used a non-reabsorbable cross-pin fixation in a prospective study of 22 patients. Two patients were reoperated because the cross-pin had migrated laterally and had to be repositioned. One of these two patients required the removal of the cross-pin after 2 years because of irritation in the iliotibial tract. Pelfort et al. [35] presented two cases of iliotibial band friction syndrome after ACL reconstruction using the transfix device. In both cases, there was a breakage of the implant, which reflects the existence of an important impingement between the implant and the surrounding soft tissues. Finally, Argintar et al. [3] present four patients who developed postoperative iliotibial band syndrome resulting from transverse femoral implant prominence due to screw prominence attributed to surgical technical error.

Lateral protrusion of the implant (Fig. 30.2) may cause overuse iliotibial irritation due to the repetitive friction between the posterior edge of the iliotibial band and the underlying implant at the lateral femoral epicondyle during repetitive flexion and extension of the leg. Biomechanical studies demonstrate a maximal zone of impingement at approximately 30° of knee flexion [13]. Iliotibial band friction syndrome subsequently may progress to AKP syndrome. Correlational studies have linked AKP to tightness of the iliotibial band [9, 21, 37]. A tight iliotibial band through its attachment to the patella by means of the lateral retinaculum could cause lateral patella tracking and patella tilt and compression [21]. The results from this study show that subjects presenting with AKP syndrome do have a tighter iliotibial band.

Lateral implant prominence is a preventable complication. Minimal incisions can compromise surgical visualization, and this could be one of the causes of this surgical error. Argintar et al. [3] encourage clinicians to make incisions large enough to sufficiently allow for digital inspection of the lateral implant in an effort to ensure that the lateral edge of the implant is flush with the lateral cortex of the distal femur. Intraoperative or postoperative radiographs give no information about cross-pin fixation because it is radiolucent. Pelfort et al. [35] recommend using the arthroscope to confirm correct positioning of the implant.

30.4.1.3 Divergent Femoral Interference Screw

Sanchis-Alfonso and Tintó-Pedrerol [45] described an unusual case of AKP after ACL

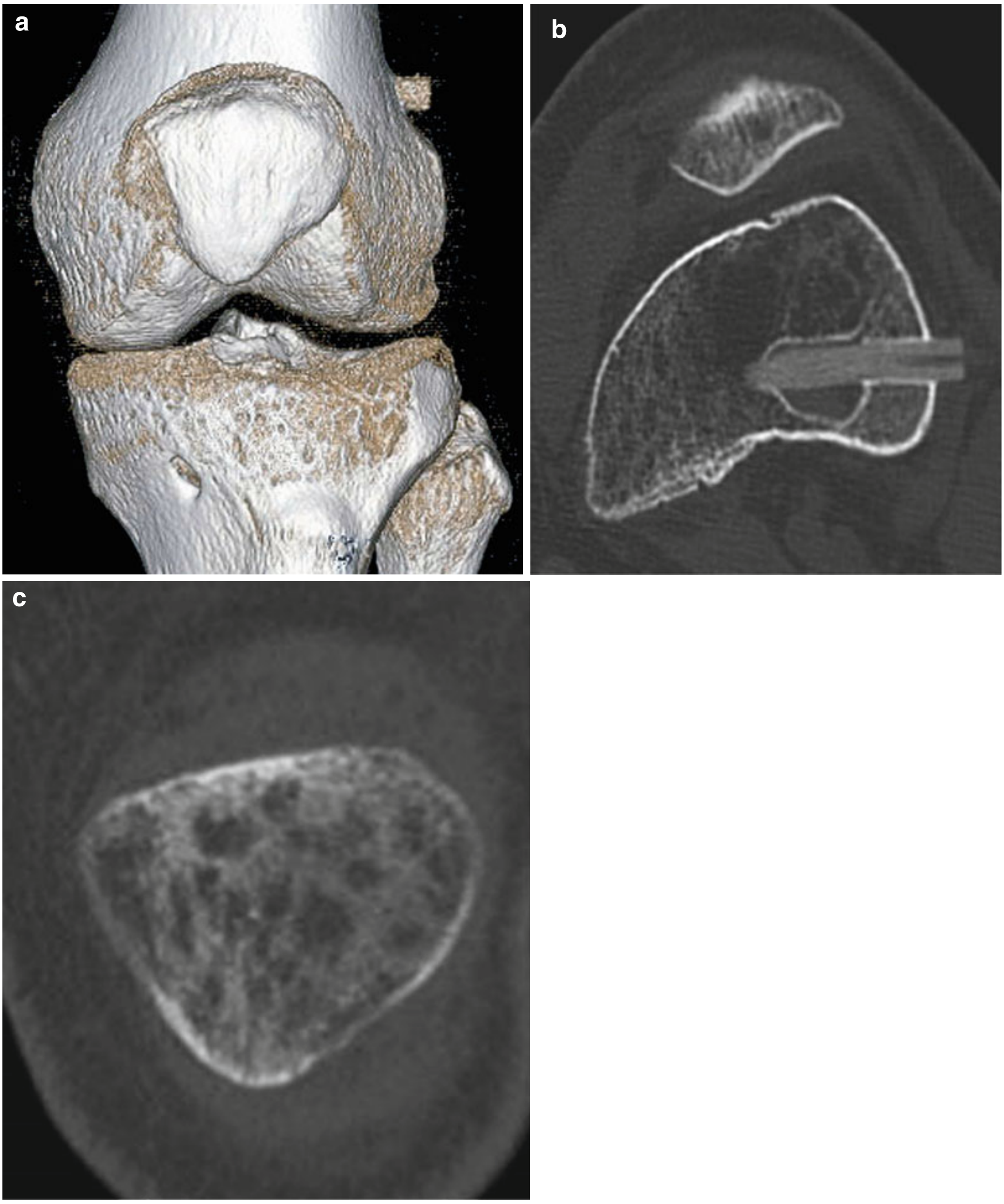

Fig. 30.2 (**a**) 3D-CT scan, and (**b**) Axial CT scan images showing protrusion of the cross-pin implant into the lateral area of the knee joint. (**c**) Osteoporosis of the patella. Sanchis-Alfonso has shown that at least in a subgroup of AKP patients, [44] neural proliferation of nociceptive axons (substance P positive nerves) mainly in a perivascular location in the lateral retinaculum could be implicated in the pathogenesis of pain. Furthermore, SP has recently been implicated as well in bone resorption both in vitro and in vivo, which can explain at least in part the osteoporosis associated in many cases of AKP. This could explain the patella osteoporosis observed in our patient

reconstruction secondary to femoral screw divergence (Fig. 30.3). Now, we must note that a severe femoral screw divergence is not necessarily accompanied by pain neither in the anterior nor posterior aspects of the knee. In the case reported by Sanchis-Alfonso and Tintó-Pedrerol [45], the screw was broken, which reflects the existence of an important impingement between the screw and the surrounding soft tissues, specifically the lateral head of the gastrocnemius. The existence of impingement depends not only on the divergence in the sagittal plane but also on the coronal plane. The authors hypothesize that a contracture of the lateral head of the gastrocnemius, caused by irritation from the femoral screw, could increase the patellofemoral joint reaction. This would contribute to increasing the overload of the subchondral bone, which could explain the AKP. Conversely, tight gastrocnemius may lead to an increase in foot pronation of the subtalar joint, resulting in an increased valgus vector force at the knee, which can cause AKP. The treatment consisted of screw removal.

30.4.1.4 Osteolytic Tibial Cyst Formation in the Osseous Tibial Tunnel and Extra-articular Pretibial Sterile Abscesses After ACL Reconstruction Using Biodegradable Interference Screws

Tibial cyst formation after ACL reconstruction using bioabsorbable interference screw provoking AKP has been published (Fig. 30.4) [31]. Curettage of the cyst results in complete recovery.

Extra-articular pretibial sterile abscesses (cultures and Gram stain negatives) with minimal osteolysis after ACL reconstruction as a local reaction to poly-L-lactic acid bioabsorbable interference screw fixation have been also described [6]. Treatment consists of drainage and excision with debridement of the biodegradable screw debris from the tibial bone tunnel.

30.4.2 Anterior Knee Pain Related to Arthrofibrosis

Arthrofibrosis, one of the recognized complications after ACL reconstruction, is an abnormal proliferation of scar tissue that limits knee range of motion and is associated with AKP [49]. Therefore, to avoid AKP at ACL reconstruction, we must emphasize early range of motion (full extension and flexion) and patella mobilization exercises to avoid scarring and joint stiffness [52]. Moreover, strengthening exercises should be avoided till range of motion and patellar mobility are achieved [52].

30.4.2.1 Pretibial Patellar Tendon Adhesions

Steadman et al. [53] described scarring of the anterior interval of the knee as a possible cause of AKP and poor functional results after ACL reconstruction. It is a subtle case of the classical infrapatellar contracture syndrome described by L. Paulos. These patients presented with pain in the infrapatellar region, flexion contracture, decrease in the medial/lateral and superior/inferior passive excursion of the patella, pain during knee extension, and inability to passively "tilt" the inferior pole of the patella away from the anterior tibial cortex. This pain is refractory to conservative care (physical therapy and nonsteroidal anti-inflammatory medications). It will be confirmed by means of magnetic resonance imaging (MRI) and arthroscopic examination.

Scarring of the anterior interval changes the mechanics of the anterior structures of the knee and may lead to refractory AKP. In a study in cadaveric knees performed by Ahmad et al. [2], the authors observed that patellar tendon adhesion to the anterior tibia provoked a subtle patella infera, and moreover, the angle formed by the quadriceps and patellar tendons decreased, causing an increase in patellofemoral joint reaction force that may be related to AKP after ACL

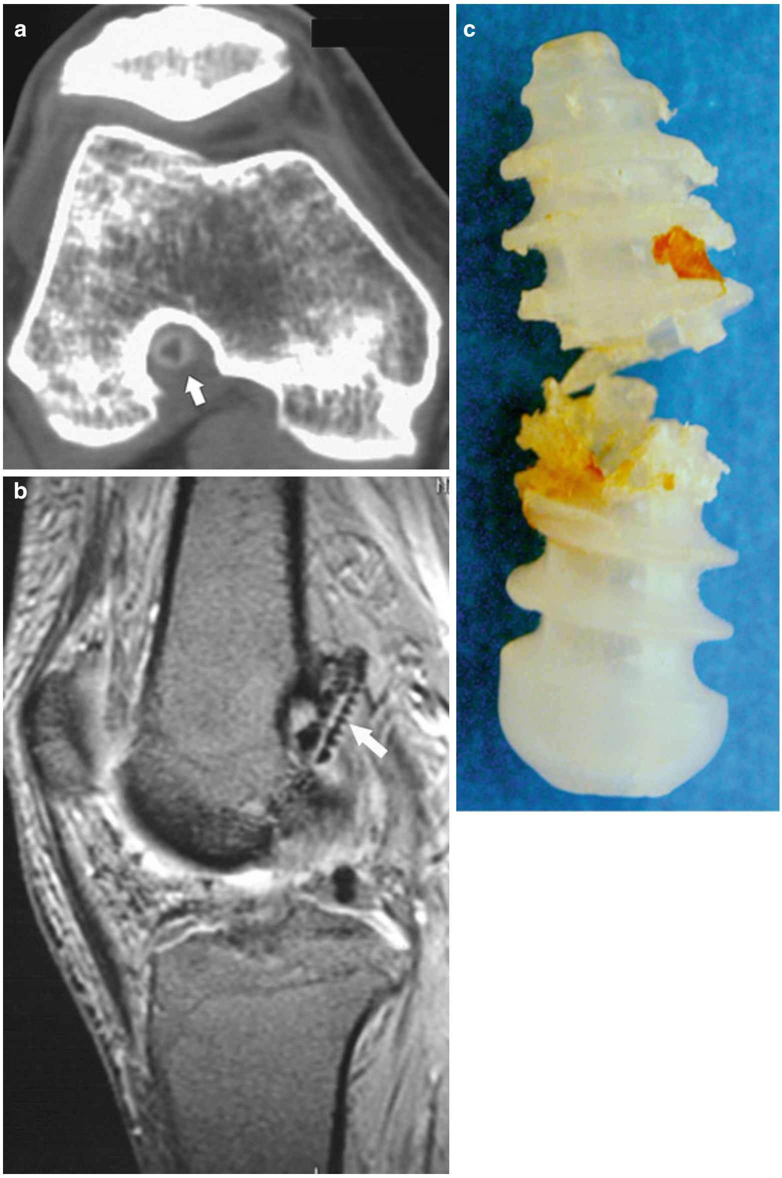

Fig. 30.3 (**a**) Axial CT scan at 0° of knee flexion demonstrating a lateral subluxation of the patella. Femoral screw (*arrow*). (**b**) Sagittal GrE T2* MRI demonstrating a severe femoral screw/tunnel divergence. Moreover, you can note that the screw is broken (*arrow*). (**c**) Broken femoral interference screw (From Sanchis-Alfonso and Tintó-Pedrerol [45]. Reproduced with permission from ELSEVIER)

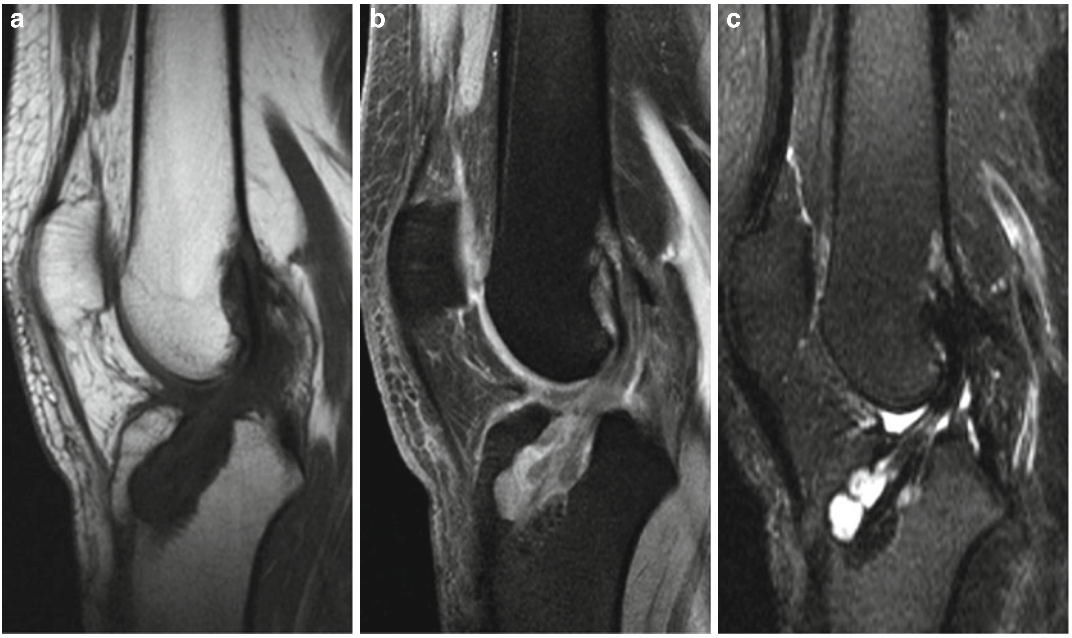

Fig. 30.4 A 38-year-old male presented with a history of continuous chronic anterior left knee pain with daily living activities refractory to conservative treatment. The patient underwent an endoscopic ACL reconstruction 5 years before using autogenous hamstrings tendons fixed with bioabsorbable polylactic acid interferencial screws. An MRI showing an osteolytic tibial cyst in the tibial tunnel. (**a**) Sagittal FSE T1 weighted. A hypointense lesion is seen at the tibial tunnel. (**b**) Sagittal fat sat FSE T1 weighted following administration of paramagnetic contrast medium. There is an irregular enhancement at the wall related to the fibrous and inflammatory component of the cavity. The cyst shows no enhancement and corresponds to the central part of the cavity. (**c**) Sagittal fat sat FSE T2 weighted. The cyst is shown as a hyperintense image. The graft shows no abnormalities

reconstruction (Fig. 30.5). Therefore, patients should be observed for subtle patella infera, which may indicate patellar tendon adhesion.

Arthroscopic release of the infrapatellar adhesions between anterior tibia and retropatellar fat pad ("anterior interval") successfully provides pain relief and improves functional outcomes in this patient population [53]. Postoperative rehabilitation must emphasize aggressive passive patellar mobility and excursion and mobilization of the patellar tendon.

30.4.2.2 Cyclops Syndrome

Cyclops syndrome (localized anterior intra-articular arthrofibrosis) described firstly by Jackson and Schaefer is one of the specific causes of loss of extension of the knee following ACL reconstruction [22]. It is caused by a fibrous nodule located in the intercondylar notch anterior to and attached to the ACL graft which causes a mechanical block to terminal extension. The pathogenesis is multifactorial: anterior placement of the graft, bony debris in the joint following drilling of the tibial tunnel, and incomplete resection of the remnants of the torn native ACL. From a clinical point of view, it is characterized by a progressive loss of knee extension, AKP, and audible and palpable clunk with terminal extension. Diagnosis is confirmed by means of MRI and arthroscopy (Fig. 30.6). This lesion is treated with arthroscopic excision with good patient outcome.

30.4.3 Anterior Knee Pain Related to Surgical Technical Errors (Graft Misplacement in the Sagittal and Coronal Plane/ Inadequate Graft Tension)

An incorrect tunnel placement is the most frequent cause of loss of motion after ACL reconstruction. So, an adequate tunnel placement is crucial for regaining full extension and flexion of the knee.

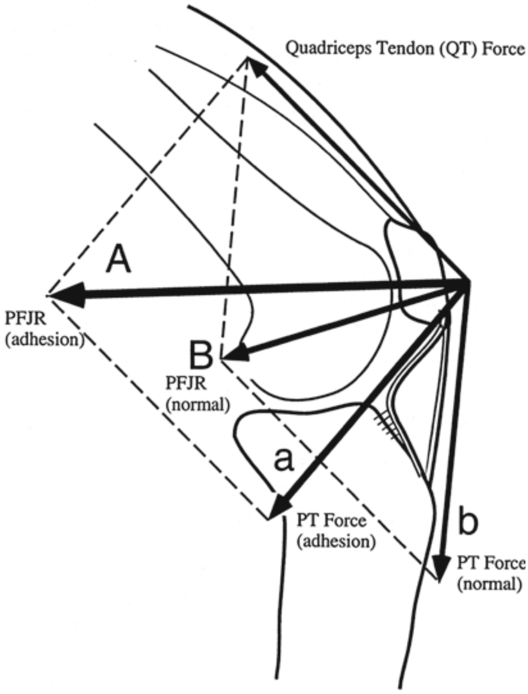

Fig. 30.5 Patellar tendon adhesion to the anterior tibia provokes that the angle formed by the quadriceps and patellar tendons decreased, causing an increase in patellofemoral joint reaction force (From Ahmad et al [2]. Reproduced with permission from SAGE Publications)

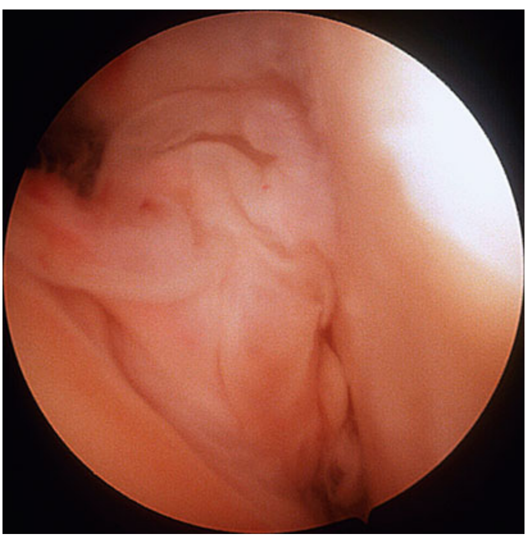

Fig. 30.6 Cyclops syndrome

30.4.3.1 Loss of Extension due to Anterior Tibial/Femoral Tunnel Placement-Prevention

Graft position must be accurate in the sagittal plane. Anterior tibial tunnel placement is a well-known cause of AKP since it causes a limited extension due to an impingement of the graft in the intercondylar notch during terminal extension (roof impingement). Moreover, anterior tibial tunnel causes a limited flexion because of excessive graft tension. Arthroscopy is a diagnostic of roof impingement when the ACL is frayed or a Cyclops lesion is present. To avoid roof impingement, the tibial tunnel must be placed 5–6 mm posterior and parallel to the intercondylar roof with the knee in maximum hyperextension [32]. An anterior femoral tunnel placement also causes an impingement of the graft in the intercondylar notch during terminal extension provoking a loss of extension and therefore AKP.

30.4.3.2 ACL Graft-PCL Impingement: Importance of the Coronal Angle of the Reconstructed ACL-Prevention

This source of AKP after ACL reconstruction should be included as a differential diagnosis when evaluating patients with AKP after ACL reconstruction given that it could be a more frequent cause of AKP than we had thought after ACL reconstruction.

The impingement of the ACL graft against the lateral edge of the PCL during knee flexion provokes an inability to fully flex the knee [32]. According to Howell, we can avoid PCL impingement placing the angle of the tibial tunnel in the coronal plane between 60° and 65° and placing the lateral edge of the tibial tunnel through the apex of the lateral tibial spine [32]. An anteroposterior radiograph is diagnostic of impingement of the ACL graft against the PCL in knee flexion when the tibial tunnel is at an angle greater than 70° with respect to the medial joint line or when the lateral edge of the tibial tunnel is medial to the apex of the lateral tibial spine (medial and vertical tibial tunnel) [32]. The treatment would be the resection of the graft and subsequent replacement of the ACL.

Strobel et al. [55] described a rare case of AKP after ACL reconstruction due to femoral misplacement of the graft ("high noon" position) combined with a slight medial tibial tunnel placement. This provokes an impingement between the ACL graft and the posterior cruciate ligament (PCL) near extension. These authors hypothesized that the ACL-PCL impingement during extension activates a proprioceptive reflex leading to a persistent functional extension deficit of 20° while the patient is awake; this deficit diminishes when the patient is anesthetized. We should consider this rare cause of AKP when the deficit of extension diminished under anesthesia because it is not due to a mechanical hindrance as we can see in the Cyclops lesion, but a proprioceptive reflex. Conventional sagittal and coronal MRI cannot detect ACL graft impingement against the PCL. MRI plus three-dimensional reconstruction software is the only way to evaluate ACL graft impingement against the PCL with the knee in an extended position (Fig. 30.7) which cannot be detected by conventional arthroscopy during the operation [15]. No ACL-PCL impingement is detected in normal knees [15]. Fujimoto et al. have found more impingement-positive cases in the knee-extended position than in the knee-flexed position [15]. The treatment would be the resection of the graft and subsequent replacement of the ACL.

In conclusion, the surgeon should pay careful attention to the coronal angle of the reconstructed ACL to prevent any impingement between ACL graft and the PCL. Therefore, graft position must be also accurate in the coronal plane.

30.4.3.3 Inadequate Graft Tension-Prevention

A tension of the graft higher than that of the native ACL has among other problems an inhibited knee extension, with the subsequent AKP.

According to Howell, the tension pattern of the ACL graft replicates that of the native ACL when the tibial and femoral tunnels are placed without PCL and roof impingement, the femoral tunnel is drilled through the tibial tunnel, and the back wall of the femoral tunnel is 1 mm thick [32].

30.4.4 Anterior Knee Pain Related to Donor-Site Morbidity

Donor-site morbidity associated with harvesting of BPTB is higher than that associated with harvesting of HT graft.

30.4.4.1 Bone-Patellar Tendon-Bone Graft

AKP causes specifically related to donor-site morbidity after BPTB graft harvesting are the following: (1) the residual bony defect and tendon defect at the donor site, (2) the subsequent donor site healing processes, and (3) the damage of the infrapatellar branches of the saphenous nerve when the BPTB autograft is harvested through a longitudinal incision along the patellar tendon.

Several authors have shown that the filling of the bone harvesting sites, not only in the patella but also in the tibial tubercle, with cancellous bone for complete restoration of the donor-site bony defect and the suture of peritenon, could contribute to the prevention of AKP [16, 52, 58]. Cervellin et al. [7] have shown the usefulness of platelet-rich plasma (PRP) in reducing subjective pain at the donor-site level after ACL reconstruction using BPTB autograft.

Kartus et al. [25] performed a prospective study of donor-site morbidity after BPTB graft harvest comparing the traditional and subcutaneous patellar tendon harvest. These authors have demonstrated a correlation between the surface of hypoesthesia and the rate of AKP. They conclude that tears of the infrapatellar branches of the saphenous nerve due to anterior approach are

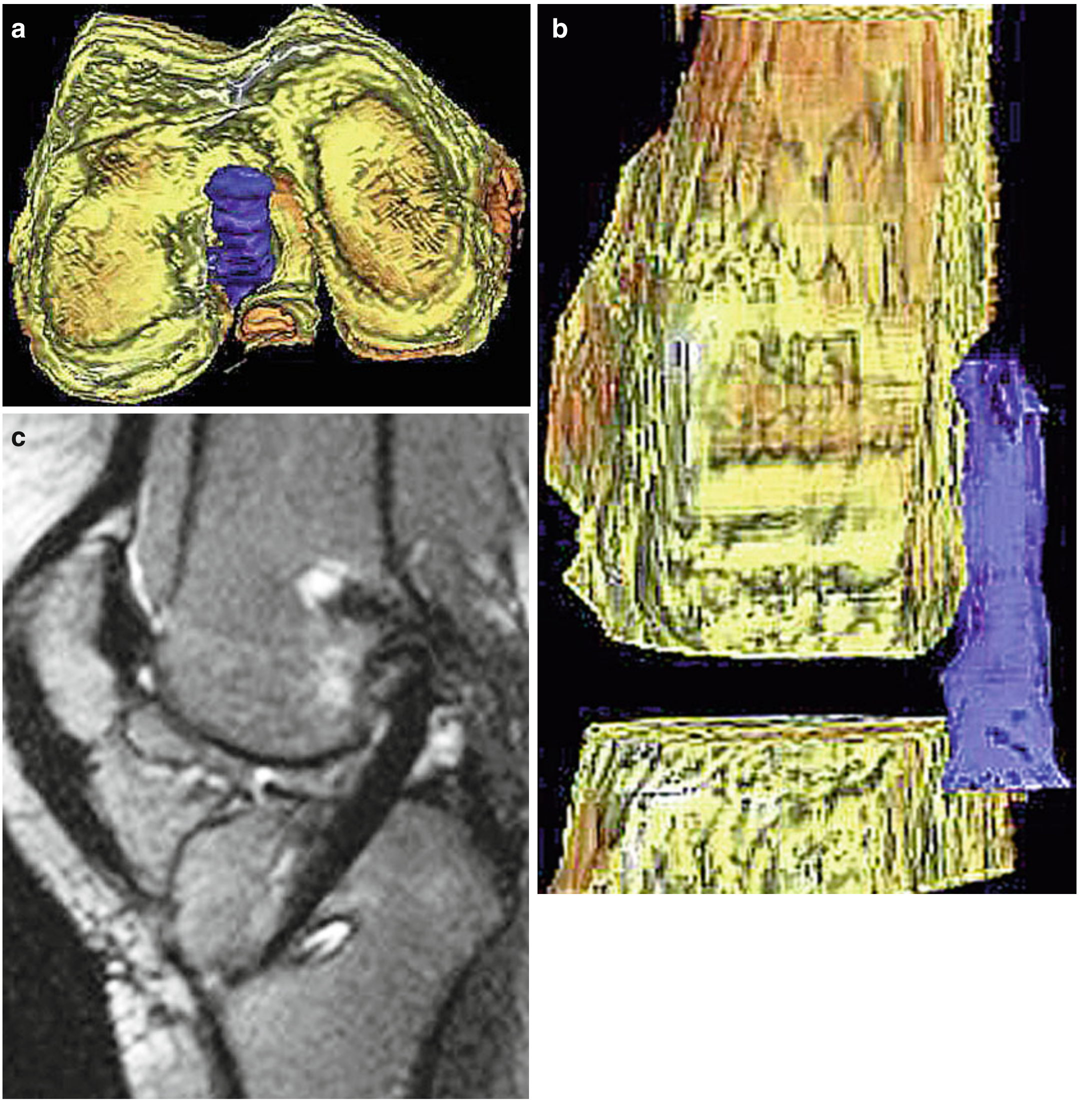

Fig. 30.7 Anterior knee pain after ACL reconstruction in a patient with a correct patellofemoral alignment. MRI 3D reconstruction in the knee-extended position demonstrated that the PCL is displaced medially and indented by a vertical ACL graft in the coronal plane. Our patient was pain-free after an anatomical ACL graft replacement. (**a**, **b**) T2 weighted 3D echo sequence in transverse acquisition with 3D rendering with surface algorithm with Barco Voxar 3D software. Bone structures (tibia, femur, patella) are segmented according to signal intensities. The segmentation is done by manually delineating the ACL graft in each of the transverse planes. Bone structures are in *yellow*, and the ACL graft is in *blue*. We can see the verticalization of the ACL graft. (**c**) Sagittal FSE T2 2D sequence where we can see the ACL as a markedly hypointense structure

a major cause of AKP after ACL reconstruction using BPTB grafts. On the contrary, Gaudot et al. [16] have not demonstrated a direct relationship between AKP and dysesthesia, but a relationship between dysesthesia and knee-walking test. They suggest that decrease of AKP with mini invasive technique is not only related with preservation of infrapatellar branches but also with preservation of the peritenon. The two-transverse-incision technique to preserve the infrapatellar branch of the saphenous nerve could also contribute to prevention of AKP [5, 16].

Finally, according to Rubinstein et al. [39], the morbidity of an isolated autogenous BPTB graft harvest appears to be of short duration and reversible. They analyzed 20 patients who had an isolated contralateral BPTB graft harvest for ACL reconstruction in the opposite knee. Rehabilitation of the harvest knee included immediate range of motion, weightbearing, and closed chain kinetic exercises with an emphasis on early strengthening. All patients regained full knee range of motion by 3 weeks. Quadriceps strength averaged 69 % at 6 weeks and returned to 93 % at 1 year and 95 % at 2 years. Patellar tendinitis was rarely restricting and resolved after the first year. No patient complained of AKP in the donor knee.

30.4.4.2 Hamstring Tendon Graft

Hypoesthesia of the lower leg is a common complication after ACL reconstruction using hamstring graft. It is caused by the injury of the infrapatellar branch of the saphenous nerve. It can occur during the skin incision, the exposure of the tendon, the dissection of tendons, the passage of the tendon stripper, and during drilling of tibial tunnel. After the saphenous nerve injury happens, special treatment is not needed, and in most of the patients, it decreases significantly by 46.3 % after 1 year [26]. According to Kjaergaard et al. [26], the orientation of the graft harvest incision (vertical versus oblique) does not influence the prevalence of postoperative hypoesthesia. It is important in prevention of neurological injury to ensure that all fascial adhesions are cleared [51]. Moreover, during the harvesting of the hamstring, it is important from a technical point of view to flex the knee and rotate externally the hip to relax the saphenous nerve on the tendon [51].

30.5 Take-Home Messages

1. AKP is an outcome predictor after ACL reconstruction (Level of Evidence: I).
2. It is not clear that AKP is related to the graft chosen (Level of Evidence: I). AKP could be related to inadequate rehabilitation techniques rather than to the graft choice.
3. Loss of full hyperextension is the most frequent cause of AKP after ACL reconstruction (Level of Evidence: V).
4. Restoration of full extension or hyperextension, if hyperextension exists in the contralateral knee, and good quadriceps strength are essential in order to diminish the incidence of AKP using any type of graft (Level of Evidence: III). Restoring immediate full knee hyperextension after autogenous BPTB ACL reconstruction does not adversely affect the ultimate stability of the knee (Level of Evidence: III). Postoperative brace in slight hyperextension prevents extension deficit after ACL reconstruction (Level of Evidence: I). Strengthening exercises should be avoided until the range of motion and patellar mobility are achieved (Level of Evidence: V).
5. In most cases, AKP arises in the anterior aspect of the knee and in the intercondylar notch. But we must not forget the possibility of AKP arising in the popliteal aspect of the knee (Level of evidence: V).
6. Arthrofibrosis is associated with AKP. To avoid AKP after an ACL reconstruction, we must emphasize early range of motion (full extension and flexion) and patella mobilization exercises to avoid scarring and joint stiffness (Level of Evidence: V).
7. AKP could be related to graft misplacement, loss of extension due to anterior tibial/femoral tunnel placement, and ACL graft-PCL impingement near extension or with flexion due to a vertical graft in the coronal plane. The surgeon should pay careful attention to the coronal angle in the ACL reconstruction surgery (Level of Evidence: V).

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Limitation of Joint Range of Motion After Surgery of the Anterior Cruciate Ligament

31

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31.1 Introduction

Reconstruction of the anterior cruciate ligament (ACL) is a more and more frequent intervention, particularly among young sportive individuals, given that 36,000 surgical interventions of this injured ligament were performed in France in 2010.

If the surgical intervention is important, the preoperative state and the postoperative course are equally so. Since the evolution is frequently favorable, complications do not seem exceptional, particularly with regard to recuperation of joint mobility. This is what interests us here, whether it is in the short-term or midterm.

31.2 The Problem

It relates to a failure to recuperate normal joint range of motion associated with residual pain.

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31.2.1 Lack of Return of Normal Joint Range of Motion

This group consists of patients who were operated for a ruptured anterior cruciate ligament irrespective of the technique, who, in the postoperative period, are slow to regain their normal amplitudes of joint motion. This delay may present rapidly in the first weeks following their surgical intervention or in a delayed fashion, when the rehabilitation program and return to work program are more consequential. The signs of severity are different, in function of the postoperative delay in their presentation. A 5–15° flexion contracture and a flexion angle limited to 100° around the third postoperative week are not dramatic since a readjustment of the reeducation program can still be envisioned to correct the problem, while a terminal extension contracture of 5–10° and a limitation in flexion of 120° around the fifth postoperative month is problematic. The longer the time from the surgical procedure, greater the chances of spontaneous recovery diminish. Advice from the physical therapist is important in order to know whether these limitations can be treated without a secondary surgical intervention.

The deficit might consist of a loss of extension, a loss of flexion, or a combination of flexion and extension loss; a classification of this pathology was proposed [25] with the four different stages being:

Type 1: less than a 10° loss of extension with normal flexion

Type 2: more than a 10° loss of extension with normal flexion

Type 3: more than a 10° loss of extension with a flexion deficit of greater than 25°

Type 4: more than a 20° loss of extension with a flexion deficit greater than 30°

This objective classification underscores the fact that an extension deficit of even a few degrees is less well tolerated than a flexion deficit, with recuperation of extension to the degree of physiologic recurvatum being indispensable with respect to achieving a good functional outcome.

The percentage of patients operated on for an ACL lesion, who developed postoperative stiffness is different when one considers a multi-ligament injury (greater than 20 %) [5, 10, 22, 24] or isolated lesions of the ACL (less than 10 %) [5, 18, 23, 24].

The meta-analyses [2, 9, 34] comparing reconstructions using patellar tendon versus semitendinosis and gracilis autograft did not show any significant differences with respect to risk of stiffness. A study [11] on the other hand showed the utilization of patellar tendon poses post more problems in regain extension, while utilization of the hamstring tendons posed more problems in regain flexion.

31.2.2 Pain

Pain always accompanies this delay in recuperation and which interferes with physical therapy. The analysis of this pain is primordial, but it is often impossible to clearly define. It is also difficult to know if the etiology of limitation in recuperating the amplitudes (this involves therefore more often a permanent pain, even at night and often in the face of an inflammatory syndrome) or the consequences of a reeducation program that is more and more aggressive and aimed at recovering the loss (this consists of a pain that improves with prolonged rest uniquely associated with an excess of work). Regardless of outcome, even if initially it relates to a purely mechanical problem, it is not rare to see a secondary apparition of an inflammatory syndrome, seemingly brought on by overworking of the knee imposed upon by a recuperation delay. These pains pose a problem to the extent where the adopted attitude vacillates between an augmentation of physical therapy treatments in order to regain on range of motion or rest to diminish the pain.

The pain can have a predominantly precise topography that is most often located in the anterior interval of the knee, evoking painful patellar phenomena frequently associated with stiffness of the joint [24] but maybe also diffuse and distanced from the joint lines.

It must be precisely evaluated as possible in an anatomical sense as well as its character, taking equally into account what was performed on the knee (tunnels, graft harvest) and what was noted at the time of surgery (femorotibial or patellofemoral cartilaginous problems, procedures on the menisci). One must equally analyze the period in which the pain began, whether immediately and forcefully or an atypical presentation that would more likely relate to an inflammatory problem.

31.3 Clinical Diagnosis of Range of Motion Deficits

Faced with a patient operated on for an ACL deficiency who presents with a delay in rehabilitation, it is important to critically analyze the following:

- The extension deficit compared to the contralateral side. If it is minimal, it can be evaluated in a prone position in a plane that measures the difference in heel height in comparison to the opposite extremity.
- The deficit in flexion can be comparatively measured using a goniometer.
- The patellar height [4] and mobility in the frontal and sagittal planes.
- The extensor mechanism (contraction and force of the quadriceps, transmission of its contraction at the level of the patellar tendon).
- The capacity to functionally dissociate the anterior musculature chain that permits extension from the posterior muscular chain.

31.4 The Causes and Diagnosis of the Deficit

31.4.1 Low-Grade Infection

It is very important to think of and eliminate it. The diagnosis is not always evident with an inflamed knee and a modification of biological constants.

We must be vigilant and, in any case of doubt, aggressive [29]. The workup consists of multiple aspirations to isolate an organism and know its sensitivity, followed by an arthroscopic lavage and appropriate antibiotic treatment as indicated. Any delay in the diagnosis is pejorative for the future of the knee and even in the best of circumstances, such a complication risks aggravating problems of recuperation with an apparition of painful phenomena that are inflammatory and bring on stiffness.

Outside of this rare problem, the diagnosis must lean upon the clinical examination and subsequent tests including radiographs and MRI and eventually a technetium bone scan.

31.4.2 A Surgical Technical Error: There Can Be Many

A poor placement of the graft at the level of the femur with a tunnel too anterior which limits the flexion of the knee, the neo-ligament being too short or at the level of the tibia with a tunnel too anterior which limits extension and creates a conflict with the anterior portion of the intercondylar notch.

A protrusion or emergence of an interference screw be it at the tibia or the femur.

In case of the patellar tendon, the emergence of the osseous block anterior to the tibial spine eminence.

Exceptionally, a subsequent bucket handle tear of the meniscus despite the surgery, or a residual ACL remnant flipped forward in the articulation and not resected at the time of the initial surgery [33] which can form a pseudo-cyclops lesion limiting extension.

31.4.3 The Cyclops Syndrome

This could correspond to an actual cyclops or simply to an enlargement of the tibial footprint of the neo-ligament.

31.4.3.1 The Cyclops

The cyclops properly described [15] corresponds to a more or less important nodule, frequently ecchymotic and distinct from the ACL. This neoformation is easily visible at the time of arthroscopy, with the knee in extension. It could pediculated at the anterior portion of the ACL footprint or on the neo-ligament itself. Exceptionally, it could be hanging from the roof of the intercondylar notch [30]. The occasional ecchymoses that appear in the nodule are caused by the crushing of the nodule between the tibial plateau and the roof of the intercondylar notch during extension of the knee. They can evolve in function of the activity that creates an intranodular bleeding that augments its volume, hence its size, hence the flexion contracture. Histologically, the cyclops contains fibrocytes, an anarchic vascularization of mature and immature osseous residuals in the process of differentiation.

31.4.3.2 The "Cyclopoïde" Aspect

The "cyclopoïde" aspect [19] less symptomatic corresponds to a conflict between the graft and the anterior portion of the intercondylar notch, interfering with extension. The foot of the ligament is therefore enlarged with a cuff signifying the point of conflict. Its evolution relates to a graft that is too voluminous, a notch that is too narrow or a tibial positioning of the neo-ligament that is too anterior.

31.4.4 Quadriceps Insufficiency and Anterior Knee Pain

These problems are intriguing. For the extensor mechanism, it consists of a functional problem with a default in the screw home mechanism in a position close to extension which in turn induces a patella with little motion in the vertical and transverse planes, causing anterior knee pain and flexion contracture [24]. This poorly functioning patella is accompanied by pain in the anterior aspect of the knee in which is difficult to know whether this is the cause or the consequence of the problem. The use of patellar tendon allograft increases the incidence of this problem with a frequency going from 29 [3] to 19 % [24] depending on the studies. The use of the hamstring or fascia lata graft does not offer protection from this type of problem.

The existence of major cartilaginous lesions, knee pain, and the effects thereof along with the eventual tendinitis of the patellar tendon related to its harvest can play a role.

31.4.5 "Complex Regional Pain Syndrome"

Some authors [7, 28] define a particularly aggravated response to a traumatism of the knee which manifests itself with intense prolonged pain even distanced from the joint lines, a delay in the functional recuperation along with trophic changes in the skin. The outcome of this symptomatology poses problems with reeducation by augmenting the discomforts and a recovery of motion that is very variable.

31.4.6 "Patellar Entrapment"

The "patellar entrapment" described by Paulos [20] as a pathologic entity seems to us more of a final consequence of one or more of the etiologies already cited such as anterior knee pain, an sympathetic dystrophy not taken into account initially, which is what evokes a three-stage classification by the author with constatations which are more and more alarming.

Prodromal stage

Edema in the region of the tendon with painful active modifications and a quadriceps that is ineffective in placing tension on the patellar tendon.

Active stage

Limitation in the range of motion, quadriceps atrophy, retropatellar crepitus, and diminution of patellar mobility, glides and tilt.

Residual stage

A particularly low and predominately fixed patella.

31.5 Prevention of Loss of Range of Motion

A certain number of precautions must be taken all along the management course for the patient.

31.5.1 Preoperatively

We must respect a delay between the trauma and the reconstruction of the anterior cruciate ligament. It is the state of the knee at the time of the operation that counts. It is important to operate a non-painful knee that has recovered its full amplitudes of flexion and extension [5, 12, 17, 18, 27, 31]. The delays necessary to achieve these parameters are variable. In the case of grade 1 or 2 peripheral lesions, these do not require a surgical intervention; the recuperation can be quite long, with medial and lateral planes of glide that must be reconstituted. Alternatively, an ACL tear that is isolated with a capsule that is intact should, after evacuation of the hemarthrosis, recover in several days.

The presence of a mixed bone bruise on MRI at the level of the tibial plateau and especially the femoral condyle must be taken into account since they are susceptible to slowing down the recuperation [21].

These declarations are not applicable in multi-ligamentous injuries that necessitate an urgency to suture and reorganize the peripheral lesions.

It seems important to us to properly examine the patient immediately preoperatively to be sure that the goal (normal range of motion, absence of pain) is achieved, with no obstacles to a full rehabilitation possible. Likewise, it must consist of a knee that is free of any arthritis.

31.5.2 Intraoperatively

Even though the reconstruction of the ACL has become routine, it is important to remain attentive to avoid any errors that could bring on:

- An aggressive harvesting of the graft whether it is the semitendinosis with risks of hematoma of the thigh or the patellar tendon where filling of the patellar bone defect with cancellous bone is desirable in terms of diminishing the risk of inferior pole patellar pain
- The anatomic positioning of the intra-articular femoral and tibial tunnel orifices which influence laxity but recuperation of full articular motion
- The strict positioning of intraosseous bone plugs and interference screws in order to avoid any impingement.
- The stability of all meniscal tissues

One must also avoid:

The important subcutaneous tissue attachments which, if detached, alter the sensitivity and sensibility occasionally associated with dysesthesias that may limit physical therapy.

Hematomas that might bring on a symptomatology similar to that previously described.

The placement of fixation material, palpable in the subcutaneous tissues in the anteromedial aspect of the tibial metaphysis. Such material may give rise to a disability, particularly in cases of direct contact. This may provoke disagreeable sensations with physical therapy.

31.5.3 Postoperatively

Outside of the eventual discomforts that must be controlled and taken into account rapidly if they present themselves, recuperation of extension is important. It is regained in a passive and active manner with an immediate awakening of the quadriceps and a screw home mechanism of the knee in extension. This attitude does not bring prejudice to the final anatomic results [6, 14, 16].

Mobilization of the kneecap is part of the baseline treatment and represents the key to the problem. It must be carried out both actively and passively in the vertical and horizontal direction. This mobilization is accompanied by a mobilization of the suprapatellar pouch. At the same time, it is important to progress in flexion.

At midterm follow-up, vigilance remains the rule and being attentive to any sign of pain that declares itself secondarily for whatever reason (overwork, beginnings of an inflammatory syndrome …).

The absence of perioperative pain is of primary importance to minimize the problems that are linked to recuperation of full joint mobility. A non-painful knee will be a good knee, a painful knee risks causing problems in the midterm period with an uncertain final result.

31.6 Course of Action

31.6.1 The Place for Mobilization Under Anesthesia

The place for mobilization under anesthesia must be discussed. It can be conceived only with very limited indications corresponding to a flexion limited to 90° at 45 days postoperatively, extension being on the other hand almost normal. This mobilization which can be carried out only in the direction of flexion must be gentle and permit passing 90° or 100° but should never search hyperflexion in order to protect the graft.

31.6.2 Arthrolysis

It must be preceded by treatment of all iatrogenic causes (intra-articular screw…); however, if the postoperative wait is too long, removal of the iatrogenic obstacle will only rarely permit the avoidance of a more aggressive gesture.

31.6.2.1 An Isolated Limitation in Flexion

The seat of the pathology is at the level of the suprapatellar, subquadricipital pouch. It adhesions at this level are progressively freed under arthroscopic guidance by anteromedial and anterolateral portals and eventually by two superomedial and superolateral portals. If the patella is fixed laterally, a release of the retinaculae of the patella that participate in its stiffness is desirable. A gentle manipulation will ensue, which will permit a recuperation of normal flexion.

31.6.2.2 Isolated Limitation in Extension [8]

The pathology is seated at the level of the anterior interval of the knee with a consolidation of tissues that limit extension. The ideal hypothesis is one in which the cyclops lesion is resected. The cyclopoïde aspect of the ACL footprint or a fibrosis on the pretibial eminence surface is more difficult to differentiate and hence treat. Appreciation of the work performed is realized on a knee in full extension. At the least doubt regarding the freedom of the ACL at its anterior portion, it is recommended to perform an osteoplasty of the intercondylar notch. The postoperative gain will correspond to what is obtained without restriction when the heel is lifted intraoperatively.

31.6.2.3 Combined Extension and Flexion Deficit

This points to a more difficult problem [8, 26] with adhesions that are more difficult to treat, a patella that is stuck against the trochlea and limiting distention of the articulation with arthroscopic fluid.

Under these circumstances the surgical procedure must be systematic with:

- A prudent creation of a space in the anterior aspect of the knee in flexion which would permit placing the fiber-optic scope and visualizing the shaver after progressive exposure of the notch, the two condyles and the anterior horns of both menisci. This surgical procedure is frequently delicate in the sense that the initial surgery is performed “blind.”
- Progressive liberation of the anterior intercondylar notch until visualization of the ACL is possible, debridement of the scar tissue that is incorporated on the graft and in the surrounding area.
- Osteoplasty of the intercondylar notch to ensure that there will be no anterior impingement, even with progressive extension of the knee.
- Progressive liberation of the suprapatellar and subquadricipital pouch which is now accessible secondary to the possibility of liberation of the patella, subsequent liberation of the medial and lateral gutters.

31.6.2.4 Supplemental Procedures Sometimes Necessary

In light of a low patella with metro tendinous sclerosis, a progressive anterior interval release of this adherence of the fat pad and the patellar tendon at the level of the pre-epiphysary surface can help gain several degrees.

In cases where there is no gain in extension despite a satisfactory anterior release, a posteromedial portal and posterolateral portal are recommended in order to treat long-standing problem that requires sectioning of the superior insertions of a contracted posterior capsule inserting on the posterior condyles.

In these circumstances, it is not rare that the mobilization to regain extension that follows can, in some ways, anatomically degrade the ACL neo-ligament. One must be careful to verify this at the end of the procedure. This degradation will only rarely have a functional outcome given the poor compliance of the knee.

31.6.2.5 The Procedure That Should Never Be Performed

Despite a low patella as a cause of stiffness, it is dangerous to treat at the same sitting given the traumatic surgical aggravation to the knee and the danger that a patellar procedure imparts for an indispensable aggressive reeducation.

31.6.2.6 Surgical Timing

It is not always easy to evaluate the moment where one must intervene. It is fundamental to initially evaluate the cause and, in function of this, decide on the action to be taken.

Beginning with the third postoperative month, if there is no improvement or gain the amplitudes of motion despite a readjustment of the reeducation effectuated and adapted to, a surgical solution could be envisioned.

If it entails an isolated extension deficit related to a cyclops lesion or an intra-articular screw that would be easy to treat surgically, a decision imposes itself rapidly since the quality of the results also depends upon the length of time between the surgical reconstruction and the arthrolysis.

On the other hand, if it consists of a major deficit in flexion and extension that is frequently accompanied by an inflammatory syndrome, the decision is more difficult to make. An adaptive medical treatment that permits an improvement of the inflammatory syndrome is desirable. If however, the improvements in flexion and extension are not clear, we find ourselves in front of an insolvable problem, since the intensive reeducation program necessary augments the pain and the inflammatory phenomena which, at their turn, cause stiffness of the knee. Based with this veritable vicious cycle, at 6 months, even in the presence of an inflammatory syndrome, arthroscopic lysis of adhesions seems justified to us, since it is still possible to perform without too much difficulty.

31.6.2.7 The Reeducation

It is intensive and requires several sessions a day particularly in the immediate postoperative period.

In the case of an isolated extension deficit linked to an intra-articular problem solved by a surgical procedure (cyclops lesion), the patient senses rapid improvement with a disappearance of the anterior conflict in the retropatellar region. The recuperation work will focus on strengthening of the quadriceps musculature isometrically in a position close to extension and to hold postures in extension. Outside of these daily therapy sessions, these exercises need to be repeated regularly several times a day.

If arthrolysis to recover extension was more difficult with a notable resection of one of the posterior condylar capsular attachments, the same work must be imposed; however, the extension postures must be maintained for longer periods of time (1 h every 4 h).

In cases of isolated flexion deficits which are rare or correspond to a deficit in the last 30° of flexion, the work will carry over to a reinforcement of the hamstring muscles and on the attitudes of forced flexion of 1 h repeated every 4 h. These periods of forced attitude are followed by treatments on a CPM machine for approximately 1 h. At night, the knee is left to rest.

In cases of mixed deficits, the reeducation work is again more aggressive with an awakening of the extensors and flexors of the knee and forced attitudes of flexion and extension alternating every 4 h for 1 h (1 h of forced flexion and 1 h later in forced extension). These attitudes are followed by work on the CPM machine.

31.7 The Results

For patients operated on for articular stiffness are less satisfactory than for those in the control group. For Harner et al. [12], one must note a loss in the amplitudes from 5° in extension and 21° in flexion without constraint on the patellofemoral joint or the residual laxity. In this study, 67 % of patients who had an arthrolysis had a good or excellent result compared to 79 % for the control group. Aglietti et al. [1] found that 58 % among 31 patients who underwent an arthrolysis were satisfied by the improvements of their symptoms and 71 % are satisfied as it relates to their range of motion. One should note that despite this, the final result is only satisfactory in 37 % of cases. For him, the result is better if the surgery is done precociously.

Tayot et al. [32] showed that 75 % of 52 patients who underwent arthrolysis recovered normal range of motion.

Hasan et al. [13] showed that there exists an average of 3° residual flexion contracture.

To summarize, one should note that despite the arthrolysis, there persists some loss of motion and the fact that extension deficits of a few degrees are more inconvenient than flexion deficits of 20–30°. The results on stability are good, but the global results are clearly inferior in comparison to those of reconstruction without complication.

Conclusions

Stiffness of the knee after anterior cruciate ligament reconstruction is not an exceptional complication but the veritable treatment is that of prevention.

Preoperatively, the knee should have recovered its full amplitudes of motion particularly in extension, be non-tender, and have a good control of the quadriceps.

Surgically, the technique must be precise and the least aggressive possible.

Postoperatively, the proper amount of pain control as well as a rapid recovery of extension is necessary.

If, despite these precautions, postoperative stiffness ensues, precocious surgery is preferable before a significant arthrofibrosis organizes itself in the periarticular tissues, with late surgery giving less favorable results.

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32 Septic Arthritis After Anterior Cruciate Ligament Reconstruction

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Contents

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32.1 Introduction

Septic arthritis following anterior cruciate ligament reconstruction (ACL) is considered a devastating complication given the simplicity, reproducibility, and favorable-associated results of this intervention.

Literature review regarding ACL reconstruction reveals 1,000 of published articles. To our knowledge and after having excluded all published case reports, only 22 published articles investigated the frequency, risk factors, surgical techniques, functional and infectious results, and/or the prevention of septic arthritis following ACL reconstruction.

32.2 Epidemiology

32.2.1 Prevalence

The prevalence varies from 0.14 [14] to 1.7 % [26] (Table 32.1). Sonnery-Cottet et al. [28, 29] reports a prevalence of 5.7 % in professional athletes who benefited from an intra-articular gesture associated with an extra-articular lateral tenodesis in comparison to 0.42 % in the control group of the same series (sample from the general population). Infection after ACL reconstruction is therefore not an exception [23, 30].

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Table 32.1 Literature review concerning the prevalence of infection after ACL reconstruction

Author	Journal	Year	Prevalence (%)
Williams et al. [33]	*AJSM*	1997	0.3
McAllister et al. [19]	*AJSM*	1999	0.48
Indelli et al. [14]	*Clin Orthop Relat Res*	2002	0.14
Schollin Borg et al. [26]	*Arthroscopy*	2003	1.7
Fong and Tan [9]	*Ann Acad Singapore*	2004	1
Binnet and Basarir [3]	*Arthroscopy*	2007	0.86
Katz et al. [18]	*Arthroscopy*	2008	0.75
Wang et al. [31, 32]	*Arthroscopy*	2009	0.52
Barker et al. [2]	*AJSM*	2010	0.58
Sonnery-Cottet et al. [28, 29]	*AJSM*	2011	5.7
	OTSR	2011	5.7
Jameson et al. [16]	*Knee*	2011	0.25

32.2.2 Risk Factors

Prior homolateral knee surgery [17], an associated peripheral surgery [28, 29, 33], and most importantly, an early surgical management after the accident [9, 28, 29, 33] are known to increase the risk of postoperative sepsis. According to Sonnery-Cottet et al. [28, 29], the delay from the date of the accident and the date of surgery was 12.6 months in the general population compared to 43 days in professional sportsmen. The author deduces that the increased risk of sepsis is principally due to the exposition of the skin to telluric compounds during sports at risk (football, rugby) and the short accident-surgery interval.

The type of transplant used in the reconstruction can also be condemned as the cause, especially in the case of allografts. This notion was investigated by Barker et al. [2] who found the use of tendon allografts to have no effect on the risk of infection. Furthermore, Katz et al. [18] reported that the use of tendon allografts actually reduces the risk of infection by twofold when compared with an autograft. In addition, the presence of bacteria on the allograft, at the time of its implantation, was not correlated to the occurrence of a postoperative infection. This therefore led the author to discourage systematic allograft bacteriological examination [6, 10].

Among the types of autografts, hamstrings tendon autografts showed the highest risk of infection [2, 17].

32.3 Diagnosis

Diagnosis is usually straightforward. It commonly occurs as an early set infection 5–8 days following the intervention. It is marked by fever associated with a hot, swollen, and painful knee. The presence of wound discharge may occur. Blood work usually reveals an elevated level of C-reactive protein. X-rays performed at this stage are usually normal as the infection remains limited to soft tissues. Knee aspiration for bacteriological culture examination should not be delayed as it is considered the first step of treatment. The usual cultured bacteria are methicillin-sensitive or methicillin-resistant *Staphylococcus aureus* and *Staphylococcus epidermidis*.

32.4 Treatment

32.4.1 Systemic Treatment

Septic arthritis of the knee following ACL reconstruction should be treated in the same manner as that of other joints. If possible, a multidisciplinary team involving the surgeon, an infectiologist, a bacteriologist, and a pharmacist should be set up to give the best chances of success.

The treatment should always include a surgical and a medical steps. Surgically, the following guidelines are followed:

- Intra-articular samples must be collected intraoperatively before starting the antibiotic treatment.
- Articular arthroscopic washout is prolonged and abundant. The use of a motorized shaver to perform a reduction synovectomy might be necessary if a hypertrophic synovium is encountered.
- Postoperative articular drainage is systematically performed.

A probabilistic parenteral antibiotic therapy is initiated immediately after having obtained the bacterial samples. It usually consists of vancomycin and gentamicin if no contraindications are present. The treatment is later adapted to the germ, passing if possible from parental to oral, according to the results of the bacterial culture and sensitivity tests. Duration of antibiotherapy is about 45 days.

32.4.2 Four Questions Give Birth to a Controversy

- Should the surgical wound be excised or does an arthroscopic lavage suffice?
- Should the fixation material be changed?
- Should the graft be removed?
- When should iterative arthroscopic procedure be proposed?

32.4.2.1 Should the Surgical Wound Be Excised or Does an Arthroscopic Lavage Suffice?

Excision of the surgical wound is, in our opinion [4], compulsory and is performed systematically even in the absence of a fistula [33]. This is because the bone tunnels create a path connecting the articular cavity to the loge surrounding the graft harvesting area (patellar tendon or hamstrings tendon). A simple arthroscopic lavage will not ascertain the adequate wound debridement of the harvest zone.

32.4.2.2 Should the Fixation Material Be Changed?

Bacteriological contamination of the fixation material, especially the bioabsorbable type, is probable and will therefore oblige to either remove or more conveniently change it. In an in vitro experimental study conducted by Gerard [12], titanium and bioabsorbable (PLLA + PDLA) screws were immersed into a *Staphylococcus aureus* solution. After contamination, the screws were washed four times in saline solution to eliminate germs adsorbed in the aqueous phase. The last step was trypsinization to detach germs remaining fixed onto the screws and contained in the biofilms of glycocalix. A germ count was made after each step. Finally, the remaining number of germs adherent to each screw was calculated. The mean count of germs found fixed in the biofilm was 17.695,10.5 for the titanium screw and idem for the bioabsorbable screw. This therefore confirms the presence of germs, even after lavage, stuck to the surface of the screws forming an antibiotic-resistant biofilm especially when bioabsorbable screws are concerned (adsorption phenomenon).

The screws, especially bioabsorbable ones, accentuate the adsorption of germs that justify their replacement. Technically, the removal of the tibial fixation is considered non-challenging in contrast to that of the femoral component. A femoral in-out or all-inside technique regardless of the fixation type (Endobutton – Smith and Nephew, intermediate like Rigid fix – Mitek or Transfix – Arthrex, and juxta-articular interference screws) renders the removal more difficult. In these cases, the surgeon should carefully consider the risk-benefit of removal versus fragility of the graft fixation.

32.4.2.3 Should the Implant Be Removed?

The transplant (autograft or allograft) is by definition acellular and avascular. It consists of an inert graft that is detected by the human body as a foreign body thus favoring the development of infections. On that account, the implant should be resected to completely eradicate the infection. However, implant resection will bring about an unsatisfactory functional result with the reappearance of the initial laxity. After considering the risk-benefit of resection, the majority of authors are more in favor of conserving the transplant (particularly in first trials of therapeutic irrigation). In the ten related publications, only three

Table 32.2 Should the graft be removed?

No			Yes		
Indelli et al. [14]	*Clin Orthop Relat Res*	2002	Williams et al. [33]	*AJSM*	1997
Fong and Tan [9]	*Ann Acad Med Singapore*	2004	Schulz et al. [27]	*AJSM*	2008
Van Tongel	*AJSM*	2007	Barker et al. [2]	*AJSM*	2010
Binnet and Basarir [3]	*Arthroscopy*	2007			
Wang et al. [31]	*Arthroscopy*	2009			
Monaco et al. [21, 22]	*J Orthop Sci*	2010			
Demirag et al. [8]	*Acta Orthop Traumatol Turc*	2011			
Sonnery-Cottet et al. [28]	*AJSM*	2011			

authors preferred transplant resection, while the remaining seven authors were able to save the transplant in 69 of 72 cases (Table 32.2). From this, we should conclude that an arthroscopic lavage is sufficient and achieves a significant reduction in the bacterial concentration thus permitting an effective antibiotic therapy despite the presence of an inert graft. An infection in the presence of prosthetic implants, which are rarely used in ACL surgery, was never specifically investigated. The implant structure favors bacterial adsorption more importantly than auto- or allografts pushing to the proposition of their resection if infected. This is only an expert's opinion.

32.4.2.4 When Should an Iterative Arthroscopic Procedure Be Proposed?

The objective, in case of an infection, is to obtain complete healing as rapidly as possible to guarantee preservation of the function and important structures especially the cartilage. That is why, in cases of septic arthritis of the knee, we have proposed repeating an arthroscopic lavage [4] whenever an unsatisfactory result presents or the ideal management regimen was not respected (long delay, resistant germ, initial unadapted antibiotic therapy). Furthermore, literature review (Table 32.3) clearly shows this notion because the number of interventions varies between 1.28 [28, 29] and 2.75 [19]. The principal of a repeated arthroscopic lavage should therefore be included in the initial management strategy and the patient informed from the start.

The principal elements to consider are:

- Delay of management
- Germ resistance
- Clinical evolution: fever, status of the knee, status of the wound
- Presence or absence of bacteria in the drains in the days following the index arthroscopy
- CRP evolution

These criteria permit the proposition of a management outline shown in Fig. 32.1.

32.5 Results

In this young population, usually without comorbidities, results regarding infection are constantly good given that an adapted and aggressive (repeated arthroscopy) management was conducted.

The functional results depend largely on the rapidity of the eradication of the infection. An immediate favorable evolution can give a chance for an integral restoration of function [28, 29]. Unfortunately, these complete results are not always obtained.

Knee stiffness may be observed and can be attributed to the formation of adhesions in the quadricipital pouch or the condylar gutters. A secondary arthroscopic arthrolysis is then necessary. MacAllister [19] and Schollin Borg [26] underline the risk of imperfect functional results most commonly related to articular cartilage involvement.

32.6 Prevention

The surgeon can directly control two risk factors.

The operative delay: if not directly contraindicated, it is not advised to perform the ACL

Table 32.3 Number of arthroscopic washout (in average)

		N of arthroscopies (average)
Williams et al. 1997 [33]	*AJSM*	1.6
McAllister et al. 1999 [19]	*AJSM*	2.75
Fong and Tan 2004 [9]	*Ann Acad Med Singapore*	1.4
Judd et al. 2006 [17]	*Arthroscopy*	2.4
Schulz et al. 2007 [27]	*AJSM*	2.4
Sonnery-Cottet et al. 2011 [28]	*AJSM*	1.28

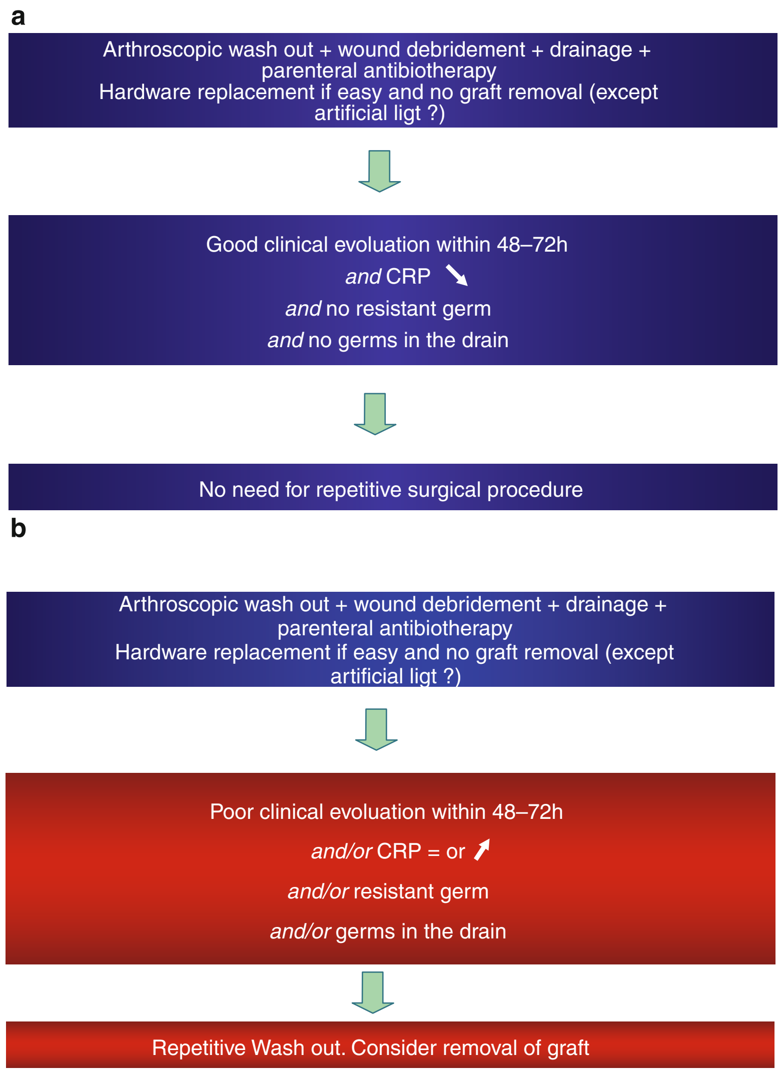

Fig. 32.1 Surgical treatment algorithm: (**a**) in case of good evolution and (**b**) in case of poor evolution

reconstruction in an acute or subacute manner but rather operate after a 45-day delay.

Associated peripheral gestures should not be performed unless otherwise indispensable. In particular, the anterolateral tenodesis in association with the ACL reconstruction should only be performed in the presence of major anterior laxity, an explosive jerk test, or in revision reconstructions.

Grayson et al. [13] have recently proposed to soak the transplant in a vancomycin solution. Soaked tendon grafts can act as reservoirs for vancomycin, with the amount released and elution profile dependent on rinsing, tendon volume, and soak solution concentration. Vancomycin elution was lower than previously reported osteoblast and chondroblast toxicity concentrations and above the minimum inhibitory concentration for *Staphylococcus*. The authors conclude that presoaking ACL reconstruction autografts with vancomycin may reduce the risk of ACL reconstruction infection without the risk of local or general toxicity.

The last point concerning prevention that merits to be discussed is the course of action when the transplant is dropped onto the operative room floor. This rare incidence can occur and may cause unexpected drawback. What should be our reaction? Eight publications [1, 5, 7, 11, 15, 20, 25, 26] were found when the keywords “contaminated graft” were searched but do not appear to offer a proven consensual solution. The following attitude can be theoretically proposed:

- Reuse the fallen implant (which is contaminated in 53 % of cases according to Molina et al. [20] with the risk of secondary infection).
- Harvest another autograft. The patient is usually not informed (except in case of spinal anesthesia), and the use of a second implant might be the source of surgical difficulties (surgical harvest, harvest and fixation material availability, surgical expertise in other types of reconstruction).

In a questionnaire sent to 20 French orthopedic surgeons, specializing in the knee by Orthorisq [24] which is a national structure devoted to collect risk factors in orthopedic surgery, 26 cases of fallen transplant were reported. In 80 % of these cases, the transplant was reused, without any reports of infection. Even though the soaking protocols were not completely identical, the majority of surgeons used an iodine-based solution. In six cases, the antibiotic therapy was prolonged for 48 h to 10 days. This practical investigation shows us that surgeons prefer a minimal risk of postoperative infection rather than a mechanical risk.

The clinical trial of Casalonga et al. [5] proposes the reutilization of the graft after soaking in a solution containing Rifocine (0.8 mg/ml [200 mg/250 ml]) associated with gentamicin (0.6 mg/ml [160 mg/250 ml]) for 10 min followed by washing using normal saline.

For the experimental study of Molina et al. [20], the comparison between three protocols of decontamination showed a superiority of the protocol involving soaking in a solution of chlorhexidine gluconate (2 % residual contamination) over the antibiotic solution containing polymyxin B and neomycin (6 % residual contamination) and that containing polyvione-iodone (24 % residual contamination).

The propositions of the Orthorisq society [24] are to reuse the fallen graft after soaking it in a chlorhexidine gluconate solution for 90 s. In relation to other incidents encountered in orthopedics, it is not necessary to prolong the antibiotic therapy more than 48 h (even more because it is a broad-spectrum antibiotic therapy). The patient has to be informed of the incident.

Conclusion

Postoperative infection after ACL reconstruction is a rare but devastating complication. The potential repercussions on the functional results (stiffness, laxity, cartilaginous lesions) demand an early diagnosis, sample acquisition and precise germ identification prior to antibiotic therapy, and an arthroscopic articular lavage combined with wound debridement. A broad-spectrum antibiotic therapy is first initialized and later adapted according to the bacterial culture and sensitivity. The surgeon should not hesitate to propose a second arthroscopic therapeutic irrigation if confronted with an unsatisfactory clinical and biological evolution. The transplant can be usually preserved. Prevention includes rigorous aseptic surgical precautions, selective and reasonable indications in operating acute or subacute cases, and/or performing an associated peripheral gesture.

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Deep Venous Thrombosis and Pulmonary Embolism After ACL Reconstruction: What Can We Do to Prevent It?

33

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33.1 Introduction

Deep venous thrombosis (DVT) and its most fatal complication, pulmonary embolism (PE), are manifestations of a single disease entity, that is, venous thromboembolism (VTE). VTE is a common and clinically relevant complication of major orthopedic surgery. Indeed, it is associated with a significant morbidity and mortality. With the advent of arthroscopic surgery, the incisions have become smaller and the rehabilitation faster, but in spite of this, there are reports of VTE following arthroscopic surgery. Most of the research is related to arthroscopic surgery alone. We have reviewed the literature and have found the DVT complication rate to be between 0.15 and 18 % in lower limb arthroscopic standard surgery (see Sect. 33.2). Arthroscopically assisted surgeries, like anterior cruciate ligament (ACL) reconstruction, are more aggressive than standard arthroscopy, take a longer time, and therefore should

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potentially be more predisposed to DVT. However, Jaureguito et al. [20] reported that patients undergoing arthroscopically assisted surgery had only a slightly higher incidence of DVT as compared to routine arthroscopic surgery, but this difference was not statistically significant. These findings, in agreement with those of Hoppener et al. [15] did not find a higher DVT risk in ACL reconstruction or in other more complex arthroscopic procedures. Also, Hetsroni et al. [13], after reviewing more 400,000 outpatient arthroscopies, found no increase in the PE risk when the arthroscopic procedure involved an ACL reconstruction or a meniscal repair, surgeries that theoretically would have a higher risk of VTE.

Literature review regarding ACL reconstruction reveals thousands of published articles. There is a commonly held view that arthroscopic ACL reconstruction is a safe procedure with low complication rates. The literature shows little information on VTE. After an extensive literature search, we have found only a few papers [1, 3, 5, 13, 17, 19, 22] specifically analyzing the incidence, risk factors, and prevention of VTE after ACL reconstruction. And, to the best of our knowledge, only one fatal PE after an ACL reconstruction has been reported [19]. The reader may therefore draw the conclusion that thrombotic events following arthroscopic ACL reconstruction do not represent a real clinical problem. Nothing could be further from the truth. DVT is an underdiagnosed entity that could lead to a fatal PE or to post-thrombotic syndrome (PTS), with long lasting effects and complications. However, despite this, we have not found a consensus in the literature on the need for VTE prophylaxis in ACL reconstruction surgery.

33.2 Incidence of VTE in ACL Reconstruction Surgery: The Current Status of the Problem

Generally speaking, the postoperative risk of VTE varies considerably with the type of surgery and reaches a peak at about 3 weeks after surgery, although risks are substantially increased up to 12 weeks postoperatively [32]. Sweetland et al. [32] estimated that 1 in 140 middle-aged women undergoing inpatient surgery will be admitted with VTE during the 12 weeks after surgery, compared with 1 in 815 after day-case surgery and only 1 in 6,200 women during a 12-week period without surgery.

The incidence of VTE in general arthroscopic surgery is highly variable. Small [28] have found symptomatic DVT in 0.15 % of arthroscopic surgeries, performed by experienced arthroscopists, with no fatal PE. Dahl et al. [6] found symptomatic, objectively confirmed DVT in only 0.6 % of 1,355 patients after diagnostic knee arthroscopy without the use of thromboprophylaxis; only one patient developed proximal DVT. However, the rates of DVT in prospective studies of knee arthroscopy, without thromboprophylaxis but with routine screening for DVT, range from 2 to 18 % [10, 27]. Stringer et al. [30] found a 4 % incidence of DVT, using venography, in 48 patients after arthroscopy. Another study had a rate of venographically detected DVT of only 3 % among 170 patients after arthroscopic knee surgery [9]. In a prospective study of 184 patients who had a venography 1 week after therapeutic knee arthroscopy, the rates of DVT and proximal DVT were 18 and 5 %, respectively [9]. No patient presented with clinically suspected PE. In another study [20], routine DUS (Doppler ultrasound) was performed 5–10 days after knee arthroscopy. Asymptomatic DVT was detected in 2 % of 239 patients, a rate ten times higher than for symptomatic DVT (0.2 %) among a cohort of 2,050 similar knee arthroscopy patients from the same institution who did not undergo DUS. Delis et al. [7] studied the incidence and vein distribution of DVT in elective knee arthroscopy in patients with no prophylaxis. DVT was diagnosed by means of color duplex ultrasound. The reported incidence was 7,8 %. Propagation of a calf DVT to the popliteal vein was identified in one patient (12.5 %), indicating that most of the thrombi form in veins distal to the popliteal vein. Finally, in a meta-analysis that included 684 patients, VTE's incidence after an arthroscopy in patients without prophylaxis was 10 %, and proximal DVT was 2 % [16]. It is important to emphasize the difference between a distal DVT, of which the clinical significance is questionable [15], and a proximal DVT that may progress to a PE, that fortunately affects less that 1 % of the patients undergoing knee arthroscopy [13]. Also, we should not forget that between 40 and 50 % of the DVT cases diagnosed by ultrasound or venogram are clinically asymptomatic [2].

As we have seen, there is great variability in the incidence of DVT after arthroscopic surgery in the medical literature published series. This variability depends on the methods used to detect the DVT (venography, DUS, color duplex ultrasound, magnetic resonance venography) and the heterogeneity of the series (depending on the inclusion or not in the series of patients with DVT risk factors – see Sect. 33.3). This variability is also found in the series specifically analyzing DVT's incidence after ACL surgery (1.78–41 %).

Adala et al. [1] found a very low incidence of DVT (1.78 %) after ACL reconstruction. They reported only two cases of DVT in a series of 112 ACL reconstructions performed by the same surgeon and no use of prophylaxis. They completed DUS only in patients who consulted for DVT symptoms. However, we must note that there are many asymptomatic DVT episodes that go undiagnosed. In most cases, the thrombi dissolve spontaneously. Inoue et al. [17] found that up to 90 % of DVT cases may show no symptoms at all. In their study, they found an incidence of DVT of 21 %. Cullison et al. [5] in their prospective study reported a 15 % incidence of DVT following ACL reconstruction, and none of the patients had received thromboprophylaxis. Finally, Marlovits et al. [22] showed that the incidence of DVT (confirmed by magnetic resonance venography) after ACL reconstruction, in patients who only received prophylaxis with enoxaparin during their hospital stay and not after discharge, was up to 41.2 % . Lastly, Janssen et al. [19] in their series of 625 arthroscopic ACL reconstructions using hamstrings found only one case of fatal PE, which is a PE incidence of 0.2 %. Also, Hirota et al. [14] showed by means of transesophageal echocardiography pulmonary emboli in all ACL reconstructed patients after tourniquet release. However, PE is very rare after arthroscopy, and most of the cases are silent and respond to treatment [2]. Symptomatic PE affects less than 1 % of knee arthroscopies performed as outpatient procedures [13].

In conclusion, patients undergoing ACL reconstruction are at risk of VTE when compared with a nonsurgical population, but much less than lower limb arthroplasty patients. Based on a middle-aged female, nonsurgical population, the general background risk of a VTE event was for a 90-day period the equivalent to 0.017 % risk. VTE rates are 26 times higher than the background risk (0.44 %) after ACL reconstruction and 120 times higher (2 %) after lower limb arthroplasty [32].

33.3 What Factors Influence The Development of DVT After ACL Reconstruction? Risk Factors and Clinical Relevance

VTE prevention is a real challenge for the orthopedic surgeon. First of all, in order to prevent a problem, in this case VTE, we need to know what the risk factors of that problem are and then act upon them. There are many risk factors in the development of VTE (see Table 33.1) that the reader may find in any internal medicine book or clinical practice guide. The analysis of those factors is not the aim of this chapter. Our intention is to analyze and to discuss only those factors that are closely related to ACL surgery in the age group of the ACL rupture patient: to use or not to use a tourniquet, tourniquet time, and the patient's age.

33.3.1 Tourniquet During ACL Reconstruction as a Risk Factor

The value of a tourniquet during ACL reconstruction is to minimize bleeding and to provide a clear field for arthroscopic visualization during the procedure. The increased risk of DVT with tourniquet use has been clearly documented in lower extremity surgery, particularly with prolonged

Table 33.1 General risk factors for venous thromboembolism

Advanced age
Obesity
Tobacco use
Varicose veins
Hormonal contraceptive use
Major systemic trauma
Lower extremity trauma
Prolonged immobilization
Personal or family history of previous deep venous thrombosis or pulmonary embolism
Full or partial paralysis of lower extremities
Pregnancy or postpartum status
Treatment with selective estrogen receptor modulators
Acute medical illness
Heart failure
Respiratory failure
Inflammatory bowel disease
Myeloproliferative disorders
Central venous catheterization
Cancer
Known thrombophilic condition

tourniquet times [8, 12, 20, 31]. Demers et al. [8] showed that a tourniquet time of more than 60 min was a statistically significant factor associated with the development of DVT. This factor can be extrapolated to ACL reconstruction surgery, where surgical times are on average longer than a standard arthroscopy. This states that patients who undergo lower limb surgery lasting for more than 60 min, including anesthetic time (defined as "high risk"), may benefit from thromboembolic prophylaxis and should be offered both chemical and mechanical prophylaxis, although this is not evidence based [25]. Hirota et al. [14] reported a significant linear correlation in the percentage of atrial emboli and tourniquet time in ACL surgery. Finally, Hetsroni et al. [13] observed that when the surgical procedure lasted longer than 90 min, the risk of PE was three times higher, compared with the procedures that lasted under 30 min.

One of the possible actions to prevent DVT would therefore be to not use a tourniquet. Bach et al. (see Chap. 14) are able to adequately visualize intraoperatively without tourniquet usage via the following guidelines: using a diluted epinephrine solution within the arthroscopic fluid solution (1.5 mL of .001 % epinephrine per 5 L bag of fluid), maintaining a systolic blood pressure less than 110 mmHg, and using arthroscopic electrocautery as needed. They inflate the tourniquet in fewer than 3 % of their cases, thereby reducing the risk of DVT and/or PE. In their experience (see Chap. 14) with more than 1,700 patients with ACL reconstructions since the transition to outpatient surgery, one patient was diagnosed with a nonfatal PE, and only one patient had a DVT postoperatively. In this way, Smith and Hing [29] observed that there may be a greater incidence of DVT in tourniquet-assisted foot and ankle procedures.

33.3.2 Age as a Risk Factor

Another risk factor for the development of DVT is age. Inoue et al. [17] found that the incidence of DVT in patients 30 years of age or older was significantly higher than in those younger than 30 years of age. Marlovits et al. [22] also concluded that 30 years of age or older as well as immobilization before surgery was statistically significant for increased risk of DVT. Hetsroni et al. [13] observed that in the group between 20 and 29 years of age, the risk of PE increased more than twofold compared to the age group under 20. This risk was increased more than sixfold for patients over 40. This indicates clearly that age is a risk factor for symptomatic PE. We should keep this factor in mind each time we perform an ACL in a patient over 30 years old.

33.3.3 Other Risk Factors

Janssen and Sala [19] describe a case of fatal PE and analyze the specific risk factors of their particular case. They found a combination of hereditary factors (protein S deficiency) and acquired factors (use of oral contraceptives and the ACL reconstruction surgery itself). They also highlight that a previous episode of thrombosis and having two or more DVT risk factors significantly increase DVT's incidence. Hetsroni et al. [13]

observed that a history of cancer increased the risk of PE threefold and that woman had a significant higher risk of PE than men. Also, Delis et al. [7] showed that the only statistically significant isolated factor was a previous history of VTE.

33.4 Diagnosis [26]

DVT can cause pain and limb edema; symptoms are often absent if the venous outflow obstruction is not complete. Edema is the most specific symptom of DVT. Leg edema that is usually bilateral rather than unilateral occurs if the iliac bifurcation, the pelvic veins, or the vena cava are affected by the thrombus.

Signs and symptoms of DVT are (1) pain in 50 % of the cases; (2) positive Homan sign (pain on dorsiflexion of the foot) in only 50 % of patients; (3) tenderness to palpation in 75 % of patients, although tenderness is also found in 50 % of patients without objectively confirmed DVT (when tenderness is present, it is usually confined to the calf muscles or along the course of the deep veins in the medial thigh); (4) a cord-like, tender subcutaneous vein can be palpated when the thrombotic episode occurs in the superficial venous system; and (5) skin discoloration of the lower extremity, the most common being reddish purple. Clinical signs and symptoms of PE as the primary manifestation occur in 10 % of patients with confirmed DVT.

No single physical finding or combination of symptoms and signs is accurate enough to establish the diagnosis of DVT. When DVT is suspected, a high-sensitivity D-dimer is a reasonable option, and if negative, it indicates a little likelihood of VTE. If D-dimer is elevated, ultrasonography is recommended. Ultrasound is less sensitive in patients who have DVT limited to the calf; therefore, a negative ultrasound does not rule out DVT in these patients. Contrast venography is still considered the definitive test to rule out the diagnosis of DVT [21].

The importance of early diagnosis to prevent mortality and morbidity associated with VTE cannot be overstressed.

33.5 Is There a Need for Thromboprophylaxis? What Does Evidence-Based Medicine Tell Us?

Contrary to popular belief, there is a real but small risk of VTE following ACL surgery (see Sect. 33.2). Whether this justifies thromboprophylaxis remains unanswered, given the lack of evidence in the medical literature. There is no accepted norm regarding thromboprophylaxis in patients undergoing arthroscopic-assisted ACL reconstruction. Moreover, there is no consensus as to the duration of therapy following ACL surgery if we give thromboprophylaxis.

We are aware of only three randomized clinical trials of thromboprophylaxis in knee arthroscopy patients that show the effectiveness and security of low-molecular-weight heparin (LMWH). In the first, patients were randomized to receive either no prophylaxis or the LMWH reviparin [33]. At the end of the study period, DVT was found in 4 % of control subjects and in 1 % of those patients who received LMWH. The only patient, in the thromboprophylaxis group, who developed DVT had low levels of protein C and protein S, which indicate a possible coagulopathy than could justify the DVT despite thromboprophylaxis. The authors recommended 10 days of prophylaxis. In the second trial [24], 130 patients undergoing diagnostic or therapeutic arthroscopy were randomized to receive either no prophylaxis or once-daily dalteparin for up to 30 days. DUS was obtained at 12 and 30 days after surgery. The DVT rates in the control and LMWH groups were 16 and 2 %, respectively. There were no cases of proximal DVT. No major bleeding complications were reported in any of the 182 patients who received LMWH in these two prophylaxis trials. Also, an excellent RCT by Camporese et al. [3] in a large sample of 1,761 arthroscopy patients with low risk for DVT showed a 72 % relative risk reduction of clinically relevant DVT in those who received LMWH for 7 days compared to those who wore full-length graduated stockings for 7 days. In this study, the primary efficacy endpoint included symptomatic PE, proximal DVT, and symptomatic distal DVT (excluding asymptomatic distal DVT). At 3 months, the cumulative incidence was 3.2 % (21 of 660 patients) in the stocking group and 0.9 % (6 of 657patients) in the 1 week LMWH. The number needed to treat (NNT) was 43 patients (95 % IC 25, 143) in order to avoid one clinically relevant VTE episode for a 3-month period. There were no significant differences in clinically relevant bleeding episodes between groups, although the 7-day LMWH had 0.9 % incidence (6 of 657 patients) and the stocking group 0.6 % (2 of 660 patients), giving a relative risk reduction of 0.3 (95 % IC −1.5 to 0.2). Interestingly, this study did not find differences between 7 and 14 days LMWH regime. In summary, although some uncertainty remains on the risk of VTE in patients undergoing knee arthroscopy, compared to most of the other major orthopedic surgery procedures, the risk appears to be low. The results of these trials have suggested that LMWHs reduce the rate of DVT without additional complications, but further studies are required before prophylaxis recommendations can be made. In the meantime, prophylaxis decisions should be made at the institutional or individual patient level.

Geerts et al. [10] reviewed the evidence-based literature about thromboprophylaxis in knee arthroscopy and only recommend prophylaxis with low-molecular-weight heparin when thrombosis risk factors were present. These are a history of VTE, age of 40 and older, length of surgery >60 min, or after a complicated/prolonged procedure (level of evidence 2B). No prophylaxis is recommended if no risk factors are found. Although these authors are not making any specific recommendations for arthroscopic ACL reconstruction patients, they are indirectly describing a great number of ACL reconstructed patients, for whom they do in fact recommend thromboprophylaxis. ACL surgery would be a moderate risk for VTE because of the tourniquet use and long duration of surgery.

We find the method used to quantify DVT risk designed by Caprini et al. [4] interesting and depending on the score obtained, different prophylaxis strategies—personalized or à la carte treatment—can be established.

33.5.1 What Do Specific ACL Series Tell Us?

Current guidelines from the statement of best practice in primary ACL reconstruction for an isolated rupture, approved by the British Orthopaedic Association, British Association for the Surgery of the Knee, and British Orthopaedic Sports Trauma Association, state that the risk of DVT following ACL surgery is very low, and routine prophylaxis is not indicated [18]. In this sense, we should emphasize that the Danish ACL registry reported that only 16 % of the patients who underwent an ACL reconstruction received pharmacologic thromboprophylaxis (see Chap. 2).

Adala et al. [1] do not recommend routine thromboprophylaxis in patients undergoing arthroscopic ACL reconstruction, who are not high-risk candidates for thrombosis and are less than 45 years old, when an early postoperative rehabilitation is followed. These authors have done an evidence level 2 prospective cohort study. They studied 112 consecutive patients under 45 years of age (61 men and 51 women), who underwent an arthroscopic ACL reconstruction with no thromboprophylaxis. In only two patients, the DUS showed a DVT. One patient was asymptomatic; the other patient was symptomatic 12 weeks after surgery with pain and swelling in his leg.

Cullison et al. [5] in a prospective study performed in men over 40 who had undergone an ACL reconstruction with no thromboprophylaxis found only 1 case out of 67 of DVT using compression ultrasonography. Furthermore, this patient was asymptomatic, and the situation resolved after 10 days. This was a case series (level of evidence IV). The authors conclude that no routine thromboprophylaxis should be recommended in male patients under 40 who undergo an arthroscopic ACL reconstruction, as long as there are no associated factors. Therefore, this recommendation cannot be extrapolated to females or to risk factor patients.

Lastly, Marlovits et al. [22] published, to the best of our knowledge, the only double-blind randomized prospective clinical trial (level I evidence) comparing the effectiveness of the duration of the thromboprophylaxis with enoxaparin for 3 weeks after an arthroscopic ACL reconstruction and for 3–8 days after surgery. The authors found a significant reduction of DVT incidence evaluated by routine magnetic resonance venography (2.8 versus 41.2 %). Thromboprophylaxis did not increase bleeding. However, what is remarkable is that the percentage of DVTs found is highly dependent on the diagnostic method used. Magnetic resonance venography has a sensitivity of 100 % and a specificity of 96 %. Furthermore, this study was performed late after surgery (from 23 to 28 days postsurgery). On the other hand, the mean duration of surgery was more than 2 h, which is a risk factor for DVT.

33.5.2 Author's Preferred Protocol

It is clear that everybody agrees on using thromboprophylaxis in patients with risk factors. There is no controversy in that. We are in favor of using thromboprophylaxis with LMWH in all patients undergoing an ACL reconstruction even when the patient has no risk factors, although the evidence supporting this is weak (expert's opinion—level V of evidence). Our reasons for doing so are (1) the possible damage that we can cause is imperceptible; (Camporese et al. [3] found no significant differences in bleeding between the group with LMWH and the group without prophylaxis; furthermore, the bleeding found was minor in both cases—level I of evidence); (2) the significance of asymptomatic DVT is still unknown, but it is very frequent, and LMWH significantly reduces it (level I of evidence); (3) LMWH reduces symptomatic DVT and therefore, theoretically, the risk of PE and also reduces pain and disability caused by DVT that would limit the scheduled physical therapy required in these patients; and (4) without strong evidence, we would not change our common practice. Once we have determined the indication to use LMWH, the question we ask ourselves is for how long? Following the recommendations of Marlovits et al. [22], we use LMWH for 3 weeks (level I of evidence).

33.6 Complications of DVT

DVT can resolve on its own, but it can also progress toward life-threatening situations, such as PE, recurrent DVT, and post-thrombotic syndrome (PTS).

33.6.1 Pulmonary Embolism

The most fatal complication of DVT is PE. Pulmonary embolism may be fatal in its immediate course or may result in pulmonary hypertension in the long term [19]. Up to 40 % of patients have silent PE when symptomatic DVT is diagnosed [23]. Approximately 4 % of individuals treated for DVT develop symptomatic PE [26]. The mortality rate for PE in hospitalized patients is 10–12 %, which indicates the importance of the prevention of this complication [26].

33.6.2 Recurrent DVT

Left untreated, 50 % of patients have a recurrent, symptomatic DVT event within 3 months [26]. Presentations are similar to DVT, with pain and edema. Recurrence increases the risk of PTS [26]. Hansson et al. [11] observed a higher recurrence rate among patients with proximal DVT.

33.6.3 Post-thrombotic Syndrome

PTS is a chronic complication of DVT that can manifest from months to many years after the initial event. There is no standardized definition of PTS, but most descriptions include chronic postural dependent edema and pain or localized discomfort in a patient with previous venous thrombosis. Symptoms range from mild erythema and localized induration to massive extremity swelling and ulceration, usually exacerbated by standing and relieved by elevation of the extremity. The PTS affects 23 % of limbs 2 years after DVT [7]. This incidence increases from 35 to 69 % at 3 years and 49 to 100 % at 5–10 years [7]. The evidence suggests that the use of compression stockings starting 1 month after diagnosis or earlier and lasting 2 years after DVT diagnosis reduces the incidence and severity of PTS [26]. The only current treatment is the use of compression hose and elevation. In many patients, this is only partly effective in relieving swelling, pain, and venous ulcers.

33.7 Take Home Messages

- DVT is an underdiagnosed entity in knee arthroscopy patients, and its incidence ranges from 1.7 to 41.2 %. There is no certainty of the real incidence of DVT because of the different methods of evaluating it. Most of the DVT episodes are distal.
- The incidence of PE or fatal complications in ACL surgery is extremely low.
- The factors influencing the development of DVT are a tourniquet time of more than 1 h, over 30 years of age, immobilization prior to surgery, female sex, cancer, etc.
- Early mobilization and non-pharmacological thromboprophylactic measures are recommended.
- Prophylaxis with low-molecular-weight heparin is recommended in ACL arthroscopic surgery as it reduces the risk of clinically relevant DVT episodes (NNT 43, 95 % IC 25–143 from one good quality and great sample RCT) and the risk of clinically relevant bleeding is not significantly increased. The influence on PE or death events is unknown.
- The risks and benefits of pharmacological thromboprophylaxis should be evaluated individually and discussed with every patient in accordance with their values and preferences.

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Videos

Video 1 ACL reconstruction augmentation technique AMB & PLB (MP4 404699 kb)

Video 2 ACL reconstruction. The surgical technique (MP4 424462 kb)

Video 3 Anatomic ACL reconstruction: (3–1) Anatomic single bundle ACL reconstruction, (3–2) Anatomic double bundle ACL reconstruction (WMV 790522 kb)

Video 4 Lateral meniscus transplantation. Surgical technique. Bonus track: medial and lateral meniscal implants (ACTIFIT) + ACL reconstruction (BTPB) (MP4 520123 kb)

Video 5 What factors should be used to allow unrestricted return to sports activities? (WMV 65050 kb)

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